Fact Sheet of the Final Report (Contract 18TTD005): Characterizing Activity and Emissions of In-Use Commercial Harbor Craft

Background:
For this study, CARB entered into a contract with the University of California, Berkeley (UCB), who subcontracted with the University of California, Riverside (UCR), and the University of Southern California (USC) to characterize CHC spatiotemporal activity and in-use CHC emissions. This work provided CARB staff with real-world emission rates of DPM and NOx using three measurement approaches.

1. **In-Use Emissions Measurements: PEMS (Portable Emission Measurement System)**

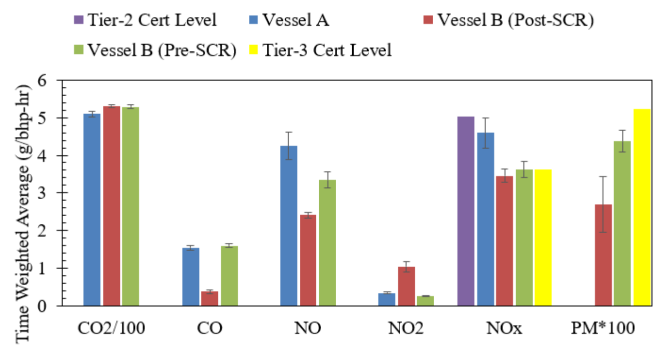
Laboratory-grade emissions measurements were performed using PEMS from a few vessels to evaluate emissions during in-use operation in relation to emissions reported during certification.

1.1 Experimental Approach:
Transient PM and NOx emissions were measured aboard two high-speed ferries, one Tier 2 (Vessel A) and one Tier 3 (Vessel B) vessel using PEMS to capture emissions from both low and high load duty cycles. Vessel B was equipped with a retrofit selective catalytic reduction (SCR) system that was not certified or verified by CARB or U.S. EPA. Emissions from Vessel B were measured both pre-SCR and post-SCR. The test route for Vessel A vessel began in Larkspur and ended in San Francisco. Vessel B traveled between Vallejo, San Francisco, and Richmond.

1.2 Results:

A. NOx and PM Emission Rates
Figure 1 shows average emission rates from both vessels for the entire test period excluding cold start data. NOx emissions from both vessels were close to the corresponding certification level. The time-weighted average NOx emission rate from the Tier 2 engine on Vessel A was 4.60 ± 0.40 g/bhp-hr, lower than the certification level of 5.04 g/bhp-hr. Pre-SCR NOx emission rates from the Tier 3 engine on Vessel B were 3.45 ± 1.03 g/bhp-hr, near the engine certification level of 3.61 g/bhp-hr. During this study, the unverified retrofit SCR did not perform as designed; for more details refer to the attached report. Pre-SCR PM emissions rates from the Tier 3 engine on Vessel B were 0.044 ± 0.003 g/bhp-hr, below the certification level of 0.052 g/ bhp-hr (page 29 of the report).

Figure 1. Average Emission Rates for Both Vessels



B. Comparison of Emissions per Passenger for Car, Bus, and Ferry.

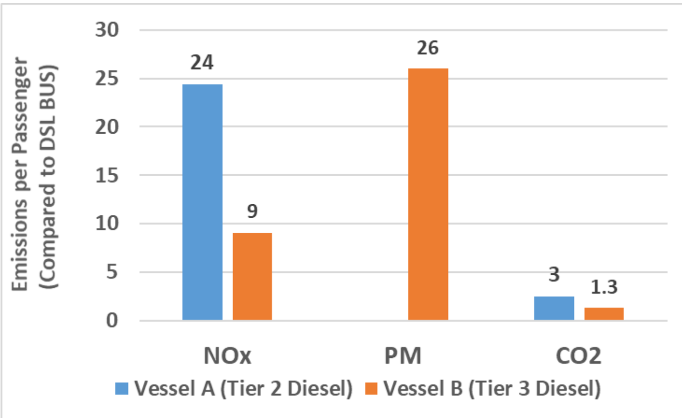
- For this analysis, the locations of the ferry terminals were used as the starting and stop points of all trips regardless of mode. The passenger car was assumed to have one passenger and the bus was assumed to have 20 passengers. Vessel A was assumed to be at half capacity of 225 passengers and Vessel B was also assumed to be at half capacity of 200 passengers (page 38 of the report).

- Vessel A emitted approximately 0.75 times the amount of CO_2 emissions per passenger and 21 times the NOx emission per passenger than a single passenger car; it emitted approximately 3 times the amount of CO2 emissions per passenger and 24 times the NOx emission per passenger than a diesel bus (Figure 2, page 40 of the report).

- Vessel B emitted approximately 0.4 times the amount of CO2 emissions, approximately 8 times the NO_x emissions and 4 times the PM emissions per passenger than a single passenger gasoline car; It emitted approximately

1.3 times the amount of CO2 emissions per passenger and 9 times the NOx emission and 26 times the PM emissions per passenger than a diesel bus (Figure 2, page 40 of the report).

Figure 2. Emissions per Passenger (Diesel Vessel vs. Diesel Bus)

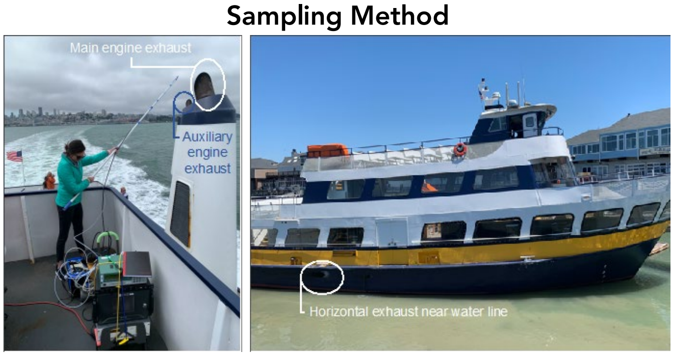


2. In-Use Emissions Measurements: On-board Plume Capture

2.1 Experimental Approach:

A plume capture approach was used to characterize in-use emissions from ferry, excursion, and commercial passenger fishing vessels. Figure 3 shows an example of the UCB contractors performing the plume capture method. The measured emission factors are fuel-based emission factors (not work based), and therefore not directly comparable to emission standards.

Figure 3. Exhaust Configurations and Plume Capture Sampling Method



2.2 Results:

A. Measured Black Carbon (BC) Emission Factors

Figure 4 shows average Black Carbon (BC) emission factors by engine tier. There was a downward trend in BC emissions from Tier 0 to Tier 4 engines, with Tier 4 engines emitting 92% less BC per kg of fuel burned than Tier 0 engines (e.g. pre-Tier 1), on average. The SCR retrofit on Tier 3 engines lead to a reduction in emitted BC from these engines compared to the Tier 3 engine without SCR (page 53 of the report).

Figure 5 shows cumulative distribution of BC emissions from the sampled fleet. The most polluting 20% of engines were responsible for nearly 40% of total BC emissions by this sampled fleet. Conversely, the cleanest 20% of engines contributed only ~5% of the total BC emitted (page 56 of the report).

Figure 4. Average BC Emission Factors by Tier

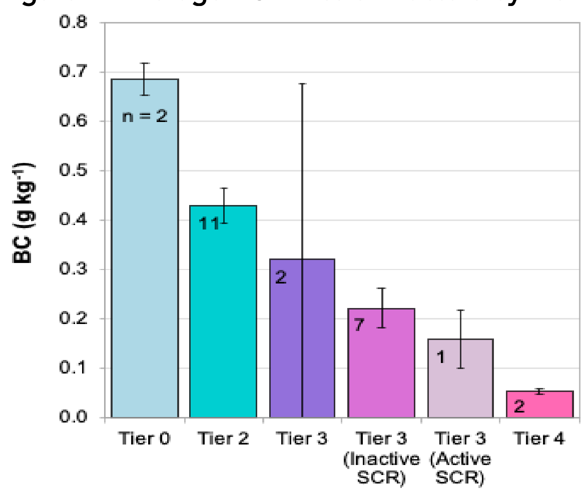


Figure 5. Cumulative Distribution of BC Emissions

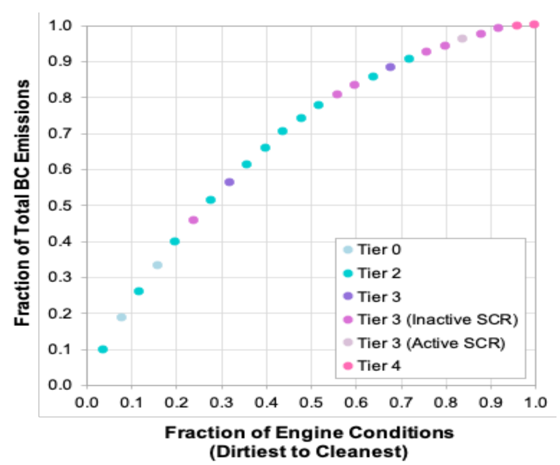
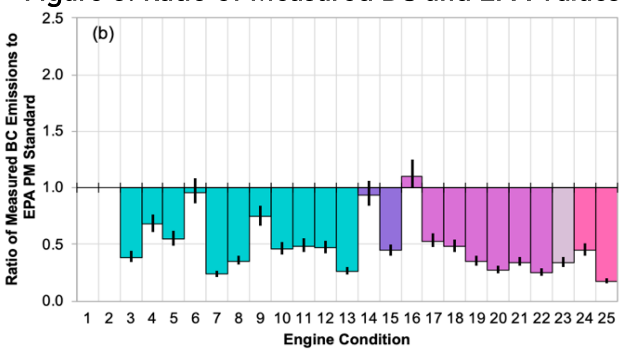


Figure 6 shows the ratio of the overall BC emission factor measured for each engine condition and corresponding U.S. EPA engine certification level and emission standard. This analysis makes an assumption for the brake-specific fuel consumption in order to compare the ratio of in-use emissions (fuel based) to emission standards (work based). The two Tier 0, most of the Tier 3, and both Tier 4 engines sampled in this study have BC emissions that were below their corresponding PM certification levels by 10–70%. All but one engine had average BC emission factors that met the PM exhaust limit (page 68 of the report).

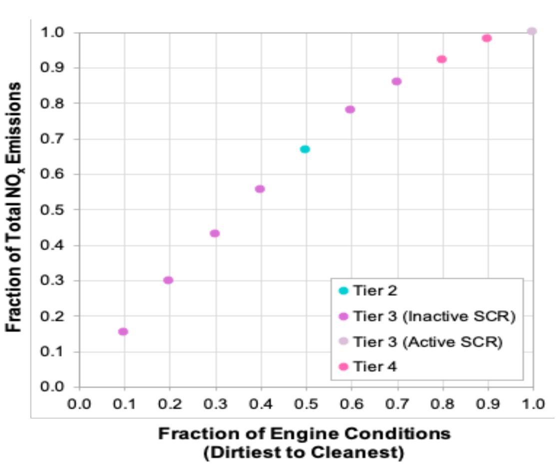
Figure 6. Ratio of Measured BC and EPA Values



B. Measured NOx Emission Factors

The plume capture method reported NOx emissions, which are discussed in the final report. In this study, the small sample size and higher uncertainty of plume capture NOx measurements did not provide conclusive results. Figure 7 shows cumulative NOx distribution within the fleet; the highest-emitting 20% of engine conditions is responsible for 30% of total emissions, while the cleanest 20% of the fleet contributed <10% of total NOx emissions (page 61 of the report).

Figure 7. Cumulative Distribution of NOx Emissions

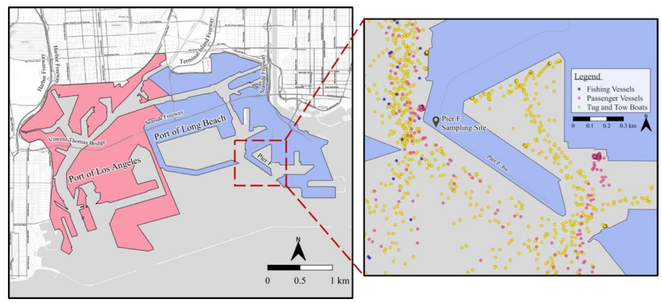


3. In-Use Emissions Measurements: Onshore Plume Capture

3.1 Experimental Approach

USC performed 78 shore-based measurements to determine BC emissions rates. Figure 8 below shows the study location, a land-based location within the San Pedro Bay Port Complex downwind of where vessels transit.

Figure 8. Map of the Study Location



3.2 Results:

The sampled fleet consisted of Tier 0, 1, 2, and 3 engines across multiple vessel types, with a fleet-average emission factor of 0.65 g BC/kg. Overall, results were similar to on-board plume measurements; most of measured BC emission rates were below PM standards (page 81 of the report).

Conclusions:

PEMS measurements showed that in-use real-world NOx and PM emissions were below certification levels and standards:

- NOx on Vessel A and B (pre-SCR) were 4.60 and 3.45 g/bhp-hr, below the certification levels of 5.04 and 3.61 g/bhp-hr, respectively.
- PM on Vessel B (pre-SCR) was 0.044, below the certification levels of 0.052 g/bhp-hr.

Characterizing Activity and Emissions of In-Use Commercial Harbor Craft

Final Report
Agreement No. 18TTD005

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California Air Resources Board

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April 2020

Disclaimer

The statements and conclusions in this Report are those of the authors and not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

Acknowledgements

This study was conducted by Chelsea Preble, Rebecca Sugrue, Anna Tarplin, and Thomas Kirchstetter at the University of California, Berkeley (UCB); Hannah Schlaerth and George Ban-Weiss at the University of Southern California (USC); and Chas Frederickson, Mark Villela, and Heejung Jung at the University of California, Riverside (UCR). The USC team led the onshore and South Coast on-board plume capture measurements. The UCR team led the on-board portable emission measurement system (PEMS) work. The UCB team led the San Francisco Bay Area on-board plume capture measurements.

We are very grateful to Grant Sellar, Dan Johnson, Timothy Hanners, and Damon Brewer for accommodating us on their vessels and for their insights. We thank MTU for their coordination with the UCR team and assistance with conducting their PEMS work. Additionally, we thank the CARB PEMS team and MTU for sharing engine data that assisted with interpreting the on-board plume capture measurements.

We thank David Quiros, Trevor Krasowsky, Wei Liu, Oliver Chang, and Ying You of the California Air Resources Board for their support and guidance throughout the study.

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Executive Summary

As reductions to on-road diesel engine emissions have been achieved in California, the relative contribution of off-road engines to statewide diesel particulate matter and nitrogen oxides (NO_x) emissions is increasing. A recent analysis indicated that some sources that have relatively small contributions to state- or air-basin-wide pollutant emissions—such as commercial harbor craft (CHC)—still contribute notably to the health risk of nearby populations. In support of forthcoming new regulations to control CHC emissions, the California Air Resources Board (CARB) is updating the emission inventory for CHC, which was last updated in 2010. This study is intended to support the development of new a CHC regulation by evaluating where CHC operate, assessing the performance of engines during real-world in-use operation, and capturing snapshots of emissions from a large number of individual engines and vessels.

The study provided CARB with data describing spatiotemporal activity patterns from individual CHC operating in California. CHC spatiotemporal activity was acquired from: (i) automatic identification system (AIS) data from 2017 and 2018 for vessels operating out of the San Francisco Bay Area and San Diego, (ii) GPS data from loggers installed on vessels operating in the San Francisco Bay Area in 2019, and (iii) questionnaire responses from vessel operators in the San Francisco Bay Area who voluntarily provided details for operation activity in 2019. Location and speed data were collected for 90 vessels across these three data sources.

The major focus of this study was a characterization of in-use CHC emissions in calendar year 2019 using three measurement approaches: (i) a portable emissions measurement system (PEMS), (ii) on-board plume capture measurements, and (iii) on-shore plume capture measurements.

PEMS

PEMS measurements were made aboard two ferries, one with a marine-certified Tier 2 engine and one with a marine-certified Tier 3 engine retrofitted with a selective catalytic reduction (SCR) system. NO_x emissions from both were close to the corresponding certification level. The time-weighted average NO_x emission rate (± standard deviation of 1 Hz data) from the Tier 2 engine on Vessel A was 4.60 ± 0.40 g bhp-hr^{-1}, lower than the certification level of 5.04 g bhp-hr^{-1}. Pre- and post- SCR NO_x emission rates from the Tier 3 engine on Vessel B were 3.61 ± 0.22 and 3.45 ± 1.03 g bhp-hr^{-1}, respectively. Both rates are near the original (non-SCR) Tier 3 certification level of 3.61 g bhp-hr^{-1}. A slight reduction in NO_x (less than 5%) suggests that the SCR system was not properly functional during the test period. The ammonium concentrations in collected particulate matter samples were indistinguishable pre- and post-SCR, indicating that urea may not have been injected into the SCR system. NO_x emission rates in bhp-hr^{-1} during 0–5% engine load operation were 2–4 times greater than the NO_x emissions during operation at higher engine loads. PM emissions were measured only on Vessel B. On average, PM emissions measured downstream of the SCR and diesel oxidation catalyst (DOC) were 0.035 ± 0.005 g bhp-hr^{-1} (post-SCR), below the certification level of 0.052 g bhp-hr^{-1}. This post-SCR PM emission rate was 38% lower than that measured pre-SCR, indicating some PM loss across the SCR system and DOC.

On-board Plume Capture

An exhaust plume capture and carbon balance method was used to characterize pollutant emissions aboard ferries and excursion vessels during typical operation in the San Francisco Bay. In total, 1,438 short duration plume capture sampling events at regular intervals during vessel operation were used to determine fuel-weighted average black carbon (BC) emission factors for 25 engine conditions on 14 vessels. NO_x emission factors were quantified for 10 engine conditions on 4 vessels. The weighted average considers the fuel consumption differences between docked/maneuvering and cruising operational modes to generate BC and NO_x emission factors that represent an engine's emissions over the full duration of a trip. The average fuel-weighted BC emission factor for the 25 engine conditions measured was 0.34 ± 0.03 g kg^{-1}. BC emissions from the ferry and excursion fleet are somewhat skewed: the most polluting 20% of engines are responsible for nearly 40% of total BC emissions by this sampled fleet. Conversely, the cleanest 20% of engines contribute only ~5% of the total BC emitted. The highest BC emitters are Tier 0 (i.e., pre-Tier 1 engines that are uncertified by the EPA) and Tier 2 engines, while the lowest-emitters are Tier 3 and Tier 4 engines. Tier 4 engines emitted 92% less BC per kg of fuel burned than Tier 0 engines, on average. The SCR retrofit on Tier 3 engines led to a reduction in emitted BC from these engines. The PEMS measurements indicated that PM reductions were due to removal within the SCR system. The plume capture measurements further indicated that the BC reduction also appears to be dependent on SCR activity: active systems emit 23% less BC per kg of fuel compared to inactive systems. On-board plume capture measurements were also made on two vessels in the South Coast Air Basin; the Tier 2 excursion vessel had an average cruising BC emission factor of ~0.5 g kg^{-1}, while cruising BC emissions from the Tier 1 fishing boat were several times higher (1.60 g kg^{-1}).

A Tier 2 engine (which is not equipped with SCR) and Tier 3 engines with inactive SCR had comparable average NO_x emission factors. The active retrofit SCR system on the Tier 3 engine sampled in this study reduced emitted NO_x by a factor of 3.5 compared to when the SCR system was inactive. In contrast, the average NO_x emissions from the Tier 4 engines equipped with original equipment SCR were reduced by only a factor of 2.0 relative to the Tier 3 engines with inactive SCR and Tier 2 engines. NO_x emissions are very slightly skewed for the subset of the fleet measured: the highest-emitting 20% of engine conditions is responsible for 30% of total NO_x emissions, while the cleanest 20% of the fleet contributed <10% of total NO_x emissions. While the subset of engines sampled in this study (and corresponding BC emission factors) are representative of the broader ferry and excursion fleet operating in the San Francisco Bay Area, the NO_x emission factors were made mostly on newer engines.

A case study comparing emissions from a Tier 3 ferry when its SCR system was active to when it was intentionally disabled shows that, on average, the active SCR system effectively reduces emitted NO_x by ~70% while the vessel is docked and maneuvering and ~90% while it is cruising. An additional analysis of NO_x emission factors measured along a ferry route suggests that SCR systems may not always yield the intended NO_x emission reductions. SCR functionality can depend on vessel operation, where systems are active during fast cruise but urea dosing may cease during low-load conditions like slow cruise and docking.

The fuel-normalized emission factors were compared to EPA engine-power normalized certification levels and emission standards for PM and NO_x using a brake specific fuel consumption (bsfc = 176.5 g bhp-h^{-1} = 236.6 g kWh^{-1}) derived from engine performance data obtained from three vessels. While the two Tier 0, most of the Tier 3, and both Tier 4 engines sampled in this study have BC emissions that are below their corresponding PM certification levels by 10–70%, many of the Tier 2 engines have average BC emissions that are 1.1–2.0 times higher than their corresponding certification values under the operating conditions in this study. Relative to the EPA emission standard, all but three engines had average BC emission factors below the PM exhaust limit. It is important to note that BC is a major but not sole constituent of diesel PM. Thus, PM emission rates may be larger than the BC emission factors reported here. Relative to the NO_x certification levels and emissions standards, all engine conditions besides the Tier 3 engine with active SCR have higher average in-use emissions in this study. The Tier 4 engines with original equipment SCR systems and the most stringent NO_x emission standard exceeded their certification values by more than a factor of 2 under operating conditions in this study. It is also important to note that these EPA values are based on specific duty-cycle tests, which the in-use operation of these ferries and excursion vessels in this study may not mirror. As such, these comparisons should not be used to determine compliance with EPA values but instead demonstrate how the certification tests do not reflect the in-use operation of these vessels.

Onshore Plume Capture

Onshore measurements captured 78 plumes to determine BC emissions rates from ~45 in-use harbor craft in the San Pedro Bay Port Complex in Los Angeles. The sampled fleet consisted of Tier 0, 1, 2, and 3 engines across multiple vessel types, with a fleet-average emission factor of 0.65 g kg^{-1}. Over 60% of the sampled vessels were tug and tow boats; tugs with load had higher average emission rates than those that were idling or without load. Fishing boats had the highest average and most variable emissions (0.88 ± 1.18 g kg^{-1}) compared to all other types of vessels, but this average was lower than the emission rate measured on-board a single fishing boat. Passenger boats had an average of 0.81 g kg^{-1} (n = 7 samples) at this location which is higher than the average emission rate measured for the SF Bay Area fleet.

Engine-power-normalized PM certification levels and emission standards were again compared to the fuel-normalized BC emission rates from onshore measurements for 27 vessels, using the same brake specific fuel consumption derived for on-board comparisons. Most of the Tier 0 and 1 vessels met their certification levels while over half of the Tier 2 and 3 vessels emissions were at least 50% above their certification values. Most of the Tier 2 and 3 vessels had measured BC emission rates that were below their PM standards.

Non-idling onshore measurements were slightly more skewed than the emissions of the SF Bay Area fleet, with the dirtiest 20% of vessels responsible for 47% of BC emissions. Unlike on-board measurements on ferry and excursion vessels in the SF Bay Area, there was no clear trend between emission tier and BC emission rate.

Conclusions and Next Steps

This study presents BC and NO_x emission factors for commercial harbor craft that are currently in-use. These new data can be used to update emission inventories and guide CARB's rulemaking process. This work also highlights topics that warrant further investigation, such as SCR performance by engine operating mode, SCR malfunction and durability, the difference in emissions between real-world operation and the certification test duty-cycles, and the prevalence and significance of high emitters. These could be addressed with additional sampling on larger numbers of vessels and multiple measurements of individual vessels.

Introduction

Background

Diesel engines are important sources of fine particulate matter ($PM_{2.5}$) and oxides of nitrogen (NO_x) air pollution in California that pose a health concern to exposed populations. NO_x is also a precursor to atmospheric formation of $PM_{2.5}$ and ozone and many areas in California are not in attainment of health-based concentration standards for these pollutants. Many areas near and adjacent to freight facilities have higher levels of risk associated with exposure to diesel particulate matter (DPM). As reductions to on-road diesel vehicle emissions have been achieved in recent decades with the wide implementation of emission control technologies, such as selective catalytic reduction systems and diesel particulate filters (Ban-Weiss et al., 2009, Dallmann et al., 2012; Preble et al., 2018), the relative contribution of off-road engines to total DPM and NO_x emissions and health risk is increasing. Agriculture operations, construction, mining, and transport refrigeration units all contribute to off-road emissions, in addition to marine vessels. A large majority of global marine vessel emissions occur within 400 km of coastlines and ports and are estimated to cause 60,000 cardiopulmonary and lung cancer deaths each year (Corbett et al., 2007; Fuglesvedt et al., 2009). Commercial harbor craft (CHC) are an important category of marine vessels and include tug and tow boats, pilot boats, passenger boats, fishing vessels, and crew and supply ships. Unlike ocean-going vessels, CHC operate locally out of ports and spend most of their operating time close to shore. Therefore, while harbor craft emissions are only a small part of basin-wide pollutant emission inventories, they still contribute notably to the air pollution and health risk of nearby populations.

A few prior studies have measured emissions from in-use harbor craft, with some emissions variability observed by vessel type, fuel sulfur content, and engine load. During the 2006 Texas Air Quality Study, Lack et al. (2008) found that tugboats had the highest BC emission factors when compared to passenger boats and even cargo vessels. These vessels were not required to use low-sulfur fuels, though, which other studies have shown can reduce BC emissions compared to heavy fuel oil (Khan et al., 2012; Lack et al., 2011; Lack and Corbett, 2012). Multiple harbor craft burning low sulfur fuels were sampled during the 2010 California Air Nexus campaign (Buffalo et al., 2014), with a fleet-average BC emission factors (geometric mean ± standard deviation) of 0.43 ± 0.46 g kg^{-1} for tugboats, 0.33 ± 0.28 g kg^{-1} for pilot boats, 0.30 ± 0.41 g kg^{-1} for passenger boats, and 0.22 ± 0.18 g kg^{-1} for fishing boats. While this study was unable to elucidate relationships between vessel load and BC emissions due to vessel-to-vessel variability, other case studies have observed that engine load may affect BC emissions (Khan et al., 2012; Lack and Corbett, 2012).

Existing Regulations on Commercial Harbor Craft

The California Air Resources Board (CARB) initially developed a regulation to reduce PM and NO_x emissions from diesel engines on CHC vessels in 2007. The regulation became effective in

January 2009, and applies to vessels including, but not limited to, ferries, tugboats, towboats, crew and supply vessels, work boats, commercial and charter fishing boats, and excursion vessels. The regulation establishes a baseline for initial reporting requirements for owners of CHC operated in all Regulated California Waters, which includes internal waters, estuarine waters, and ports and coastal waters within 24 nautical miles of the California coast. Newly purchased CHC vessels are required to meet the Tier 2, Tier 3, or Tier 4 marine engine emission standards set by the U.S. Environmental Protection Agency (EPA) at the time of purchase. This provision ensures that total emissions from CHC will decrease with fleet turnover. The regulation also requires in-use CHC to meet EPA Tier 2 or Tier 3 standards, a key driver for emission reductions from the CHC sector. Compliance for in-use CHC is based on a schedule with deadlines through 2022, which will continue to reduce emissions from older and higher emitting engines.

Existing Inventory for CHC in California

CARB staff previously estimated during rule development that CHC was responsible for 3.3 and 73 tons per day (TPD) of DPM and NO_x, respectively, before the current regulation was implemented. Today, there is some uncertainty in DPM and NO_x emissions from CHC because the emission inventory has not been revised since 2010. Parameters that were used to model emissions include vessel population, annual operational hours, emission factors reported to the EPA during engine certification, and engine specifications that allowed quantification of PM and NO_x emission rates. This project will support the development of an updated emissions inventory and forthcoming amendments to the CHC emissions regulation.

Study Objectives and Goals

To accurately estimate the emissions from CHC and the associated cancer risk from exposure to DPM, CARB staff needs real-world data describing spatiotemporal activity patterns and in-use emissions from individual CHC operating in California, summarized by vessel type.

For this study, we sought to characterize CHC activity via three data sources:

- Automatic identification system (AIS) data from 2017 and 2018 for vessels operating out of the San Francisco (SF) Bay Area and San Diego (SD)
- GPS data from loggers installed on vessels operating in the SF Bay Area in 2019
- Questionnaire responses from vessel operators in the SF Bay Area who voluntarily provided activity details in 2019

This logged data for individual vessels during normal revenue service will provide CARB staff with a better understanding of the locations that CHC vessels spend most of their time, and thus, the distance between these emission sources and the receptor locations used in CARB's health risk assessment. The final dataset will aid in refining estimates of cancer risk from exposure to emissions from CHC.

For this study, we also sought to characterize in-use CHC emissions to provide CARB staff with real-world emission rates of DPM and NO_x using three measurement approaches:

- Portable Emissions Measurement Systems (PEMS)
- On-board plume capture measurements at the exhaust tailpipe
- On-shore plume capture measurements as vessels pass by

PEMS measurements provide continuous, near-laboratory-grade emissions characterization and engine information and operation history during in-use, real-world operation, and are accepted by the EPA for official regulatory testing requirements. Therefore, results from the PEMS testing can be used to evaluate if CARB's emission inventory model should account for real-world operational differences from EPA certification test duty cycles. PEMS measurements are costly and time-consuming, though, so they can only be made on a small number of in-use vessels. As such, this study also conducted in-use measurements for a larger sample of vessels operating in the SF Bay and South Coast Air Basin, using the lower cost methods of on-board and on-shore exhaust plume capture.

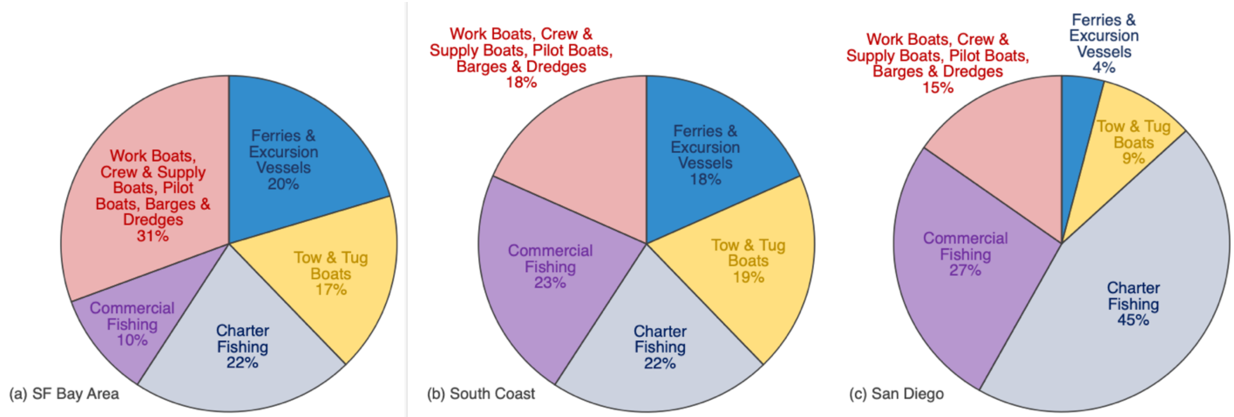
With the plume capture method, an exhaust plume is sampled momentarily and is measured as a peak event where pollutant concentrations rise above and then return to background levels. This sampling method has been widely used to characterize particle and gaseous emissions from diesel trucks, light-duty vehicles, locomotives, and airplanes (e.g., Lobo et al., 2012; Preble et al., 2015; Tang et al., 2015; Wang et al., 2015). Measurements performed using the plume capture method provide a relatively cost- and time-effective approach to measure emissions from a large sample of in-use vessels compared to PEMS testing. A large sample size is critical for obtaining a representative sample of emissions from the CHC population. In particular, it is important to capture and characterize emissions from the less common but important "high emitting" engines and include these high emitters in the measured fleet-average emission rates. Emission measurements of short duration from a larger number of engines and vessels can also be useful for characterizing how emissions vary with normal engine wear-and-tear, especially if they are collected periodically over the course of many years.

Overview of Sampled CHC Fleets

From the 2020 preliminary CARB emission inventory for commercial harbor craft operating in California, it is estimated that three air basins will contribute 70% of statewide CHC DPM emissions in the year 2023: 32% in SF Bay Area, 21% in South Coast, and 17% in San Diego (CARB, 2020). These CHC fleets include passenger ferry and excursion vessels, tug and tow boats, charter and commercial fishing boats, work boats, crew and supply boats, pilot boats, and barges and dredges. Figure 1 shows the projected relative contribution of DPM emitted by vessel type in each study area in 2023. Figure 2 shows the composition of the San Francisco Bay Area and South Coast CHC fleets by engine tier, based on projected 2023 engine count estimates (CARB, 2020).

In the SF Bay, ferries and excursion vessels comprise 28% of the CHC fleet by engine count and are expected to emit 20% of fleet's DPM in 2023. These harbor craft operate close to shore with frequent docking and carry large numbers of people that are often close to the engine exhaust tailpipes. These vessels also offered a unique opportunity for on-board sampling that captures the full duty-cycle of normal operation across many in-use engines. Therefore, these passenger vessels are the focus of the present study to capture real-world emissions data in the SF Bay Area.

Figure 1: Relative Contribution to Total DPM Emissions from CHC

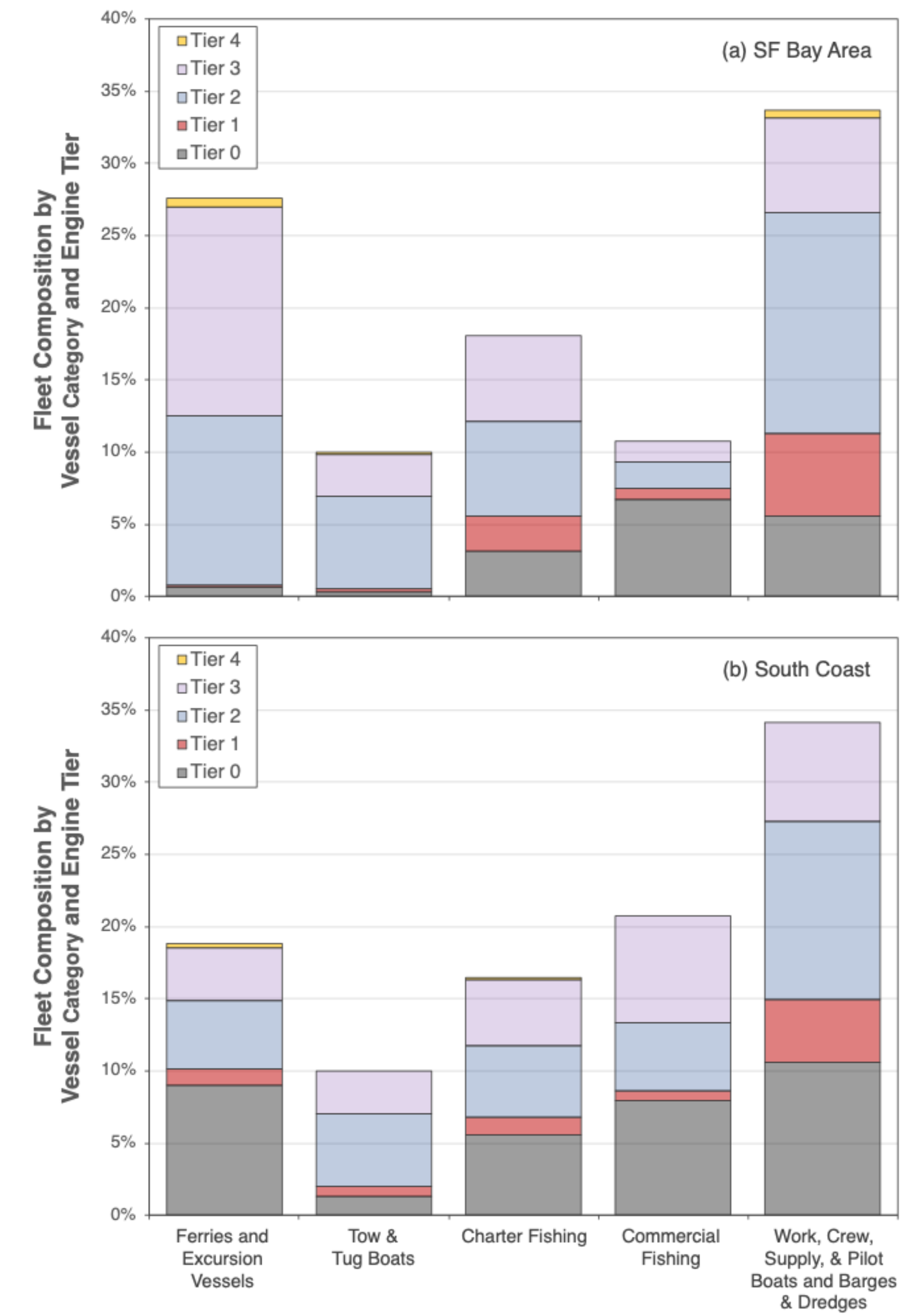


Projected relative contributions of diesel particulate matter (DPM) emitted from commercial harbor craft operating in (a) the San Francisco Bay Area, (b) South Coast, and (c) San Diego in 2023 (CARB, 2020). The total of each relative distribution may not equal 100% due to rounding. Note that these plots are based on preliminary emission inventory data and are subject to change as updated information becomes available.

In the South Coast Air Basin, tug and tow boats represent only 10% of the CHC fleet by engine count but will be responsible for 19% of total DPM emitted by the fleet in 2023. These vessels also frequently operate close to shore (see Figure 2 in next section), thereby making the on-shore capture of their emissions plumes possible. Given the frequency of their near-shore activity, these tug and tow boats are the focus of the present study to capture real-world emissions data in the South Coast Air Basin. At the static shoreside sampling locations used in this study, it was also possible to capture the exhaust plumes from a smaller number of pilot, passenger (i.e., ferry and excursion), and fishing boats.

For the spatiotemporal activity portion of this study, CARB requested that data collection be focused on San Diego rather than the South Coast Air Basin. The San Diego fleet's DPM emissions are expected to be dominated by fishing operations in 2023, while passenger vessels and tow and tugboats contribute less than 10% of DPM emissions.

Figure 2: Composition of CHC Fleets by Engine Tier



Composition of (a) SF Bay Area and (b) South Coast CHC fleets by engine tier, based on projected 2023 vessel count estimates (CARB, 2020). The fractional distributions are relative to the total fleet count in each area, such that the sum of all category bars equals 100%. Note that these plots are based on preliminary emission inventory data and are subject to change as updated information becomes available.

Spatiotemporal Activity Characterization

Data Sources

CHC activity was characterized with Automatic Identification System (AIS) data for vessels operating out of the SF Bay Area and San Diego. Historical AIS data were obtained from two sources and includes four 30-day periods from calendar years 2017 and 2018 to capture seasonal differences in activity patterns. The 2017 dataset was downloaded from a publicly accessible online database of vessel traffic data for 28 vessels, covering the months of March, June, September, and December of that year at approximately 5-second time resolution (Marine Cadastre, 2019). The 2018 dataset was purchased from an historical AIS data service for 59 vessels, covering Feb 15–Mar 15, May 15–Jun 15, Aug 15–Sep 15, and Nov 15–Dec 15 of that year at 5-minute time resolution (VesselFinder, 2019).

GPS data loggers (GlobalSat DG-500) were installed on three vessels in the SF Bay Area for ~2.5 weeks in February 2019. Location and speed were recorded at 5-second time resolution.

We also distributed questionnaires to vessel operators in the SF Bay Area, and twelve operators voluntarily provided activity details in 2019. The questionnaire is included in Appendix A and asked for vessel information, including typical activity and engine make, model, and tier.

Vessel Types

Table 1 summarizes the data collected in this study by vessel category in San Diego and the SF Bay Area, and the target number of vessels in each category requested by CARB. The location and speed data were collected for a total of 90 vessels between the three data sources.

Table 1: Vessel Counts by Region and Category

Region	Vessel Category	No. of Logged Vessels	Target No. of Vessels
San Diego	Ferry & Excursion	14	12
	Tug &Tow	7	7
	Charter Fishing	4	6
	Commercial Fishing	13	2
	Other	3	3
	Unspecified Fishing	4	N/A
SF Bay Area	Ferry & Excursion	14	9
	Tug & Tow	13	7
	Charter Fishing	2	5
	Commercial Fishing	6	5
	Other	6	4
	Unspecified Fishing	4	N/A

Vessel counts reported in this study by region and category versus the CARB-provided target distributions.

Data Analysis

The project team delivered to CARB the following data files:

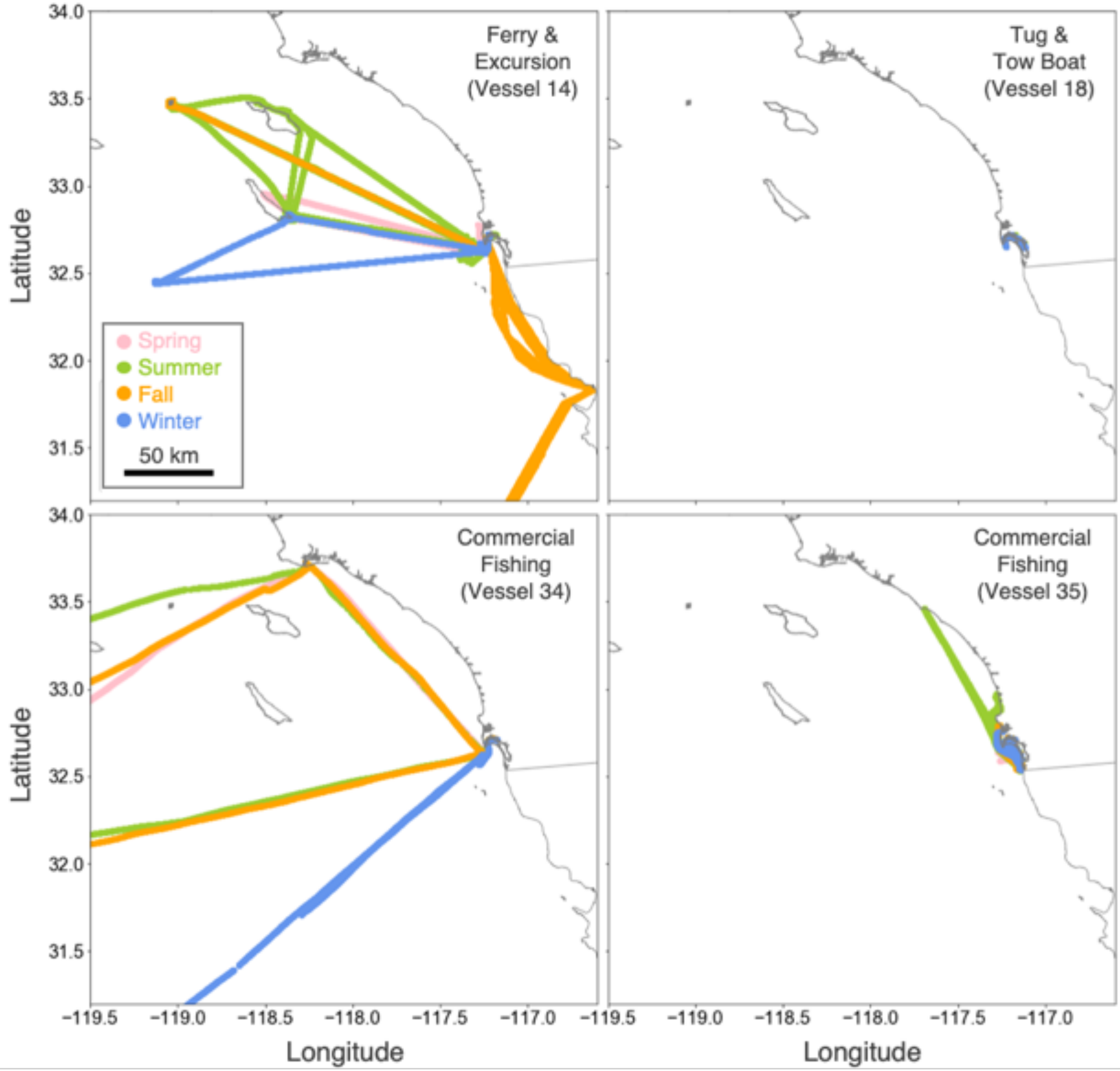
- csv files separated by region and category of vessels, including "read me" txt files that describe the reported AIS and GPS data
- kmz files for individual vessels
- maps of vessel locational data by season (see Figure 4 and Figure 3 below for examples), as well as by day and by reported vessel speed in each season
- responses from the questionnaire
- a Master List of vessel ID numbers (#1–90) unique to this study, which we refer to in the above data products and below figures

The data source for each vessel is explicitly reported in the csv files. Two vessels were repeated in the 2017 and 2018 AIS datasets, so there are 92 kmz files that correspond to 90 unique vessels in the Master List.

Figure 3 and Figure 4 show example maps of AIS-based vessel locational data for CHC operating in San Diego and the SF Bay Area, respectively. In SF, ferry and excursion vessels and tug and tow boats tend to operate within the Bay itself, while commercial fishing vessels typically operate outside of the Bay. This fishing can occur along the coastline, but vessels tend to travel further off-shore. In SD, ferry and excursion vessels and tug and tow boats can operate exclusively within San Diego Bay and the adjacent coastline, as well as further off-shore towards nearby islands. Fishing operations in SD are similarly either along the coastline or further off-shore. In both regions, the operational range and direction of vessel activity—especially fishing—can be seasonal.

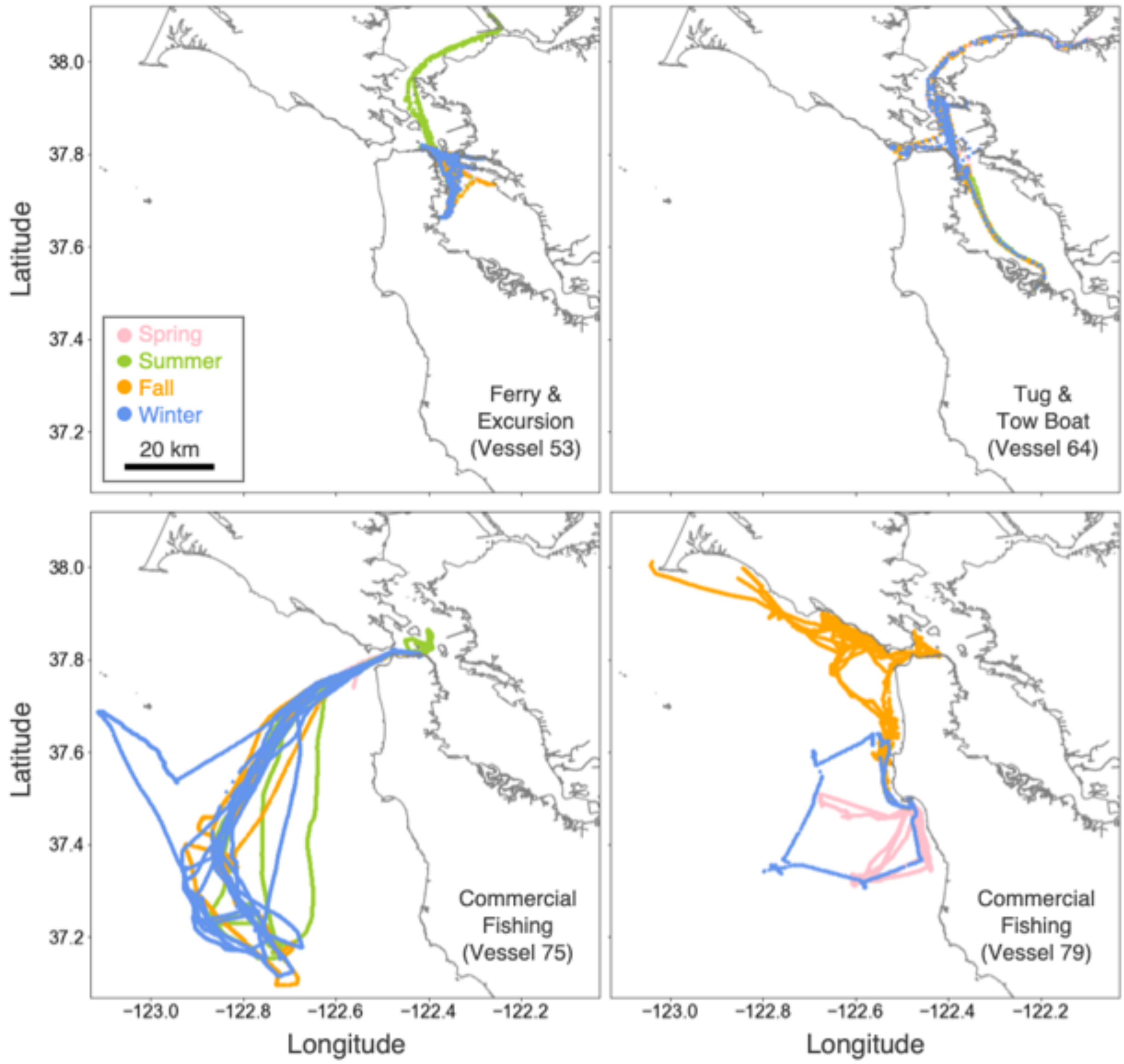
Vessel activity can also vary seasonally by day, as summarized in Table 2 and Table 3. These tables summarize the fractional daily activity during each seasonal ~30-day period for unique vessels in each region, based on the 2018 AIS dataset and with ID numbers corresponding to the Master List included in the Task 1 Data folder. If any AIS data was reported for a given vessel on a day in the specified period, it was counted towards the fractional total. Activity varied widely, from 0–100% of the ~30-day periods. A seasonal fraction less than one means that there were days of vessel inactivity during the period. Generally, fishing is more seasonal than tug and ferry operations. For example, vessel 24 was a commercial fishing boat that did not report AIS data for the Spring and Summer periods in 2018, and was only active for 9 days in each of the Fall and Winter months. Vessel 18, on the other hand, was a tugboat with AIS reported nearly every day in those same time periods. Note that the locational data of vessel 18 is also shown in Figure 3.

Figure 3: Examples of Seasonal Vessel Locational Data, San Diego



Examples of AIS-based vessel tracks for different vessel types operating in San Diego. Each mapped point represents the vessel's reported AIS locational data in the specified ~30-day period for each season.

Figure 4: Examples of Seasonal Vessel Locational Data, SF Bay Area



Examples of AIS-based vessel tracks for different vessel types operating in the San Francisco Bay Area. Each mapped point represents the vessel's reported AIS locational data in the specified ~30-day period for each season.

Table 2: Seasonal Activity of Vessels, San Diego

San Diego					
Vessel ID	**Vessel Category**	**Spring**	**Summer**	**Fall**	**Winter**
1	Ferry/Excursion	0.94	1.00	0.97	1.00
2	Ferry/Excursion	0.55	0.56	1.00	0.90
3	Ferry/Excursion	0.00	0.00	0.19	0.97
4	Ferry/Excursion	0.00	0.56	0.91	0.00
5	Ferry/Excursion	0.94	1.00	1.00	0.29
6	Ferry/Excursion	0.00	0.00	0.00	0.65
7	Ferry/Excursion	0.94	1.00	1.00	1.00
8	Ferry/Excursion	0.32	0.47	0.38	0.16
9	Ferry/Excursion	0.94	1.00	1.00	1.00
10	Ferry/Excursion	0.00	0.00	0.56	0.23
11	Ferry/Excursion	0.10	0.00	0.09	0.87
12	Ferry/Excursion	0.65	0.53	0.63	0.77
15	Tug/Tow	0.94	1.00	1.00	0.74
16	Tug/Tow	0.58	0.66	0.50	0.19
17	Tug/Tow	0.55	0.59	0.00	0.74
18	Tug/Tow	0.94	1.00	1.00	1.00
19	Tug/Tow	0.94	1.00	1.00	0.52
22	Charter Fishing	0.00	0.03	0.19	0.06
23	Charter Fishing	0.16	0.19	0.34	0.00
24	Charter Fishing	0.00	0.00	0.28	0.29
26	Commercial Fishing	0.55	0.75	1.00	0.42
27	Commercial Fishing	0.16	0.00	0.91	0.16
28	Commercial Fishing	0.61	0.44	0.66	0.55
29	Commercial Fishing	0.74	1.00	0.06	0.39
30	Commercial Fishing	0.00	0.34	0.00	0.90
39	Other	0.10	1.00	1.00	0.29
40	Other	0.00	0.34	0.16	0.19
41	Other	0.87	0.63	0.13	0.97

Fraction of each ~30-day period for which vessel activity was reported, based on 2018 AIS data for the vessels operating out of San Diego. If any AIS data was reported for a given vessel, then the day was counted. For example, a fraction equal to 0.50 means that the vessel was inactive for half of the days in that specified seasonal period. Green colors here represent frequent activity across the seasonal period, yellows represent medium activity, and reds represent inactivity. Vessel IDs not included in this table did not have 2018 AIS data, but were included in this study via 2017 AIS or 2019 GPS data.

Table 3: Seasonal Activity of Vessels, SF Bay Area

SF Bay Area					
Vessel ID	**Vessel Category**	**Spring**	**Summer**	**Fall**	**Winter**
46	Ferry/Excursion	0.00	0.00	0.28	0.74
47	Ferry/Excursion	0.38	0.41	0.56	0.35
48	Ferry/Excursion	0.14	0.38	0.22	0.39
49	Ferry/Excursion	0.34	0.53	0.56	0.55
50	Ferry/Excursion	1.00	1.00	1.00	0.55
51	Ferry/Excursion	0.17	0.34	0.34	0.26
52	Ferry/Excursion	0.90	0.66	0.28	0.65
53	Ferry/Excursion	0.62	0.81	0.81	0.77
54	Ferry/Excursion	1.00	0.84	0.97	1.00
55	Ferry/Excursion	0.79	1.00	0.91	0.97
56	Ferry/Excursion	1.00	1.00	1.00	1.00
57	Ferry/Excursion	0.79	0.97	0.19	0.90
60	Tug/Tow	0.03	1.00	1.00	0.90
61	Tug/Tow	1.00	1.00	0.69	1.00
62	Tug/Tow	1.00	1.00	1.00	1.00
63	Tug/Tow	1.00	1.00	0.84	0.00
64	Tug/Tow	0.55	0.31	0.50	0.52
65	Tug/Tow	1.00	0.03	1.00	1.00
66	Tug/Tow	1.00	1.00	1.00	1.00
67	Tug/Tow	1.00	1.00	1.00	0.10
68	Tug/Tow	0.76	0.78	0.75	0.81
69	Tug/Tow	1.00	1.00	1.00	0.26
70	Tug/Tow	1.00	0.31	0.91	1.00
71	Tug/Tow	1.00	0.72	1.00	1.00
73	Charter Fishing	1.00	1.00	1.00	0.06
81	Other	0.00	0.00	0.88	0.06
82	Other	0.97	0.00	0.19	1.00
83	Other	0.83	0.44	0.84	0.61
84	Other	0.34	0.34	1.00	1.00
85	Other	0.00	0.00	0.00	1.00
86	Other	0.66	0.66	0.72	0.58

Fraction of each ~30-day period for which vessel activity was reported, based on 2018 AIS data for the vessels operating out of the San Francisco Bay Area. If any AIS data was reported for a given vessel, then the day was counted. For example, a fraction equal to 0.50 means that the vessel was inactive for half of the days in that specified seasonal period. Green colors here represent frequent activity across the seasonal period, yellows represent medium activity, and reds represent inactivity. Vessel IDs not included in this table did not have 2018 AIS data, but were included in this study via 2017 AIS or 2019 GPS data.

In-Use Emissions Measurements: PEMS

Experimental Approach

Transient PM and NO_x emissions were measured aboard one Tier 2 (Vessel A) and one Tier 3 (Vessel B) vessel using an AVL Micro-Soot Sensor (MSS) and a SEMTECH Portable Emission Measurement System (PEMS), respectively. The Tier 3 vessel was equipped with an aftermarket selective catalytic reduction (SCR) system that by design, was expected to control NO_x emissions to the Tier 4 standard of 1.8 g/kWh. Pollutant concentrations were measured before and after the SCR system on this vessel. The testing took place on the vessel's normal routes without any special accommodations for the measurements.

Vessel A is a Tier 2, waterjet propelled, passenger-only fast ferry. The vessel was built in 1998 by Dakota Creek Industries and entered the fleet in 2011 after renovations. Vessel A has a deadweight of 40 tons, gross tonnage of 99, and loaded displacement of 228.6 tons. This vessel has four diesel MTU manufactured engines and is equipped with a water muffler from Marine Exhaust that injects sea water into the exhaust system above the water line behind the vessel, which reduces heat and noise (Marine Exhaust, 2019). The four MTU engines produce a combined power of 8,000 kW. It was not equipped with a diesel particulate filter (DPF) or any other aftermarket emission control technology. The forward port engine was tested during this study; however, all engines operating had equally distributed load. During testing the vessel ran on 3 engines instead of 4, due to one engine being down for service. The remaining engines operated a higher load. The results are presented on a brake-specific basis and do not appear to be heavily impacted. The fleet owners assured that this not an uncommon occurrence and roughly 10% of operation is spent in this state. The vessel has two auxiliary engines that are Northern-Lights with a power of 145 kW.

Table 4: Vessel A and Vessel B Engine Specifications

Vessel	Make	Model	Model Year	Power (kW)	Engine Speed (rpm)	# of Cylinders	Displacement (L)	EPA Tier	# of Main Engines	Total Runtime Before Testing (hrs)
Vessel A	MTU	12V 4000 M73	2009	2000	2005	12	51.7	2	4	18096
Vessel B	MTU	12V 4000 M64+	2015	1455	1830	12	57.2	3	2	6392

Vessel B is a 135-foot passenger-only ferry that has a carrying capacity of 400 passengers and 50 bikes. The vessel is double decked and is propeller propelled. The Tier 3 vessel is equipped with two MTU engines with a combined power of 2,910 kW. The port engine was tested. A retrofit SCR system was installed on the vessel. The exhaust is vented through stacks at the rear of the ship. The vessel was built in April of 2017 by Vigor Industrial LLC. Vessel B has a gross tonnage of 95 and a loaded displacement of 179.9 tons. The vessel is equipped with two auxiliary engines, one on each side, that are both 2014 John Deere engines with a power of 120 kW. These auxiliary engines are used for internal power onboard the vessel.

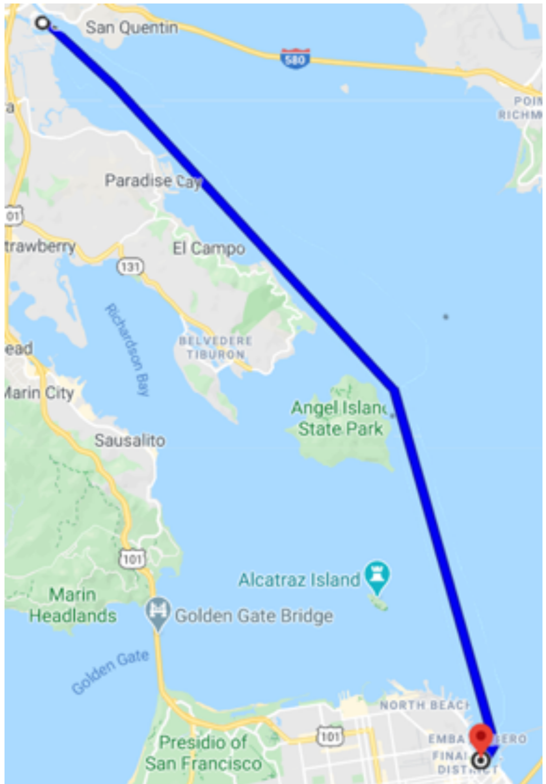
Test Routes

The test route for Vessel A vessel began in Larkspur and ended in San Francisco. Emission measurements were made in both directions along this same route. Testing began at 5:30AM to measure the cold start of the engine. Testing continued through the early morning commute to San Francisco until 2PM. During the first two early morning trips the vessel was at capacity on the way to San Francisco and mostly vacant on the return trip. The route of the vessel is shown below in Figure 5 via Google Maps. The GPS unit attached to the gaseous measurement device was unable to connect to GPS satellites due to its position in the engine room. Fifteen hours and fourteen minutes of testing took place over two days. The measurement period each day began with a cold start then five round-trips were data logged. Table 5 shows that the average amount of time for a one-way trip was 33 minutes with a standard deviation of three minutes and the average time unloading and loading eleven minutes with a standard deviation of six minutes. When the vessel was in transit past the no-wake zones, it would accelerate to near full load. The vessel operated between 85% to 100% load when velocity was not metered. Vessel A averaged 90% load with a standard deviation of 11%.

Table 5: Average Trip and Docking Times for Vessel A

Trip	Average Length (minutes)	Standard Deviation (minutes)	Average Load (Past No-Wake Zone) (%)	Standard Deviation (%)
Larkspur & San Francisco	33	3	90	11
Docked (Unloading/Loading)	11	6	N/A	N/A

Figure 5: Vessel A Test Route



Vessel B travels between Vallejo, San Francisco, and Richmond. Figure 6 displays GPS data taken during the two days of testing. The GPS data is visualized on Google Earth. The red route represents the morning commute and the blue route represents the evening commute. The total testing time for this vessel was 20 hours and 47 minutes, including two cold starts, two morning commutes, and one evening commute. The morning commutes consisted of a single trip from Vallejo to San Francisco, a single round trip from San Francisco to Richmond, a two-hour break in San Francisco, and then a trip back to Vallejo for a midday break before starting the evening commute. The morning commute took place from 4:30AM to 12:00PM, this is including the cold start and an hour for engine warmup. The evening commute consisted of three round trips between Vallejo and San Francisco starting at 2:30PM and ending at 8:30PM. Table 6 below gives the average and standard deviation of the trip lengths and unloading/loading time. Vessel B operated between 85% and 100% when in transit past the no-wake zones. It averaged 92% ± 6% load for the main trips between Vallejo and San Francisco.

Figure 6: Vessel B Test Route

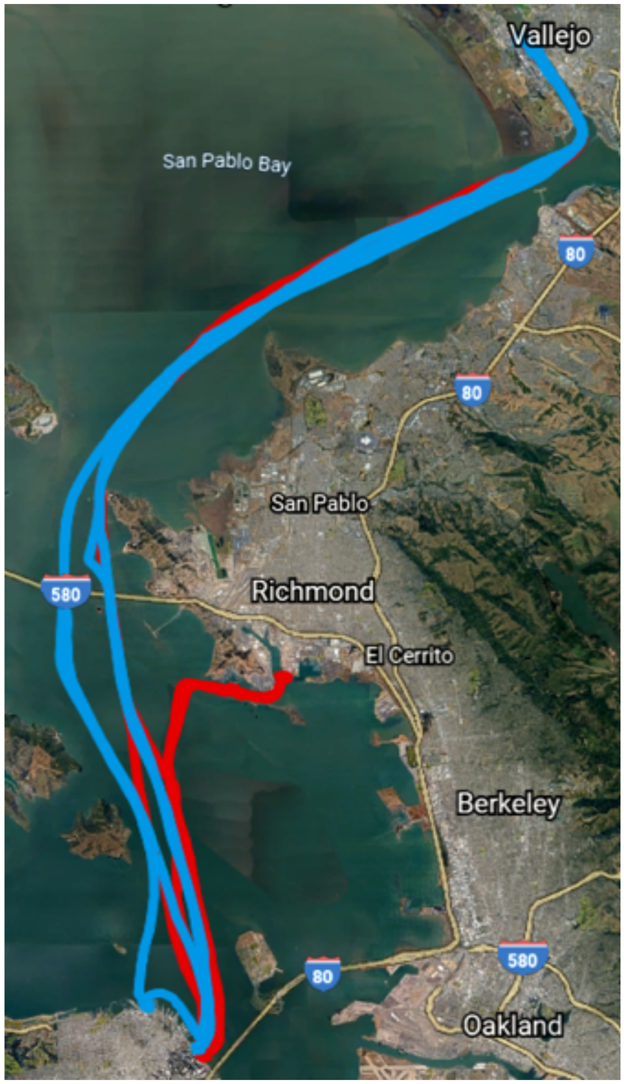


Table 6: Average Trip and Docking Times for Vessel B

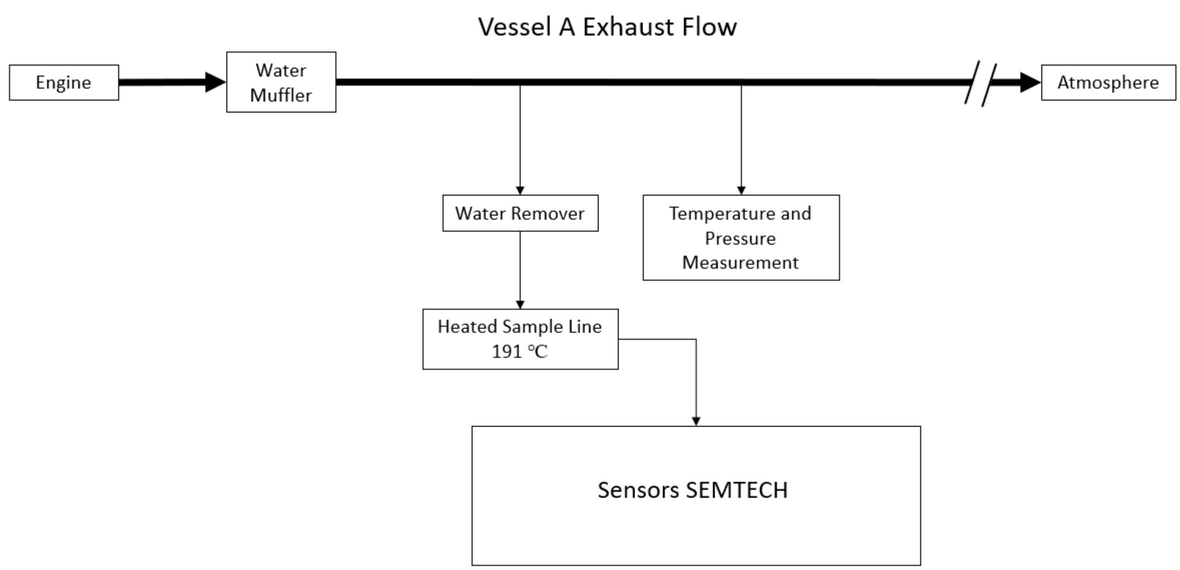
Trip	Average Length (minutes)	Standard Deviation (minutes)	Average Load (Past No-Wake Zone) (%)	Standard Deviation (%)
Vallejo & San Francisco	64	4	92	6
San Francisco & Richmond	31	2	92	4
Docked (Unloading/Loading)	10	5	N/A	N/A

Experimental Setup and Sampling Locations

Vessel A

Figure 7 diagrams the exhaust flow and relative sampling position of the instruments. The SEMTECH gaseous PEMS sampled the engine exhaust after the vessel's water muffler. Our pressure and temperature sensors were positioned after the gaseous sample port. Water remover was located in our sampling line ahead of the instrument, which is described further and shown below in Figure 11.

Figure 7: Exhaust Flow and Sampling Diagram for Vessel A



Vessel B

Figure 8 illustrates the exhaust flow and relative sampling position of the instruments on Vessel B. The instruments maintained the same order as with Vessel A. The water removers were not required for this set up. The instrument sampling inlets were either placed downstream of the SCR system (post-SCR) or upstream of the SCR system (pre-SCR). A heated sample line extension for the AVL PM PEMS was required to reach the sample port of both the pre- and post-SCR positions.

Figure 8: Exhaust Flow and Sampling Diagram for Vessel B

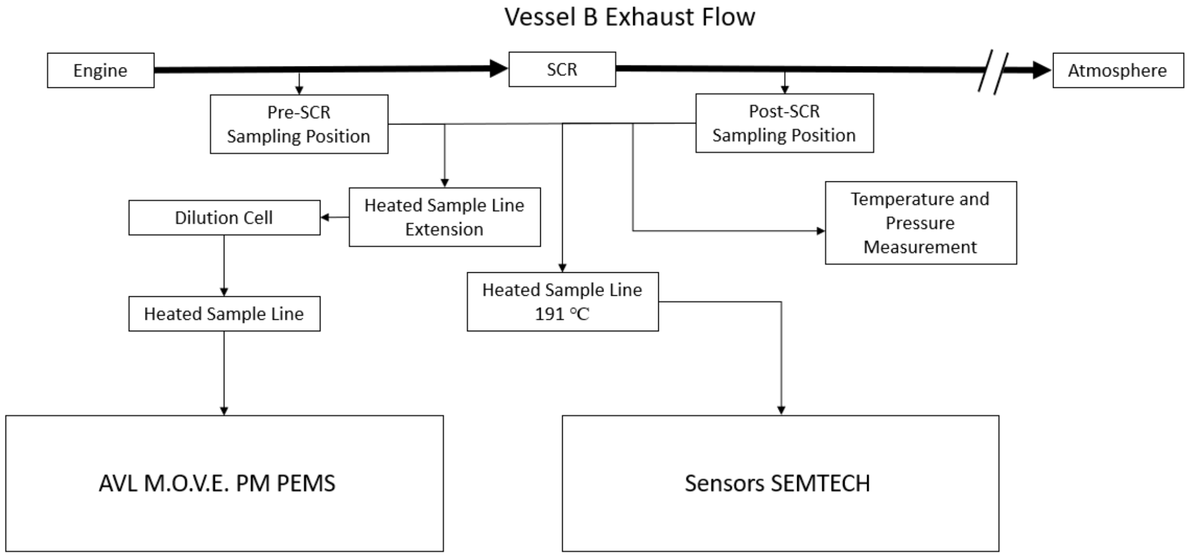


Diagram applies to both sampling locations.

Portable Emission Measurement System (PEMS)

The SEMTECH-DS analyzer is intended for on-vehicle diesel or gasoline emission monitoring. This instrument was used to analyze total hydrocarbons (THC), nitric oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2) in the exhaust. The SEMTECH uses a heated flame ionization detector (FID) to measure the THC. A portion of the exhaust gas passes through an internal heated filter into the heated FID chamber for measurement. This analysis requires THC FID fuel which consists of a 40/60 blend of hydrogen and helium (Sensors Inc, 2019). NO_x is measured with a non-dispersive ultraviolet (NDUV) analyzer. Prior to this analyzer the exhaust sample is dried with an ambient temperature coalescing filter and then a thermoelectric chiller for the removal of heavy hydrocarbons. The non-dispersive infrared (NDIR) analyzer used for CO, CO_2, and HC requires a similar exhaust drying process with a coalescing filter and thermoelectric chiller that removes interfering water vapor. Finally, an electrochemical oxygen sensor is used to produce a signal that is proportional to the partial pressure of oxygen within the exhaust sample (Sensors Inc, 2019).

The AVL M.O.V.E. PM PEMS was used to analyze soot samples from the vessel's exhaust. The AVL M.O.V.E. uses a combination of two different mass related measurement methods. The first is the photoacoustic method and the main operating mode of the instrument. The soot particles are exposed to a modulated laser beam that causes periodic heating and cooling within the particles. Expansion and contraction of the particles caused by the periodic heating results in a sound wave that is detected by microphones (AVL, 2019). The second analysis method is a gravimetric filter module. A portion of the exhaust is diluted and drawn through a Teflon filter. The dilution air can be adjusted to an optimal filter mass loading time.

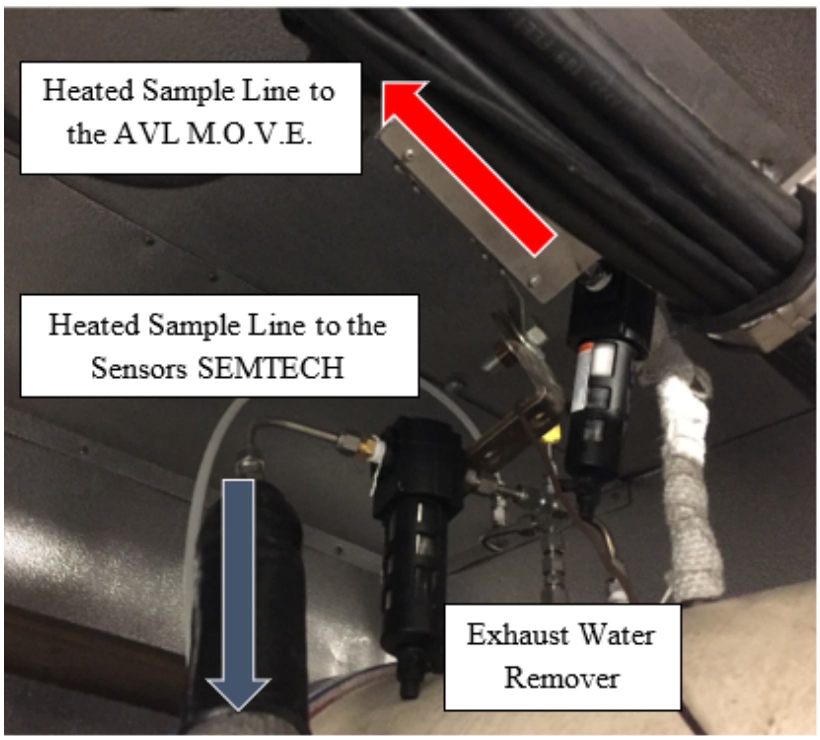
Figure 9: Gas PEMS (Sensors, Inc. SEMTECH-DS)

Figure 10: PM PEMS (AVL M.O.V.E.)

Heated Transfer Line, Probe, and Exhaust Water Remover

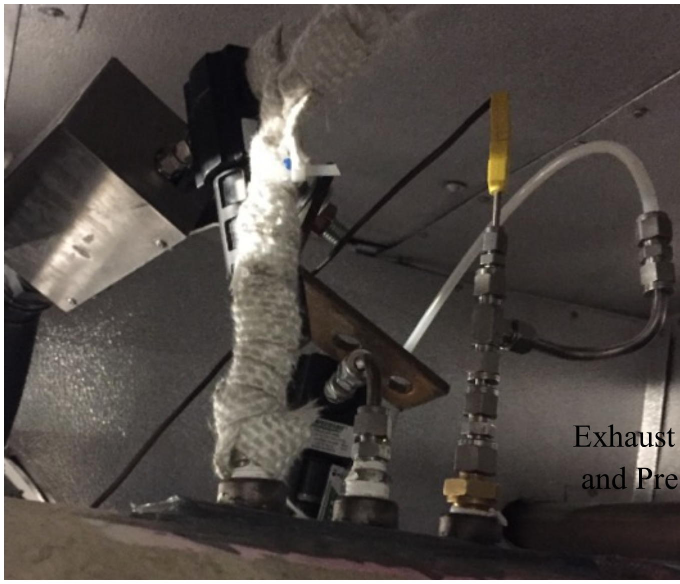
Both the AVL M.O.V.E. and the SEMTECH use heated sample lines. The SEMTECH sample line operates at 191 ºC. The inner tube is made of conductive Teflon which is then wrapped in a heater that is then encased in an insulated flexible tube. The sample line is 12 feet (3.7 meters) in length. The AVL M.O.V.E. sample line is heated to 52 ºC and has a conductive inner tube. For the testing on board Vessel B, a second heated sample line was required for the AVL M.O.V.E. in order to reach the sample ports. This sample line has inner tubing made of Teflon and is an in-house built sample line. The AVL M.O.V.E. heated sample line is 6.5 feet (two meters) long and the second extension sample line is 12.3 feet (3.75 meters). The heated sample lines used during testing are shown in Figure 14. Temperature and pressure probes were used on vessels and were monitored with an in-house built instrument. The PM probe consisted of a steel pipe that was ground down on one end to expose the inner hollow area (Figure 13). The probe was positioned in the exhaust flow so that the ground down area was facing the oncoming exhaust. The gas probe was as steel multi-hole probe. This probes orientation to the exhaust flow was not as important as the PM probe. A 150 psi compact general purpose water filter from SPEEDAIRE were used to remove water in the sample flow for both instruments while testing on board Vessel A due to the vessel's water muffler (Figure 11). The AVL M.O.V.E. was not used on Vessel A due to unforeseen data collection challenges presented by the water muffler and the strict testing schedule.

Figure 11: Exhaust Ports on Vessel A



Gas and PM exhaust ports on Vessel A. Exhaust water removers are installed before the heated sample lines.

Figure 12: Back Side of Exhaust Ports on Vessel A



Displayed in this photo are the exhaust temperature and pressure probes.

Figure 13: Sampling Probes

Gaseous probe (left) and PM probe (right).

Figure 14: Heated Sample Lines for the AVL

AVL M.O.V.E heated sample line (top), its extension (middle), and heated sample line for the Sensor SEMTECH (bottom).

Sample Port Locations

Emissions were measured from the exhaust of Vessel B at two locations: upstream of the retrofit SCR+DOC system, and downstream of the SCR+DOC system. Vessel B is shown in Figure 15, the sample ports were located behind a panel on the exhaust stack on the second-story deck. This provided easy access to the ports. The instruments were located within the exhaust stack on the first-floor deck and served as a middle point between the pre- and post-SCR sample positions. The pre-SCR sample ports were located in the engine room. A pressure reducer was required for this location. These port locations are shown in Figure 16.

Figure 15: Post-SCR Sampling Position on Vessel B

Post-SCR sampling position on the second story deck of Vessel B.

Figure 16: Pre-SCR Sampling Position on Vessel B

Pre-SCR sampling position in the engine room of Vessel B.

ECM Data Measurement (MTU)

Engine parameters were recorded using MTU computer software (Diasys version 2.6). The engine controller unit of the MTU engine is called ADEC (Advanced Diesel Electronic Control) ECU7.

Exhaust Flow Calculation

The exhaust flow is an important parameter to calculate emission rates of an engine. Whereas the exhaust flow can be measured conveniently for on-road engines by installing a flow meter into the exhaust stream. This is achieved by removing parts of the muffler and attaching an exhaust pipe with a pitot tube already installed. The exhaust flow and stack diameter of 1500-kW marine engines does not allow for the removal of any part of the exhaust piping. EPA Method 2 uses as an alternative method for the determination of stack gas velocity and volumetric flow rate (EPA, 2019). EPA Method 2 calculates the exhaust gas flow from the average velocity measured with a Type S pitot tube and a measurement of the gas density. Neither vessel was equipped with a pitot tube in the exhaust stream so this method would have required an extra sample port hole in the exhaust stream and was therefore not an optimal method for our team. The method we used to calculate the exhaust flow was accomplished by the carbon balance method facilitated by the actual fuel consumption rate provided by the ECM. The carbon balance method we used assumed that the carbon coming in as fuel is completely transformed into carbon monoxide and carbon dioxide. All other carbon containing species were assumed to have negligible mass. The equation below shows how the exhaust flow was calculated in moles per second.

$$\dot{n}\left(\frac{mol}{s}\right) = w_{fuel} * \dot{Fuel}\left(\frac{l}{hr}\right) * \frac{1\ (hr)}{3600\ (s)} * \rho_{fuel}\left(\frac{g}{l}\right) * \frac{1}{M_c}\left(\frac{g}{mol}\right) * \left(\frac{1}{CO_2(\%) + CO\ (\%)}\right) * 100$$

Where $\dot{n}$ is the molar exhaust flow rate, w_{fuel} is the mass fraction of carbon in the fuel, $\dot{Fuel}$ is the actual fuel consumption in liters per hour as measured by the ECM, ρ_{fuel} is the fuel density in grams per liter, M_c is the molar weight of carbon atom, and the term $CO_2\ (\%) + CO\ (\%)$ is the volume fraction of carbon containing gases in the exhaust. The carbon mass fraction of ultra-low-sulfur diesel is 0.87 and the density is 832 g/l, as defined in CFR Title 40 Part 1065.

Emission Rate Calculation

With continuous sampling conditions the concentration signal was continuously updated under a varying flow rate. The calculated exhaust flow rates were time aligned with our second-by-second emission data using AVL Concerto software. The total mass of the pollutant emissions was obtained by multiplying the concentration (mole fraction) and molecular weight of pollutant in the exhaust by the molar exhaust flow rate. This is described in equation 1065.650-4 in CFR 1065 and is shown below.

$$m_p = M_p * \sum_{i=1}^{N} x_i * \dot{n}_i * \Delta t$$

Where:

$$\Delta t = 1/f_{record}$$

In the equation m_p is the total mass of the pollutant based on the number, N, of records. M_p is the molecular weight of the pollutant, x_i is the concentration fraction of the pollutant in the exhaust, $\dot{n}_i$is the molar flow rate of the exhaust, and Δt is in inverse of the frequency of the 1 Hz sample rate.

The result of the calculations must be in brake-specific emission values to be in accordance with the methods outlined in the CFR 1065. The fuel specific method that was used to calculate the brake-specific emissions can be simplified and expressed as:

$$e_p\left(\frac{g}{bhp * hr}\right) = \frac{\sum\left(g_p * \frac{ECM\ fuel}{CO_2\ fuel}\right)}{\sum Work} = \frac{\sum m_p}{\sum Work}$$

The *work* in this calculation was provided by the ECM in kW and was converted to bhp. The mass fraction of emissions in the exhaust, m_p, was solved for previously.

Results

CHC Activity Based on Engine Load

The Load profile Analysis with load profile Manager (LAMA) report contains historic activity, which indicated 18,096 cumulative hours of operation for Vessel A as of September 22, 2018, and 6,392 cumulative hours of operation for Vessel B as of January 26, 2019. Figure 17 and Figure 18 provide a camparison of each vessel's historical activity and tested activity. The two CHC showed the highest activity at the 5–30% engine power bin followed by the 0–5% engine power bin. While other bins showed less but non-negligible activities for Vessel A, absence of activity in the medium engine load bins indicated Vessel B was operated at near full load except docking and undocking. According to an operational manager operating CHC engines up to 80% of load and avoiding 100% load is recommended to reduce engine noise and to encourage prolonged service life of the engine. However, the LAMA report showed signifiant amount of operation in the 90–100% engine power bin for both vessels.

Figure 17: Historic Load and Testing Activity for Vessel A's Forward Port Engine

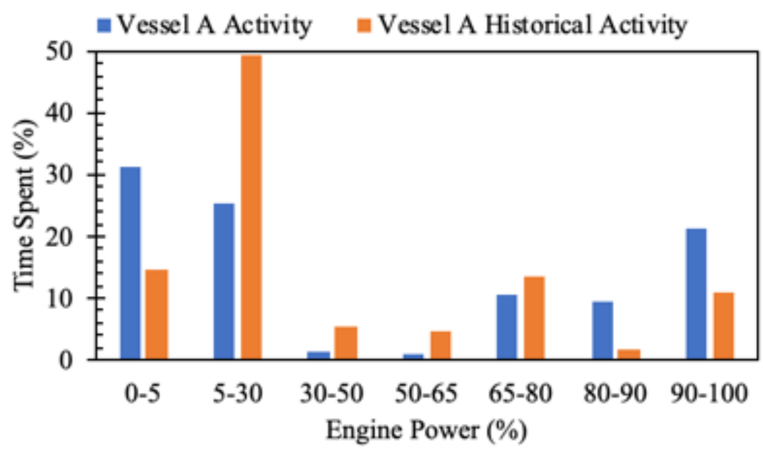
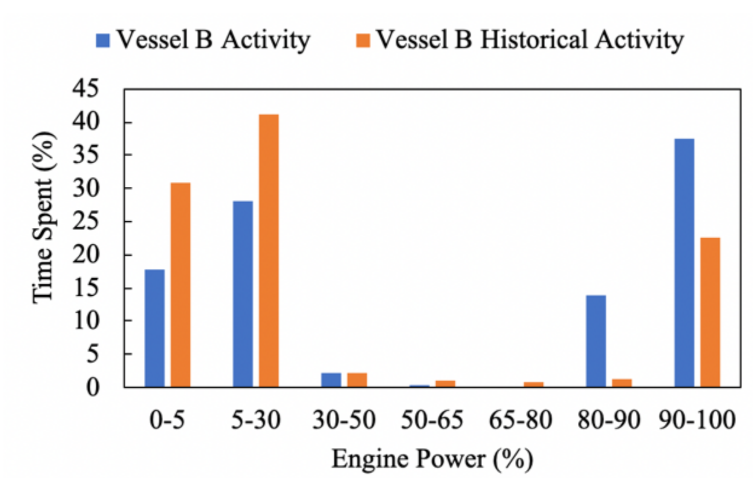


Figure 18: Historic Load and Testing Activity for Vessel B's Port Engine



During the test period, the activity data of Vessel A represents the 11.62 hours of normal run time. Higher activity at 0–5% bin for Vessel A can be attributed to prolonged warm up times due to the testing. The activity of Vessel A during the test period was very similar to its historic activity except that the operation at 80–90% engine load was significant during the test period. The activity of Vessel B represents the 12.33 hours of normal run time during the test period and was very similar to its historic activity except for increased operation at 80–90% engine load during the during the test period. Vessel B spent less time at low load during the test period.

Emissions

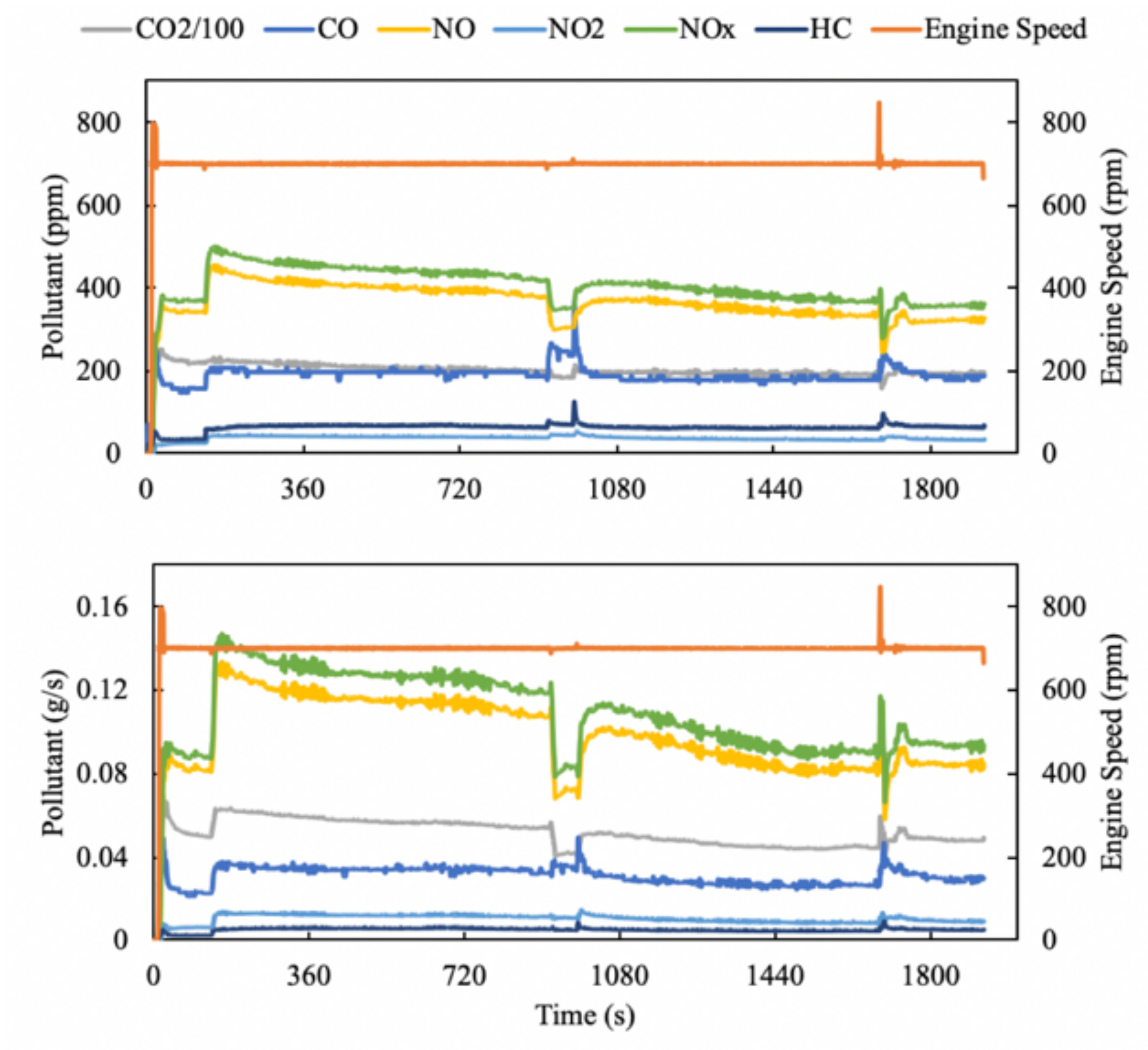
Cold Start

This section gives cold start plots of the two vessels observed during the testing period. Both vessels were docked when their engines were started and remained docked for the duration of this test while their engines idled. The plots give the emissions, in concentration and mass, in reference to the engine speed. The mass rate was calculated from using the molar exhaust flow rate, pollutant concentrations, and molecular weights, as described above. The molecular weight of HC was assumed to be 13.8 g mol^{-1}, which corresponds to Diesel #2 fuel (GPO, 2019).

For Vessel A, the displayed cold start in Figure 19 is from the 1/23/19 testing day and shows a few abnormalities along with a general decrease in emissions as the engine warms up. The engines undergo startup procedure to reduce white smoke and HC emissions. During this procedure, the engines start in full engine mode for a short period and then switch to half engine mode. During half engine mode, only half of the cylinders are operating. The beginning of fuel injection (BOI) starts earlier and gets later as the engine warms. The BOI timing will increment until it reaches a value in the BOI map for a warm engine. The idle engine speed of the tested engine was approximately 700 rpm and was held constant for most of the test. The initial decrease in emissions cannot be fully explained without additional investigation but it is hypothesized by MTU and UCR personnel that the delay of emissions is due to the wet exhaust system. This initial decrease in emissions was only observed onboard Vessel A, making the wet exhaust system a possible cause. The second dip in emissions around 950 seconds, the engine briefly switched to full engine mode for a minute and then switches back to half engine mode. The decrease of NO_x corresponds with an increase of CO and HC emissions because during the full engine mode the injection quantity per cylinder decreases to maintain the same power output and this decreases the combustion temperature.

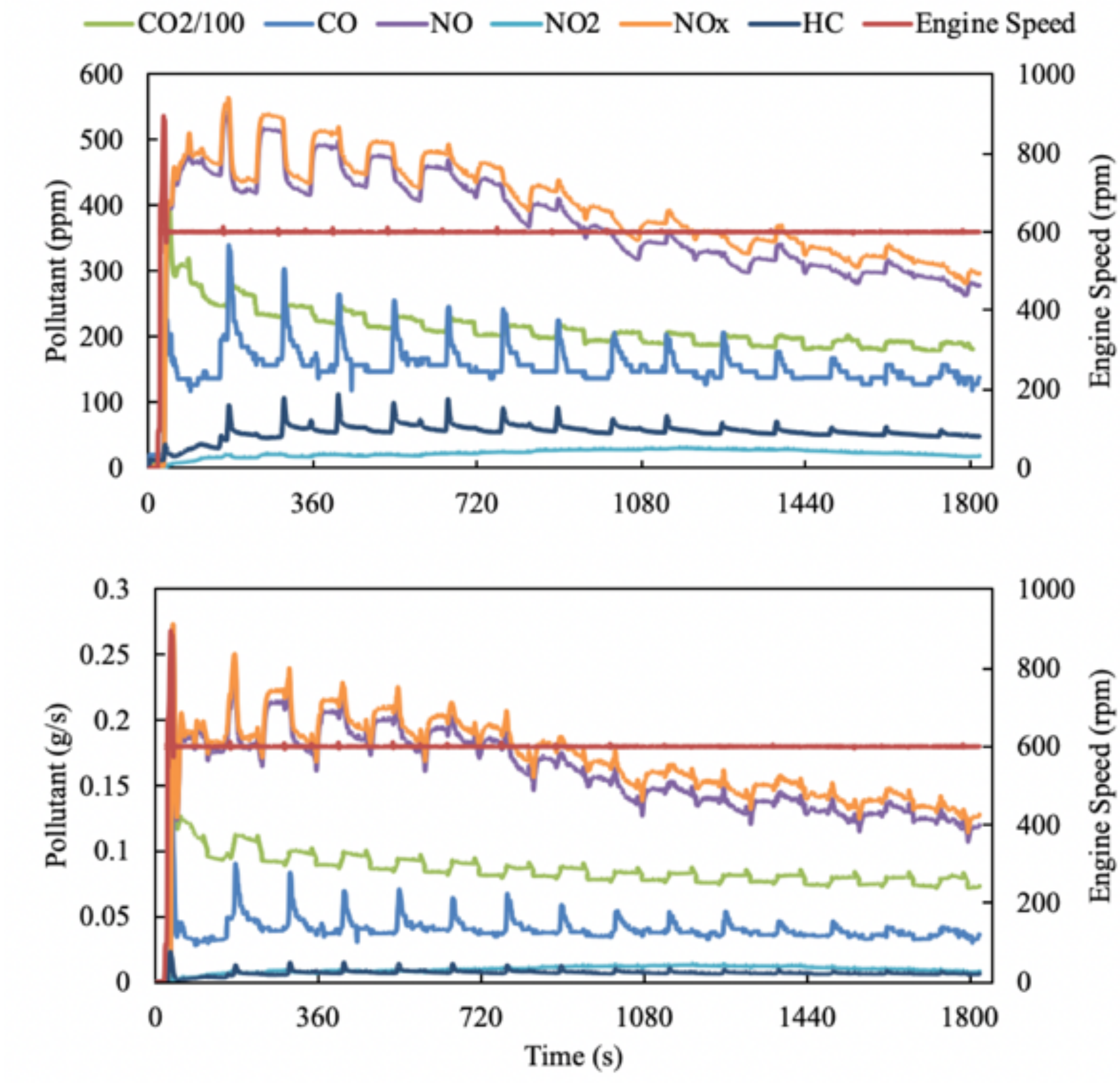
For Vessel B, the displayed plots shown in Figure 20 are from the 1/28/19 testing day. During this test the instrument sampling placement was post-SCR. The SCR system would not have been operational yet because of the low temperature of the engine and exhaust stream. Figure 21 shows that the sample exhaust in the sampling line (as opposed to raw exhaust at the exhaust pipe) temperature at the post-SCR sampling location. At the end of the cold start period the exhaust temperature is 58.7 °C. Vessel B's engine start-up procedure involves warming up the cylinders by switching between each half the cylinders every 60 seconds. This cylinder cut-out mode occurs as a function of engine speed and load. At low load and idle engine speed of 600 rpm the cut-out mode is active. The periodic spikes and dips in the emissions can be explained by the cylinder cut-out mode. Similar to Vessel A, the BOI of Vessel B shifts from early to late BOI as the engine warms up. The warming of the engine and the shift of the BOI is evident in the gradual decrease of the emissions.

Figure 19: Vessel A Gaseous Cold Start Emissions and Engine Speed



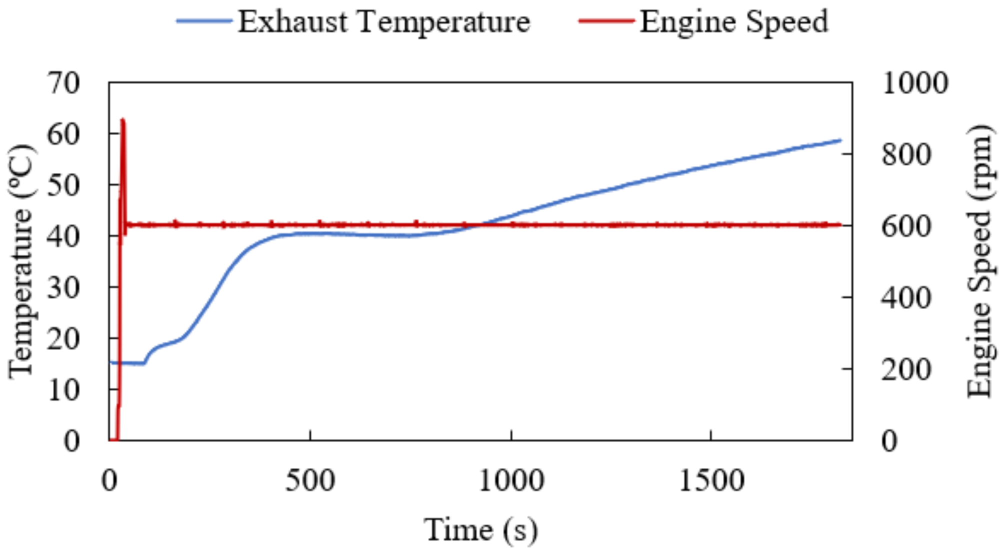
Gaseous emissions, in concentration and mass, and engine speed for the 1/23/19 cold start of Vessel A.

Figure 20: Vessel B Gaseous Cold Start Emissions and Engine Speed



Vessel B gaseous emissions, in concentration and mass, for the 1/28/19 cold start. HC emissions were measured for each cold start but not during in-use operation.

Figure 21: Engine Exhaust Temperature at the Post-SCR Position



Engine exhaust temperature as measured in the sample line branched from the exhaust pipe in the post-SCR position.

Normal Operation

Figure 22 shows average emission rates from both vessels for the entire test period excluding cold start data shown in the previous section. Cold start made up 7% of the total testing time for Vessel A and 6% of the total testing time for Vessel B. For Vessel B we present pre-SCR and post-SCR data, which are not simultaneous data because the team had only one set of sample lines. However, there were insignificant differences between the CO_2 emission factors between test runs measured pre-SCR versus post-SCR test, which suggest that test runs were generally repeatable and differences in other pollutants can be more similarly compared. Vessel A (Tier 2) CO_2 emission factors were 3.9 ± 1% less than Vessel B (Tier 3). NO_x emissions from both vessels were close to the certification level (Table 7). The Tier 2 NO_x certification level is 5.04 g/bhp-hr and the Tier 3 NO_x certification level is 3.61 g/bhp-hr. Vessel A, Tier 2 vessel, had a higher NO_x emission factor than Vessel B, Tier 3 vessel. Vessel A average NO_x emission rates were 4.60 ± 0.40 g/bhp-hr, slightly lower than the certification level of 5.04 g/bhp-hr. Vessel B average pre-SCR and post-SCR NO_x emission rates were 3.61 ± 0.22 and 3.45 ± 0.18 g/bhp-hr, respectively. Both rates are close to the Tier 3 certification level of 3.61 g/bhp-hr. The uncertainty of these values represents the standard deviation of the data from all recorded runs with the exclusion of one outlier Post-SCR run. This excludes cold starts and extended periods of idle and maneuvering around ports when not carrying passengers.

Figure 22: Average Emission Rates for Both Vessels

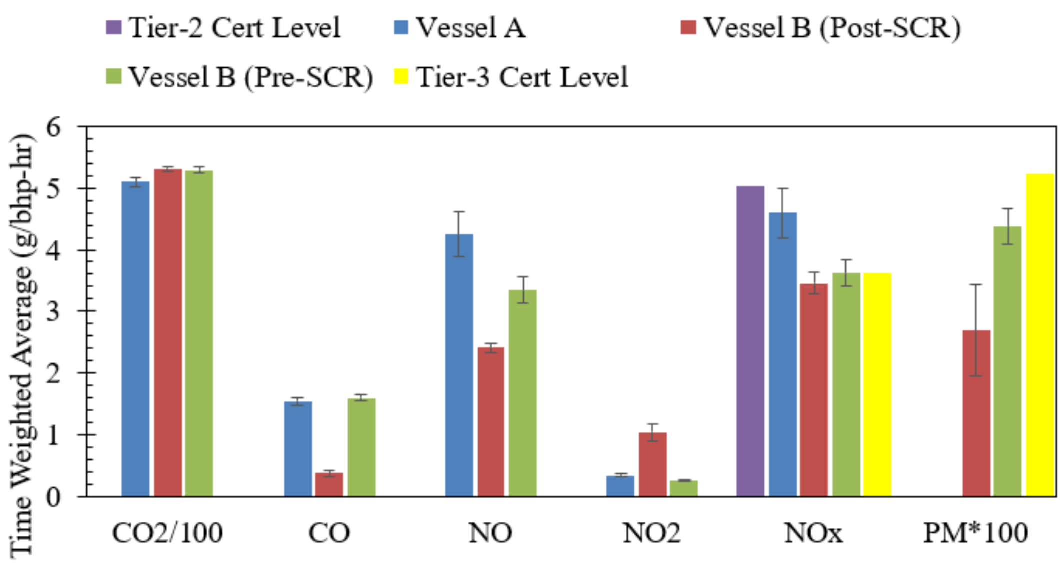


Table 7: Overall Emissions Relative to Certification Levels

Vessel	EPA Tier	NO_x Certification Value (g/bhp-hr)	Measured NO_x (g/bhp-hr)	PM Certification Value (g/bhp-hr)	Measured PM (g/bhp-hr)
Vessel A	2	5.037	4.60 ± 0.40	0.111	N/A
Vessel B	3	3.612	Pre-SCR: 3.45 ± 0.18 Post-SCR: 3.62 ± 0.22	0.052	Pre-SCR: 0.044 ± 0.003 Post-SCR: 0.027 ± 0.007

A reduction of 0.17 g/bhp-hr in NO_x at the post-SCR location compared to the pre-SCR location is less than the experimental uncertainty of 0.18 g/bhp-hr for the pre-SCR and 0.22 g/hbp-hr for the post-SCR measurements (Table 7). After testing was completed, the vessel operator found a mechanical issue that prevented injection of diesel exhaust fluid (DEF) into the SCR system. As such, all testing results presented here are from an inactive SCR retrofit with no urea dosing. Monitoring of DEF consumption could help ensure SCR systems are active and effectively reducing NO_x emissions throughout normal operation.

Even though the retrofit SCR system was not injecting DEF, downstream SCR and diesel oxidation catalysts impacted post-SCR emissions. Higher NO_2 and lower NO emission rates were observed post-SCR location compared to pre-SCR, while the NO_x concentration appeared have not significantly changed. The increase of NO_2 and decrease of NO is due to oxidation of

NO at the catalytic surface. This was also true for CO which showed higher emission rate at the pre-SCR location compared to the post-SCR location. The failure of the DEF injection halted the intended the SCR reactions and may have increased the oxidation of NO and CO.

PM emissions were measured only on Vessel B. PM average emissions were 0.035 ± 0.005 g/bhp-hr, which is less than the certification level of 0.052 g/bhp-hr. The pre-SCR emissions were 0.044 ± 0.003 g/bhp-hr and the post-SCR emissions were 0.027 ± 0.007 g/bhp/hr. Post-SCR location shows 38% less PM emission rate compared to that at pre-SCR location. This may be due to filtration of particles at the SCR, or oxidation of the semi-volatile or organic constituents of PM across either the SCR or DOC.

Average emission rates during four different engine load bins are shown in Figure 23. Average emission rates were highest in the lowest engine load bin (0–5%) for Vessel A ferry. This was most pronounced for NO and NO_2 and much less significant for CO_2 and CO. NO_x emission rate was 11.61 g/bhp-hr for 0–5% load bin which it ranged from 3.19 to 4.87 g/bhp-hr at higher load bins. In each load bin the NO emission rate corresponds above 90% of NO_x emissions.

Figure 24 shows a typical test run of Vessel A during its service from Larkspur to the San Francisco. From time zero to 50 seconds, the vessel was docked to load passengers and the operators kept the vessel in gear to keep the vessel pinned to the dock. After the loading, the vessel transited through a no wake zone and then the operator accelerated to the full load for the majority of the route. There were minimal directional changes, so Vessel A did not have to reduce load during transit. The vessel then entered another no wake zone and moved through the marine traffic to reach the appropriate port. While unloading and reloading the vessel was kept in gear to keep it pinned to the dock. This reduced the rocking of the vessel while it was being tied to the dock and unloaded.

Figure 23: Average Emissions by Engine Load for Vessel A

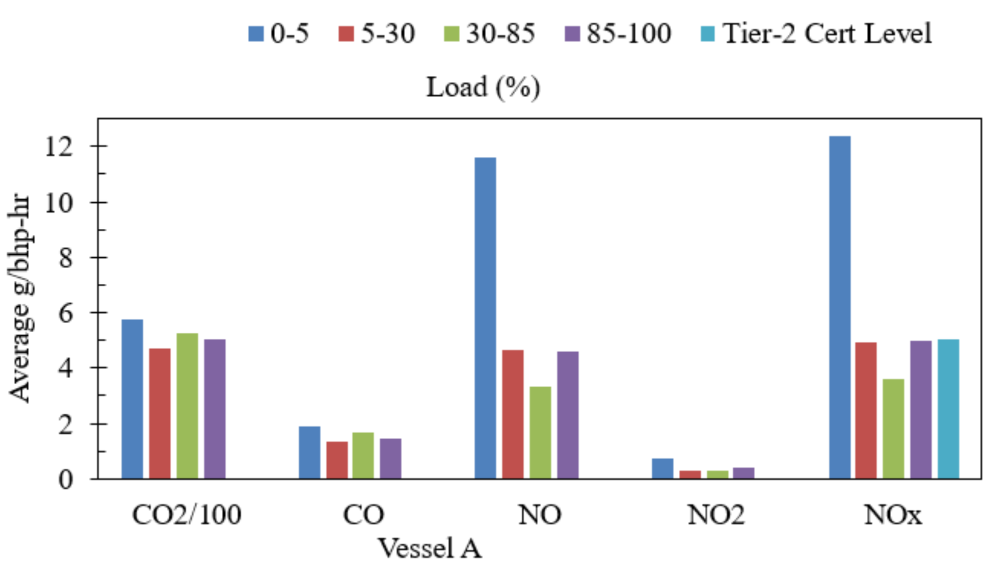
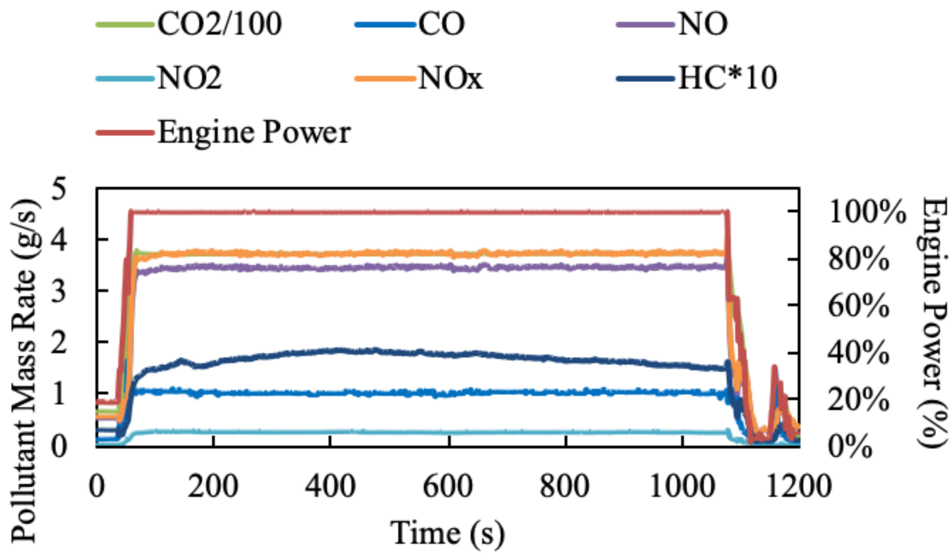


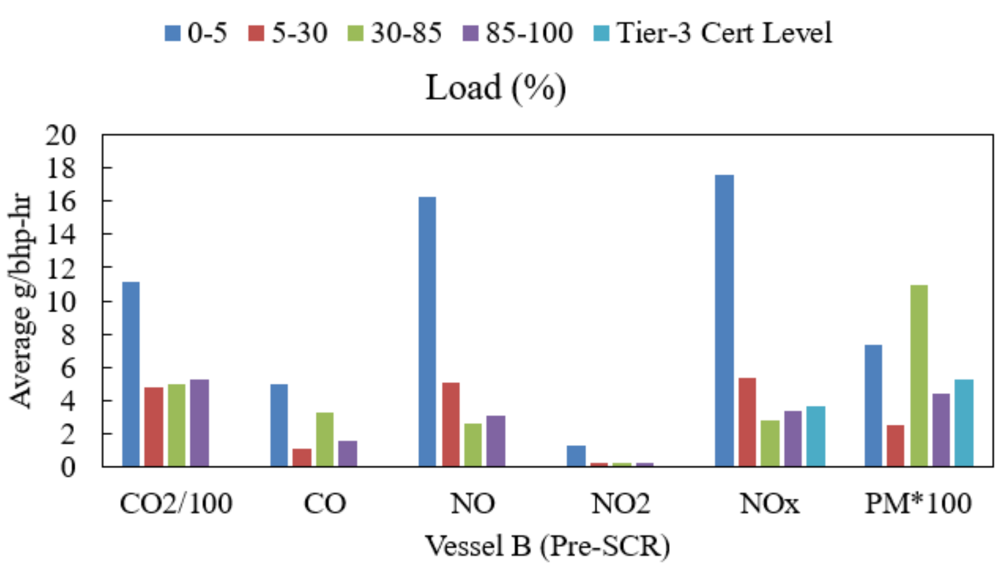
Figure 24: Example Time Series of Emissions for Vessel A



Time series of emissions for run 3A on 1/22/2019 on Vessel A.

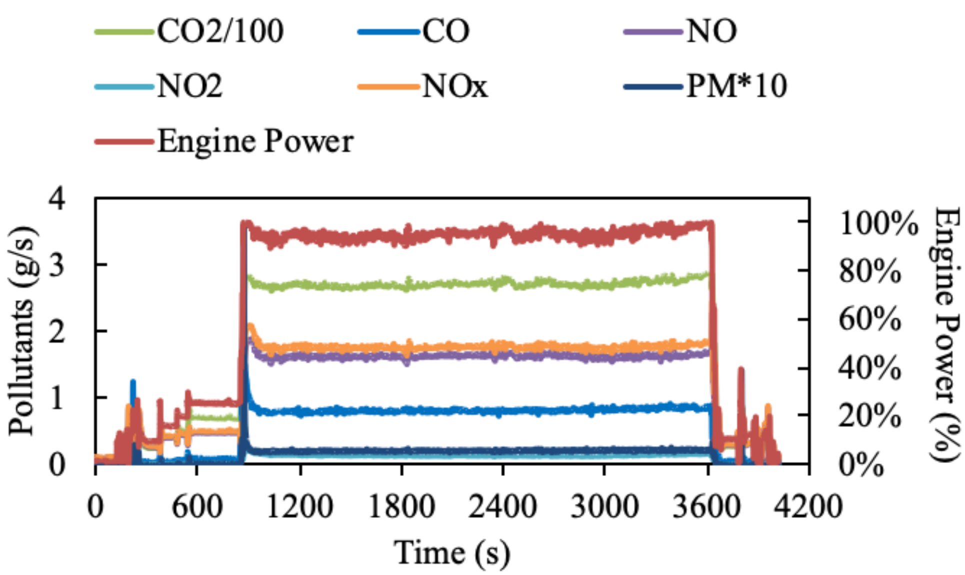
Figure 25 gives the average emission rates of Vessel B in the pre-SCR sampling position. All runs on 1/29/2019 are incorporated in the averages. This sampling position can also be considered engine out. Greater than 90% of the NO_x is in the form of NO rather than NO_2 and the 0–5% load bin shows the largest emission rate across all pollutants.

Figure 25: Average Emissions by Engine Load for Vessel B, Pre-SCR



The transient emission data was shown in Figure 26 for Vessel B in the pre-SCR or engine-out sampling position. This was a typical run for the vessel. The overall operational states of the vessel are quite similar to Vessel A. While loading and unloading the vessel is kept in gear to keep the vessel still. A vessel operator explained that keeping the engine "clutch ahead" or under a fast idle (~1000 rpm or less) stops the vessel surge and lowers the pitch and yaw motion. The surge of the vessel is front/back translational motion. The pitch and yaw are rotational motions of the up/down rotation and the turning motion, respectively. This helps prevent any jarring motion while the vessel is tied up and the ramp is connected. The vessel then moves through a no wake zone as it leaves and enters a port. The vessel then accelerates to near full load. Vessel B uses a lower power level to keep the vessel pinned to the port and the power fluctuates more so than Vessel A. Vessel B has a longer run than Vessel A with more changes in direction. The time series of emissions from a run of Vessel B indicates how transient loads on ferry vessels primarily occur toward the beginning and the end of the routes; mid-route, loads are more constant and resemble the steady-state loads used during certification. On this run the jump in engine power around 800 seconds. The acceleration to full load took about 25 seconds. PM emission rates display a maximum in the 30–85% load bin. This is because PM emission rates are the highest during the transient operation of the engine. Hydrocarbon emissions were not measured on Vessel B during normal operations due to the passenger safety risk as the THC measurement required carrying a hydrogen cylinder for the FID.

Figure 26: Example Time Series of Emissions for Vessel B, Pre-SCR

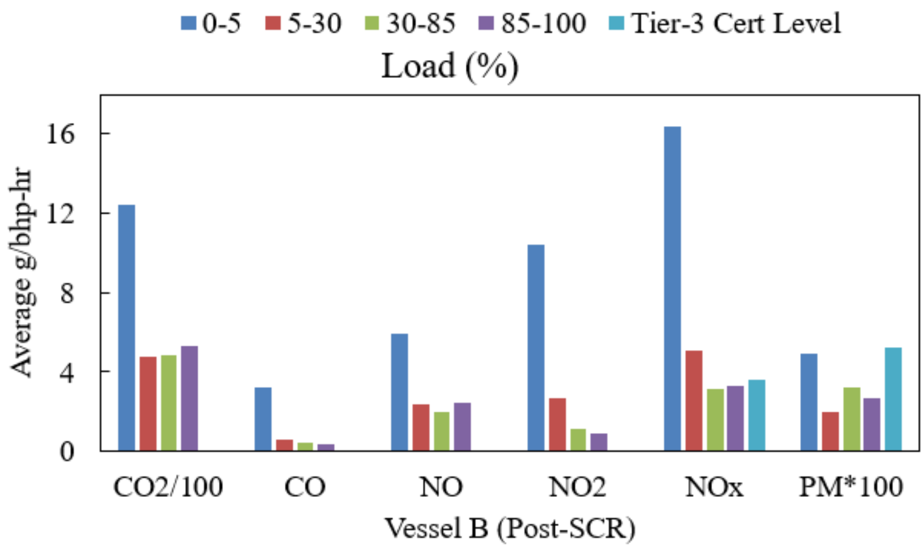


Time series for Vessel B (pre-SCR sampling location) for Run 14 on 1/29/19.

Figure 27 gives the average emission rate for Vessel B in the post-SCR sampling position. All the runs on 1/28/2019 are incorporated in the averages. The NO_2 emission rate was higher than anticipated and might be explained by the conversion of NO to NO_2 on the catalytic surface within the SCR system. As explained earlier, we speculate the DEF was not injected into SCR system. PM emission rates display a maximum in the 30–85% load bin in Figure 25 for the Pre-

SCR. However, PM in this load bin Post-SCR was reduced to a third of what is shown in Figure 25. This is due to the wall loss at the SCR.

Figure 27: Average Emissions by Engine Load for Vessel B, Post-SCR



By comparing Figure 27 with Figure 25, we could determine how much NO_2 was produced by oxidation at the SCR system. Figure 28 shows that the total average NO emission factor drops from 3.34 to 2.42 g/bhp-hr from pre-SCR to post-SCR. Figure 29 provides the NO_2 percentage in NO_x for Vessel B in both sampling positions. It shows that a large portion of NO is being converted NO_2 as it passes through the exhaust after-treatment systems. The percentage of NO_2 in NO_x increases from 7.5% to 30% from pre- to post-SCR. There was an average 21% percent increase of the NO_2/NO_x ratio from the post-SCR position to the pre-SCR position in total during operation. During low load operations this increase is substantially more. SCR control technologies have a limit set by CARB verification procedure 13 CCR 2700-2711 of a 20% increase.

Figure 28: NO and NO_2 Emissions for Vessel B, Pre- and Post-SCR

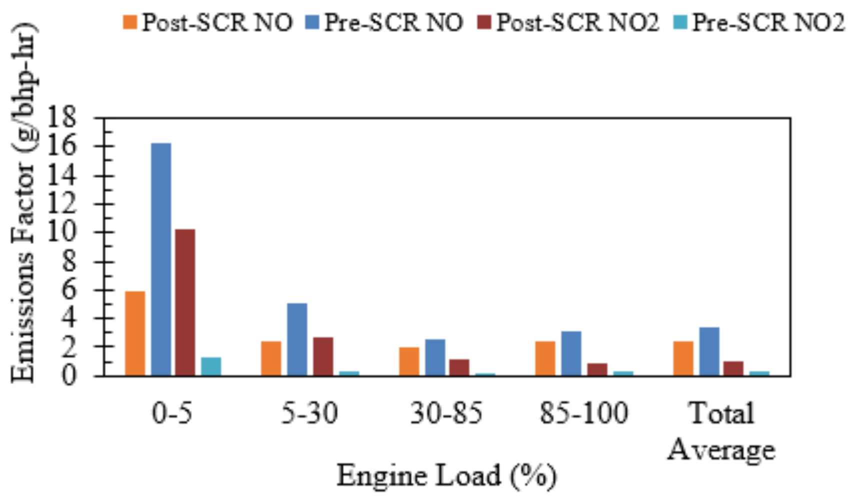
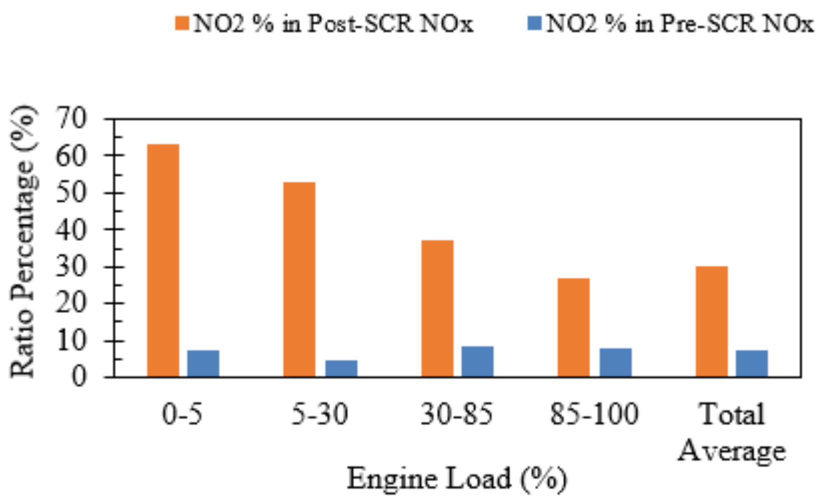


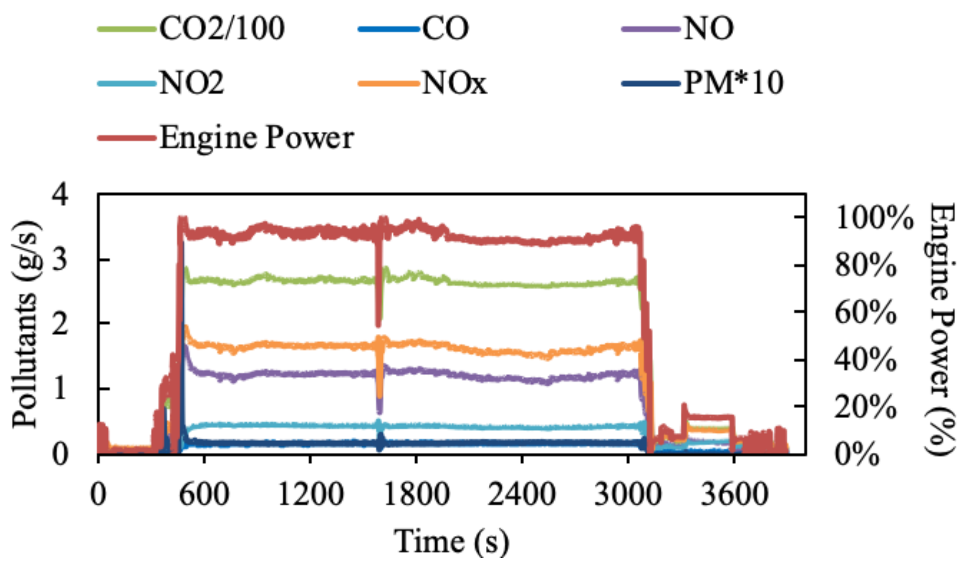
Figure 29: NO_2 Percentage in NO_x for Vessel B



Difference between Post- and Pre-SCR NO_2 divided by the Pre-SCR NO_x.

The transient emission mass rate for Vessel B in the post-SCR sampling position is given in Figure 30. It shows a very similar trend compared to Figure 26, the pre-SCR test, except the concentration of NO_2 is much higher and a bit lower NO concentration due to NO to NO_2 conversion. NO_x remained almost the same compared to the pre-SCR test shown in Figure 26.

Figure 30: Example Time Series of Emissions for Vessel B, Post-SCR



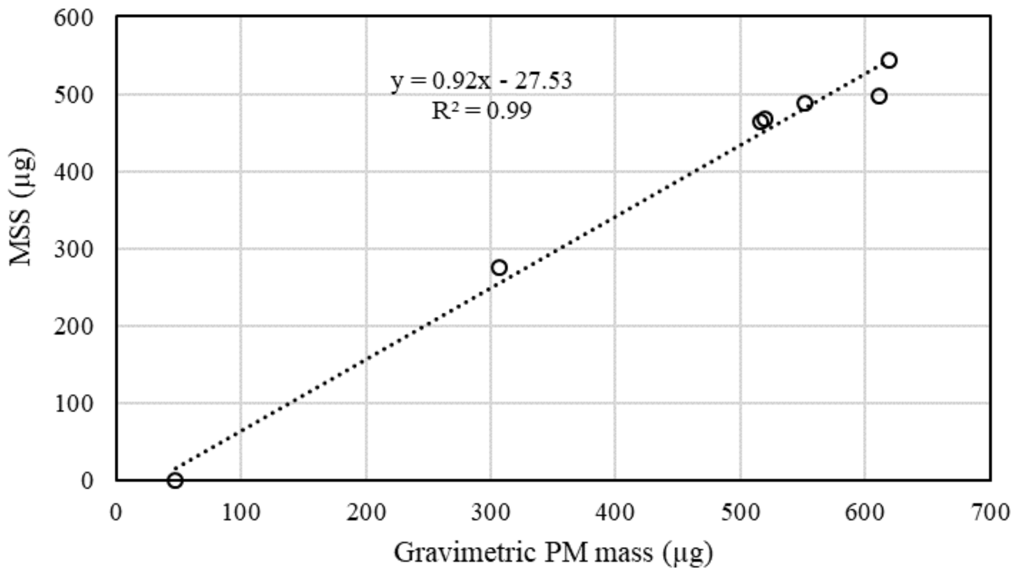
Time series for Vessel B (post-SCR sampling position) for Run 11 on 1/28/19.

PM Analysis

PM mass measured by the gravimetric method was compared with those by AVL M.O.V.E. for Vessel B. Filter samples collected over the six runs were compared with cumulative PM mass reported by the AVL M.O.V.E. The AVL M.O.V.E. had a slope of 0.92 against the gravimetric PM, as shown Figure 31.

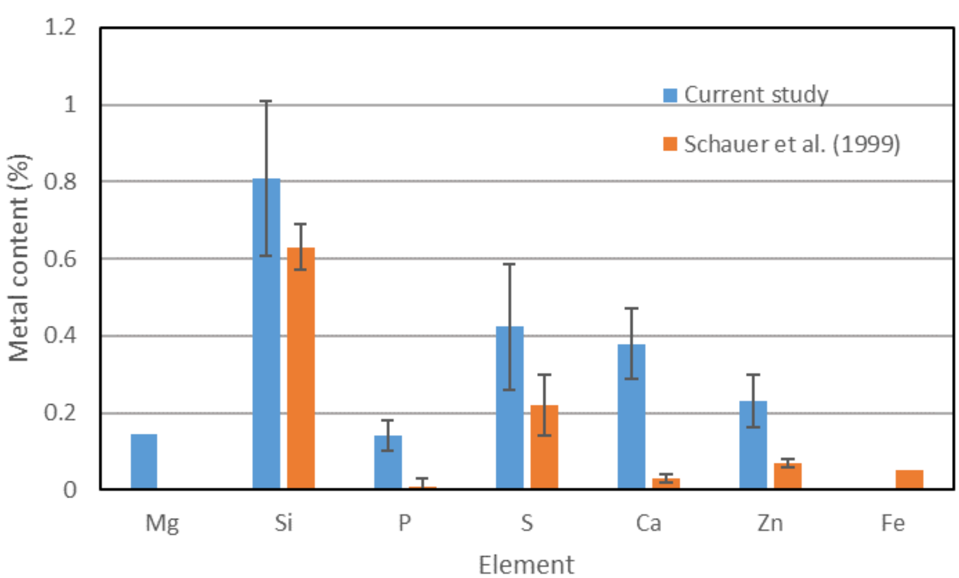
XRF analysis was conducted at the CARB laboratory for PM samples from pre-SCR tests for Vessel B and the results are shown in Figure 32. Mg, S, P, S, Ca, and Zn were detected. Their values ranged from 0.14 to 0.81% of the total PM mass. Sulfur may have come from both fuel and lube oil. Ca, Zn and P (Jung et al., 2003) may have originated from lube oil. Mg could be from lube oil and the origin of Si is uncertain. These levels of metal emissions are somewhat similar to a previous study by Schauer et al. (1999), as shown in Figure 34. They collected diesel PM from medium duty diesel truck over FTP cycle in 1999 when the low sulfur diesel (max 500 ppm sulfur) was used with no requirement of DPF. Note that the reporting limit of Fe for the current study was 0.97 µg per filter. As our filter weight ranged from 307 µg to 620 µg which is translated to 0.15 to 0.3%. This may be a reason why the current study could not quantify Fe.

Figure 31: Comparison of PM Mass Measurement Methods



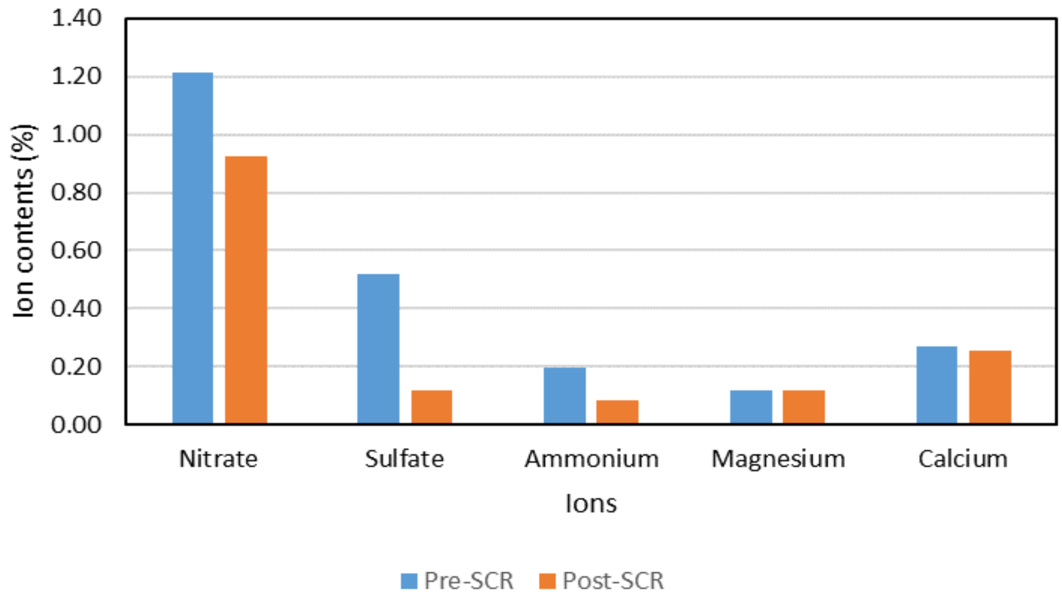
Comparison of PM mass measured by gravimetric method and MSS for Vessel B.

Figure 32: XRF Analysis of PM Samples from Vessel B, Pre-SCR



IC analysis was conducted for PM samples from Vessel B for both pre- and post-SCR tests. One would expect higher ammonium ion concentrations if urea was injected and ammonia was used for the SCR reaction. The ammonium ion concentrations in PM pre- and post-SCR were indistinguishable, indicating urea was not injected to the SCR system. Ion concentrations ranged from 0.08 to 1.55% and they were abundant in the order of nitrate, sulfate, calcium, ammonium, and magnesium.

Figure 33: IC Analysis for PM Samples from Vessel B, Pre- and Post-SCR



Emissions per Passenger per Trip

This analysis compares the emissions per passenger for three modes of transportation within the San Francisco Bay Area: passenger car, bus, and ferry. For this analysis, the locations of the ferry terminals were used as the starting and stop points of all trips regardless of mode. The passenger car was assumed to have one passenger and the bus was assumed to have 20 passengers. Vessel A was assumed to be at half capacity of 225 passengers and Vessel B was also assumed to be at half capacity of 200 passengers. The half capacity of the vessels was chosen due to reflect the observation that heavy commute trips were full in one direction and close to empty on the return. The bus capacity was chosen to be half of the capacity listed by Golden Gate Bridge Highway and Transportation District (2019). The half capacity of the buses was chosen to match the observations of the vessels, that not all trips will be at capacity.

The emission data for the vehicles was taken from CARB's EMission FACtor (EMFAC) 2017 database using the following parameters: sub-area of San Francisco, calendar year of 2019, winter, and model years and speeds aggregated. The vehicle categories chosen were Light Duty Automobile (LDA) and Urban Bus (UBUS). Gas, diesel, and natural gas were chosen as fuel types. The total emission data were used and includes the running, idle, and start exhaust emissions. The EMFAC emissions per vehicle type are listed in Table 8. Using Google Maps, it was determined that the distance between the Larkspur start point and the San Francisco end point was 16 miles for both passenger car and bus. The distance between the Vallejo start point and the San Francisco end point was found to be 30.5 miles for the passenger car and 35 miles for the bus. The difference in the distance is due to the bus routes.

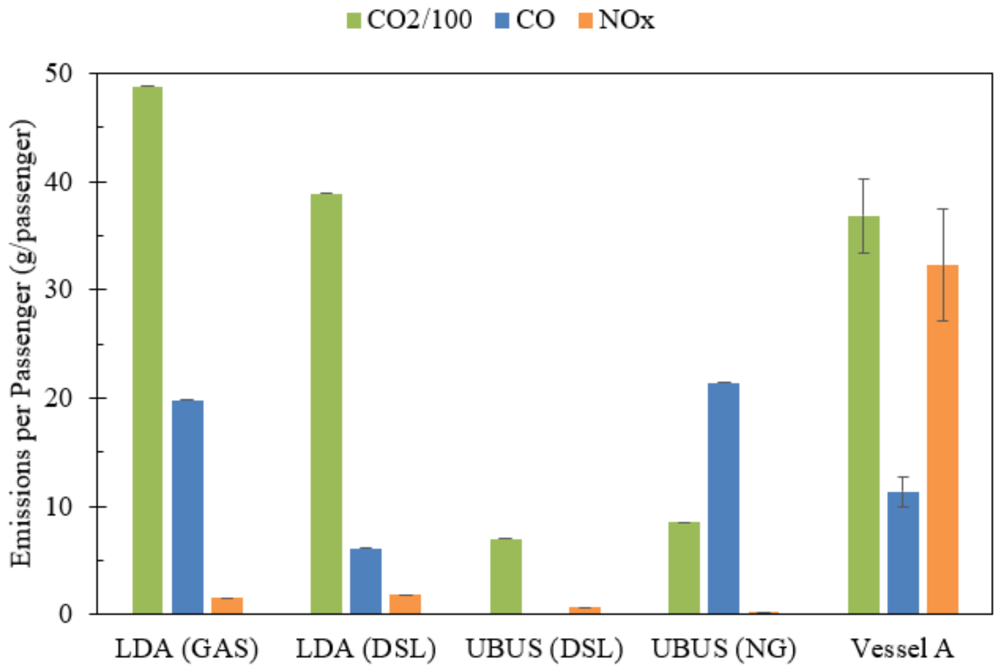
This per passenger emission analysis is not representative of the fleets of Vessel A or Vessel B. Single vessel emission measurements are being compared to entire vehicle category averages. As stated earlier, Vessel B's SCR system was not properly functioning at the time of measurement. The vehicle emission rates in grams per mile were calculated from the vehicle miles traveled per day and the total emissions per day. Driving conditions such as weather, traffic, and road closures could not be addressed in this analysis. For the aggregated speeds and model years, the individual vehicle subgroup contributions in tons per day add together to get the total tons per day for the vehicle category.

Table 8: Emission Factors from EMFAC

Category	Fuel	Population	Vehicle Miles Traveled (per day)	CO_2	CO	NO_x	PM
				(tons per day)			
Light Duty Auto	Gas	1.52E+05	5.46E+06	1.83E+03	7.46E+00	5.79E-01	1.30E-02
	Diesel	2.05E+03	7.56E+04	2.03E+01	3.19E-02	9.60E-03	9.38E-04
	Electric	2.74E+03	1.00E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Urban Bus	Diesel	5.78E+02	5.32E+04	9.97E+01	1.20E-02	9.69E-02	3.78E-04
	Natural Gas	1.21E+02	1.04E+04	2.38E+01	5.99E-01	5.81E-03	3.77E-05

Figure 34 shows that Vessel A has lower CO_2 and CO emissions per passenger than a passenger car but it has higher emissions than a bus. The vessel emits more NO_x than either vehicle and less CO than a natural gas-powered bus. These emissions are assuming that the bus is at capacity and the vessel is at half capacity of passengers. During heavy commute times it was observed that the ferry was packed in one direction and mostly vacant on the return trip. With a gasoline passenger car as a baseline Table 9 gives the ratios between of the emissions between the transportation categories. This analysis suggests Vessel A emits approximately 0.75 times the amount of CO_2 emissions per passenger and 21 times the NO_x emission per passenger than a single passenger car.

Figure 34: Comparison of Emissions per Passenger by Travel Mode (Vessel A)



Emission comparison per passenger between the Light Duty Automobile (LDA), Urban Bus (UBUS), and the Vessel A. The LDA is given for gas and diesel fuels. The UBUS is given for diesel and natural gas fuels. Emission data for the vehicles was provided by the EMFAC2017 model.

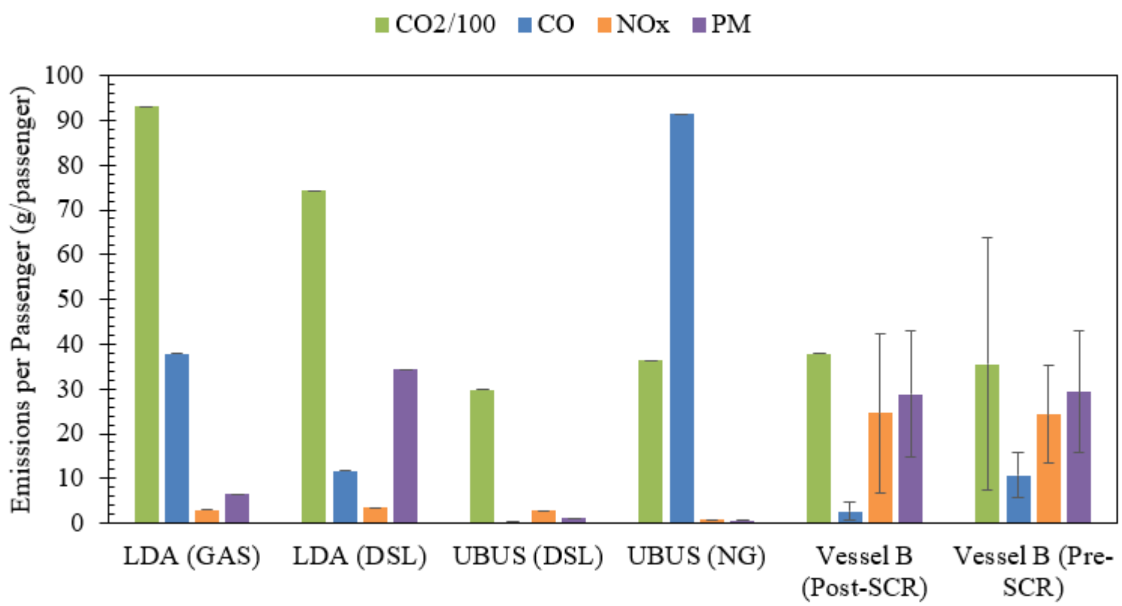
Table 9: Transportation Categories Relative to Gas-Fueled Passenger Car Baseline

Vessel Trip Comparison	Ratio Category (All Normalized to LDA Gas)	$CO_2/100$	CO	NO_x	PM
Vessel A	LDA DSL	0.80	0.31	1.20	N/A
	UBUS DSL	0.28	0.01	0.86	
	UBUS NG	0.34	2.10	0.26	
	Vessel A	0.75	0.57	21.0	
Vessel B	LDA DSL	0.80	0.31	1.20	5.23
	UBUS DSL	0.32	0.01	0.98	0.17
	UBUS NG	0.39	2.41	0.30	0.09
	Vessel B (Pre-SCR)	0.40	0.07	8.40	4.38
	Vessel B (Post-SCR)	0.38	0.28	8.28	4.47

Each row represents the ratio of the specified transportation category to a gasoline-fueled passenger car.

Figure 35 shows that Vessel B is higher than the bus for CO_2 emissions per passenger and is lower than a light duty passenger car. Vessel B emits more NO_x than either vehicle per passenger. The route chosen for the vehicles was the shortest route possible, but it might not always be available due to traffic. Table 9 also gives the ratios between the transportation categories for this vessel trip with the gas passenger car as the baseline. Vessel B emits approximately 8 times the NO_x emissions and 4 times the PM emissions per passenger than a single passenger gasoline light duty automobile.

Figure 35: Comparison of Emissions per Passenger by Travel Mode (Vessel B)



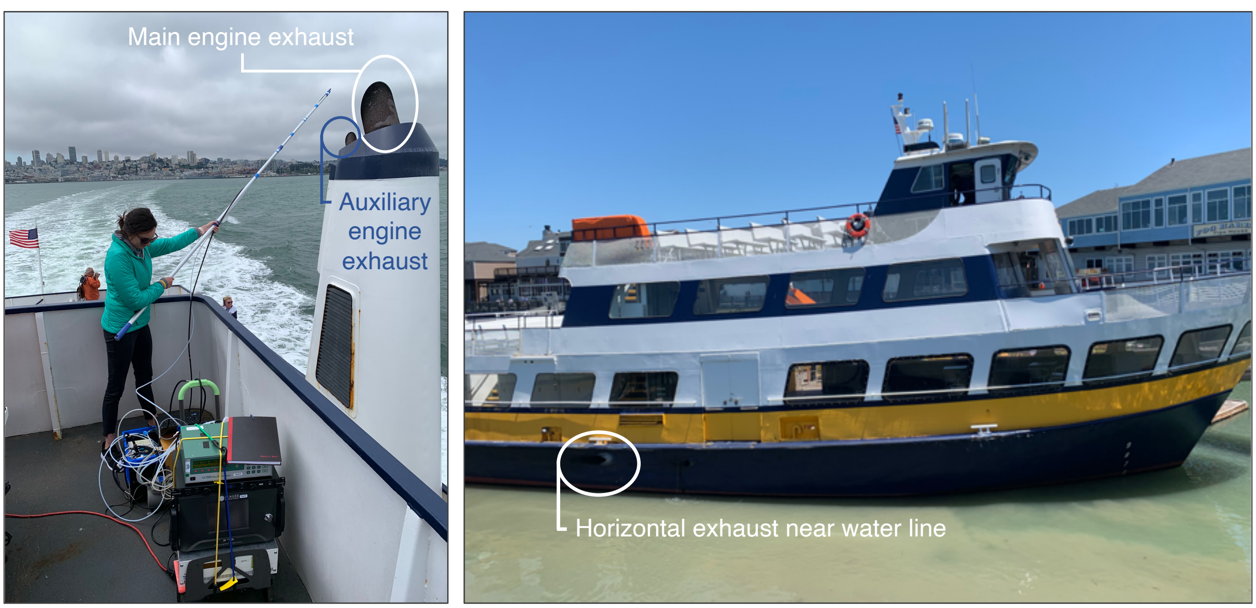
Emission comparison per passenger between the Light Duty Automobile (LDA), Urban Bus (UBUS), and the Vessel B for both sampling positions. The LDA is given for gas and diesel fuels. The UBUS is given for diesel and natural gas fuels. Emission data for the vehicles was provided by the EMFAC2017 model.

In-Use Emissions Measurements: On-board Plume Capture

Methods

We used a plume capture approach to characterize in-use emissions from ferry and excursion vessels operating in the SF Bay, as well as from a passenger vessel and a charter fishing boat operating in the South Coast Air Basin. Typically, each vessel had a pair of main and auxiliary engines on the port and starboard side for maneuverability. The study focused on vessels with dry exhaust systems, with accessible exhaust tailpipes that were either vertically-oriented on the top deck or horizontally-oriented near the water line or at the vessel stern. Figure 36 shows an example of each tailpipe configuration. On these vessels, one backup auxiliary engine would be in use each day, alternating daily between port and starboard side. The exhaust for the auxiliary engine was separate from the main engine, and identified as either next to the main engine tailpipe or as located underneath the hull of the vessel. The active auxiliary engine was noted and the opposite main engine was sampled, thereby ensuring that only main engine exhaust was sampled when possible. Combined main and auxiliary engine exhaust measurements are noted explicitly below. Most San Francisco ferry and excursion vessels that employed wet exhaust systems—wherein exhaust gas is cooled with sea water before exiting the tailpipe—were catamaran-style boats with inaccessible exhaust tailpipes located underneath the vessel hull. As such, only a handful of wet exhaust systems with accessible exhaust tailpipes were sampled in this study, including two ferry engines in the San Francisco Bay and the Southern California passenger boat.

Figure 36: Exhaust Configurations and Plume Capture Sampling Method



(Left) Vertically-oriented exhaust, with auxiliary engine exhaust adjacent to the main engine exhaust tailpipe. The gas and particle sample lines are attached to the pole, which is extended intermittently into the main engine exhaust plume. (Right) Horizontally-oriented main engine exhaust.

Exhaust from the main engine tailpipe was sampled by extending gas and particle sample lines into the exhaust plume using an extension pole. Pollutant concentrations in the exhaust were measured for approximately 10 seconds at regular intervals of around once per minute (Figure 36). Exhaust concentrations of CO_2, BC, and NO_x were measured with a suite of instruments. CO_2 was measured with three nondispersive infrared analyzers (LI-COR, models LI-7000 and LI-820; PP Systems, model SBA-5). BC was measured with three filter-based light absorption photometers (custom-built UC Berkeley Aerosol Black Carbon Detector (ABCD); AethLabs, model MA300; Magee Scientific, model AE33). NO_x was measured by chemiluminescence (Eco Physics, model CLD64). All of these analyzers were operated at 1 Hz during this study. Given space and power restrictions on-board many vessels, the primary sampling setup in the SF Bay relied on the lower cost and battery-powered sensors: the LI-820 and SBA-5 for CO_2, and the ABCD and MA300 for BC. When plug-in power was available on-board for a subset of vessels, the high-grade analyzers were also used: the LI-7000 for CO_2, AE33 for BC, and CLD64 for NO_x. The Southern California measurements were made exclusively with the ABCD for BC and a LI-COR LI-840A for CO_2, which operates and performs the same as the LI-820 model used for the SF Bay measurements. NO_x was not measured on the two Southern California vessels.

Fuel-based BC and NO_x emission factors were calculated via carbon balance for each 10-second plume capture event:

$$E_P = \frac{\int_{t_1}^{t_2}\left([P]_t - [P]_{t_1}\right)dt}{\int_{t_1}^{t_2}\left([CO_2]_t - [CO_2]_{t_1}\right)dt}\,\frac{44}{12}\,w_c$$

The emission factor for pollutant P (E_p) has units of g of pollutant emitted per kg of fuel burned and is calculated over the time interval $t_1 \leq t \leq t_2$. Since sensors can have different response times, t_1 and t_2 are determined independently by the inflection points of each peak. The numerator and denominator represent the baseline-subtracted peak areas for pollutant P and CO_2, respectively. This ratio compares the relative abundances of pollutant P and CO_2 in the sampled exhaust plume when [P] and [CO_2] have mass concentration units (e.g., $\mu g\ m^{-3}$). The factor of 44/12 converts CO_2 to carbon mass and the weight fraction of carbon in diesel fuel (w_c = 870 g C per kg diesel) converts ratio to a per mass of fuel burned basis. This analysis assumes that all fuel carbon is converted to CO_2 during combustion, with negligible emissions of carbon monoxide and volatile organic compounds relative to emitted CO_2. In the text below, the terms emission rates and emissions are used as synonyms for emission factors and do not imply total mass or time-normalized emissions.

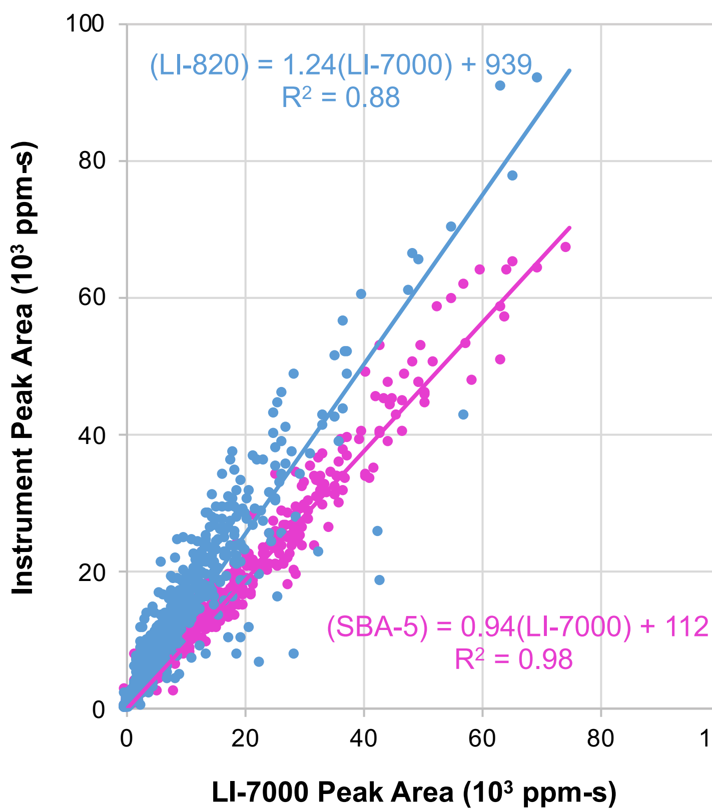
BC concentrations measured with the ABCD were adjusted for the aethalometer's filter loading artifact:

$$BC = \frac{BC_o}{a\left[exp\left(\frac{-ATN}{100}\right)\right] + (1 - a)}$$

This adjustment is a modified version of the correction equation developed by Kirchstetter and Novakov (2007). BC and BC_0 are the adjusted and unadjusted BC concentrations, respectively, and ATN is the attenuation of light by the filter. The correction parameter, a, adjusts BC_0 such that BC concentrations are independent of filter loading. For the ABCD, the value of a = 0.64, as described by Caubel et al. (2019). The MA300 and AE33 aethalometers employ native algorithms to adjust reported BC concentrations for this artifact.

Lab experiments with certified gas cylinders validated the response of CO_2 analyzers up to 15,000 ppm CO_2. Measured concentrations that exceeded this threshold were excluded from the data set because these measurements could not be validated within 5% of the calibration concentration. Lab and field data also showed that the LI-820 typically overstates and SBA-5 understates the integrated CO_2 peak areas relative to the high-grade LI-7000. As such, emission factors determined with the LI-820 and SBA-5 were adjusted based on linear relationships to the LI-7000 CO_2 peak area (Figure 37). Emission factors calculated with the LI-820 and the very similarly performing LI-840A were adjusted by a factor of 1.24 and SBA-5 emission factors were adjusted by a factor of 0.94 to account for these differences. Thus, all reported emission factors are "LI-7000 equivalent," regardless of the CO_2 sensor used.

Figure 37: CO_2 Peak Areas Calculated with the LI-820 and SBA-5 vs the LI-7000



Linear relationships of CO_2 peak areas (ppm-seconds) calculated with the LI-820 and SBA-5 relative to the faster-responding LI-7000 for the same plume capture events measured on-board in-use vessels.

For the SF Bay measurements reported below, BC emission factors were determined with the ABCD and SBA-5 pair, as these low-cost options were included in nearly all sampling setups. NO_x emission factors were also primarily determined with the SBA-5. For a minority of measurements, the SBA-5 was not available and the LI-7000 was used to calculate CO_2 peak areas. As mentioned above, all BC emission factors for the Southern California measurements were determined with the ABCD and LI-840A pair.

A GPS logger (GlobalSat DG-500) was used to record vessel location and speed during exhaust plume sampling. The team also recorded the general operation of vessels in a logbook, including when they were docked at a pier, maneuvering in and out of dock, and cruising at steady speed. When vessels were docked at a pier, the engine was either idling or working to keep the vessel steady against the dock as passengers boarded and disembarked.

San Francisco Bay Measurements of Ferry & Excursion Vessels

Sampled Fleet

Between January and November 2019, measurements of 21 engines were made on-board 14 ferries and excursion vessels during typical operation in the San Francisco Bay. Some sampling was conducted on the same engine under more than one condition, including when using different fuel types and when selective catalytic reduction (SCR) systems were active or inactive. In total, 25 engine conditions were characterized in this study, as summarized in Table 10.

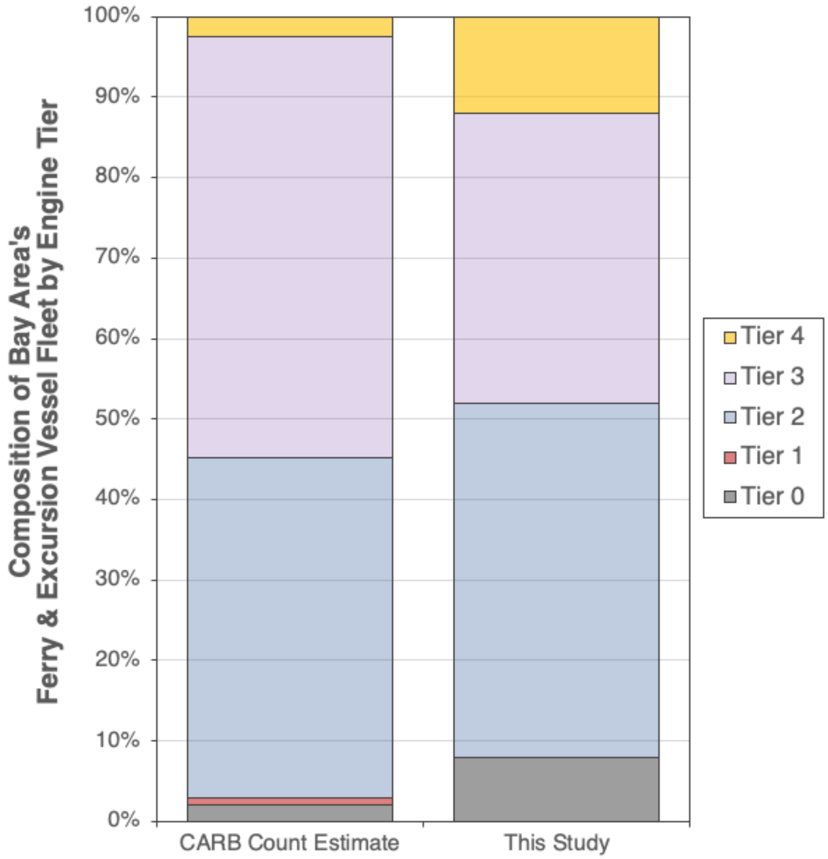
As shown in Figure 38, the subset of engines sampled in this study are generally representative of the broader fleet of engines on-board ferry and excursion vessels operating in the San Francisco Bay Area. According to CARB-provided estimates of total fleet engine counts, 52% and 42% of engines are certified to meet Tier 3 and Tier 2 federal emission standards, respectively (CARB, 2020). The remainder of the fleet is approximately equally split between Tier 0, 1, and 4 engines. The sampling conducted in this study captured a similar distribution of engines, with most engine tiers within 5–10% of the above-described broader fleet breakdown. Tier 3 engines were the main exception and were slightly under-sampled in these measurements, accounting for around one-third of the sampled subset of engines rather than half.

Table 10: Summary of Sampled Bay Area Fleet

Vessel #	Route Type	Engine #	Engine Condition #	Engine Condition Parameters		
				Engine Tier	Fuel Type	Notes
1	LH	1	1	0	ULSD #2	
		2	2		ULSD #2	
2	SH	3	3	2	R100	Auxiliary engine on
			4		CARB ULSD	
3	SH	4	5		R99	
4	SH	5	6		R99	
5	SH	6	7		R99	
6	SH	7	8		R100	
		8	9		R100	Auxiliary engine on
7	SH	9	10		ULSD #2	
		10	11		ULSD #2	
8	SH	11	12		ULSD #2	Wet exhaust system
		12	13		ULSD #2	
9	SH	13	14	3	R100	
10	SH	14	15		R99	
11	LH	15	16	3 (Retrofit SCR)	CARB ULSD	Inactive SCR
12	SH	16	17		ULSD #2	Inactive SCR
			18		ULSD #2	
		17	19		ULSD #2	
			20		ULSD #2	
13	SH	18	21		ULSD #2	Inactive SCR
		19	22		ULSD #2	
			23		ULSD #2	Active SCR
14	HS/LH	20	24	4 (SCR)	ULSD #2	Active SCR
		21	25		ULSD #2	

SCR systems were confirmed as active or inactive with data downloaded from the engine room or by noting any system errors or alarms during sampling. Vessel routes were categorized as short-haul (SH), long-haul (LH), and high-speed/long-haul (HS/LH), as discussed in detail below and summarized in Table 11.

Figure 38: Composition of Bay Area Ferry and Excursion Vessel Fleet by Engine Tier



The CARB distribution shows projected emission inventory engine counts for ferry and excursion vessels operating in the San Francisco Bay Area in 2023 (CARB, 2020).

Operating Modes

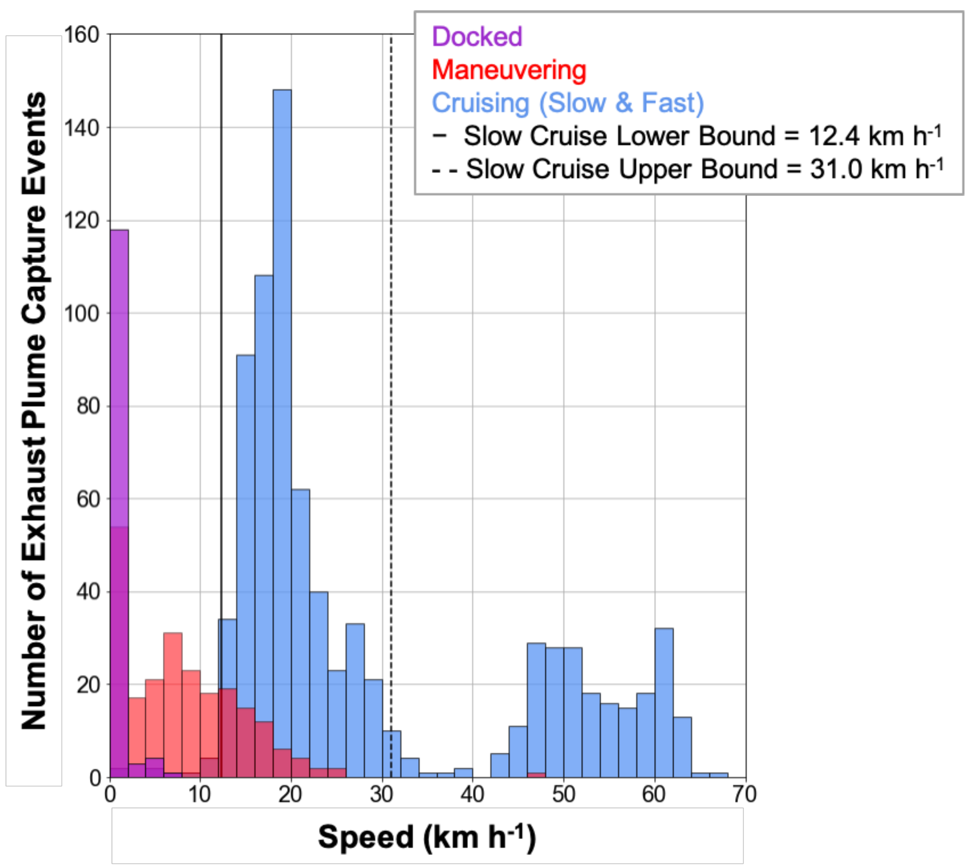
Emission factors are categorized below according to vessel operating mode. As noted above, when a vessel was docked, its engines were either idling or working to keep the boat pushed steady against the pier. Maneuvering includes times when vessels were moving in or out of dock, as well as around tourist destinations around the Bay (e.g., the Golden Gate Bridge and Alcatraz Island). Cruising captures all other times, when the vessel was traveling at a steady speed between destinations, and is split into fast and slow categories. Fast cruising occurred primarily when vessels like commuter ferries were traveling at higher speeds on long stretches between docks. Slow cruising occurred when vessels were operated at lower speeds while traveling along corridors, in harbors, or between tourist destinations.

Handwritten notes served as the primary reference to distinguish between vessel operating mode, but they did not distinguish between cruising and maneuvering operations within the Bay (e.g., the turnaround at the Golden Gate Bridge). As such, the GPS speed data were used to reassign emission factors initially classified as cruising. Data that was not explicitly noted as a “slow cruise” along corridors or in harbors were re-categorized based on recorded speed: emission factors measured for speeds <12.4 km h^{-1} (mean + 1 standard deviation of speeds during field-noted maneuvering) were categorized as maneuvering rather than cruising. Cruising data not explicitly qualified as slow or fast were also re-categorized using an upper-bound speed threshold for slow cruising, 31.0 km h^{-1} (mean – 1 standard deviation for field-noted fast cruising speed data). It should be noted that not all engine conditions had both slow and fast cruising operational modes, such as excursion vessels with speeds that never exceeded 31.0 km h^{-1}.

Figure 39 shows the distribution of speeds by operating mode during each plume capture event. In total, 1438 BC and 589 NO_x emission factors were measured across the 25 engine conditions sampled. Approximately 65% of these measurements were during cruising (combined slow and fast), 25% during maneuvering, and 10% while docked.

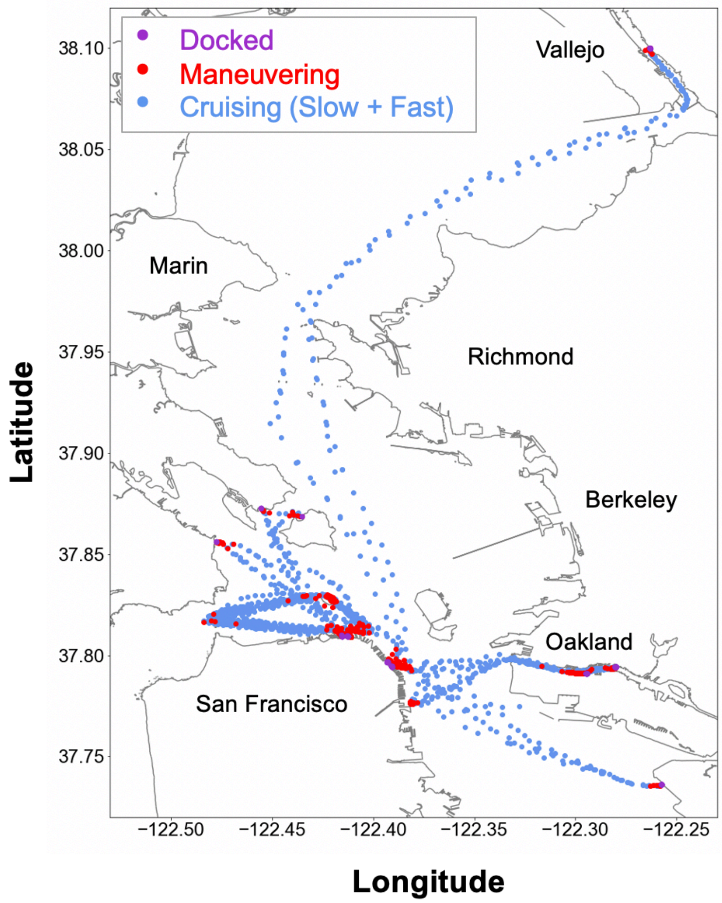
Figure 40 shows a map of these operating modes, with each mapped point representing the location of the vessel during a plume capture event. Note that most maneuvering occurs close to docking, with the exception of those points within the Bay at the Golden Gate Bridge and around Alcatraz Island.

Figure 39: Speed Distributions by Operating Mode



Distribution of vessel speeds during 1438 plume capture events, where each event resulted in a calculated BC emission factor. Each emission factor was categorized by operating mode, as described above in the text.

Figure 40: Map of All Measurements, Categorized by Operating Mode



This map shows 1438 individual plume capture events of 25 engine conditions on 14 ferry and excursion vessels across the San Francisco Bay. Each measurement is categorized by operating mode, based on handwritten field notes and refined by speed data, as described in the text.

Emission Factor Weighting

An overall emission factor for each sampled engine condition was calculated as a fuel-weighted average of the average emission factor for each mode, as described below. Engine data provided by CARB, UCR, and MTU for three types of vessel operation indicate that the majority of fuel is consumed in the cruising mode of each route type (Table 11). These three data sets captured the typical vessel routes observed for the sampled fleet, including: (1) a slower-moving, "short-haul" tour around the Bay, as measured on a Tier 2 excursion vessel; (2) a "long-haul" commuter ferry traveling across the Bay (e.g., Vallejo to San Francisco), as measured on a Tier 3 ferry; and (3) a designated "high-speed" long-haul commute across the Bay, as measured on a Tier 4 ferry. The fuel and energy consumption during these vessel routes are summarized in Table 11 by operating mode, and the differences are assumed to be the result of the vessel operation rather than the engine tier.

Table 11: Average Fuel and Energy Consumption by Operating Mode and Emission Factor Weighting by Vessel Route Type

Route Type	Operating Mode	Mode Average					Overall bsfc ($g\ bhp\text{-}h^{-1}$)
		Fuel Consumption		Fraction of			
		Rate ($kg\ h^{-1}$)	Brake Specific, bsfc ($g\ bhp\text{-}h^{-1}$)	Total Time	Fuel Consumed	Energy Used	
Short-Haul (Tier 2 Excursion)	D + M	13.7 ± 0.2	248.1	0.29	0.11	0.04	199.7
	SC + FC	46.6 ± 0.2	197.7	0.71	0.89	0.96	
	$\boldsymbol{EF_{overall,SH} = 0.90(\overline{EF}_{SC+FC}) + 0.10(\overline{EF}_{D+M})}$						
Long-Haul (Tier 3 Ferry)	D + M + SC	30.2 ± 0.4	213.8	0.48	0.09	0.08	171.4
	FC	301.9 ± 0.2	167.7	0.52	0.91	0.92	
	$\boldsymbol{EF_{overall,LH} = 0.90(\overline{EF}_{FC}) + 0.10(\overline{EF}_{D+M+SC})}$						
High-Speed/ Long-Haul (Tier 4 Ferry)	D + M + SC	26.6 ± 0.8	285.7	0.49	0.04	0.03	158.3
	FC	381.2 ± 4.4	154.7	0.73	0.96	0.97	
	$\boldsymbol{EF_{overall,HS/LH} = 0.96(\overline{EF}_{FC}) + 0.04(\overline{EF}_{D+M+SC})}$						

Engine data was provided by CARB, UCR, and MTU for three vessels that followed a short-haul (SH), long-haul (LH), and high-speed/long-haul (HS/LH) routes. Data was categorized by operating mode: docked (D), maneuvering (M), slow cruise (SC), and fast cruise (FC). The product of mode-average fuel consumption rate and fraction of total time gives the fraction of fuel consumed in that mode, which are the route-specific weighting factors for determining overall emission factors (see equations). The overall weighted bsfc for each route is the sum of the products of mode-average brake specific fuel consumption (bsfc) and fraction of energy used in that mode; these bsfc values are used to convert measured emission factors from a fuel to engine power basis.

In general, the overall emission factor for a given engine condition was calculated as the weighted sum of the average emission factor when cruising and the average emission factor when docked or maneuvering. For most vessels (i.e., those on a "short-haul" route), the combined slow and fast cruising mode was weighted by 90% and all other modes combined made up the remaining 10%. Based on the differences in fuel consumption between fast cruising and the other three operating modes reported in Table 11, this rule has two exceptions. For "long-haul" ferry routes, a majority of fuel is consumed during the fast cruising operating mode that is characterized by high engine loads. As such, the periods of slow cruise are weighted less for these vessels and combined with the docked and maneuvering emission factors. Specifically, the overall emission factors determined for the high-speed commuter ferry (Vessel #14) were instead weighted 96% fast cruise and 4% combined, docked, maneuvering, and slow cruise. For the other long-haul ferries that were not specifically designated as high-speed (e.g., Vessels 1 and 11), the average emission factor for fast cruising was weighted by 90% and the average emission factor when docked, maneuvering, or slow cruising was weighted by 10%. The weighting conditions applied for each route type are noted in Table 11, including the equations for determining the overall, weighted-average emission factor. The condition applied to determine the overall BC and NO_x emission factor for each engine condition is also explicitly noted above in Table 10.

For all on-board plume capture results, the presented overall emission factors refer to the above-described mode-averaged values and are presented in fuel-normalized units of g kg^{-1}. These emission factors are also compared below to EPA engine-power normalized certification levels and emission standards using a brake specific fuel consumption (bsfc) to convert from units of g kg^{-1} to g kWh^{-1}. Following the approach of fuel-weighted emission factors, energy-weighted bsfc values were calculated for each route type as the sum product of the average bsfc in each operation mode and fraction of total engine power used in that mode. These energy-weighted bsfc values ranged from 158.3–199.7 g bhp-h^{-1} (212.3–267.8 g kWh^{-1}; Table 11). Additionally, a typical average value for all vessels was calculated using the combined dataset (176.5 g bhp-h^{-1} = 236.6 g kWh^{-1}).

BC Emission Rates

Table 12 reports average BC emission factors (± 95% confidence intervals) within each operating mode and averaged over all modes for each of the 25 engine conditions. Tier average and fleet average values are also reported, where the confidence intervals are propagated uncertainties.

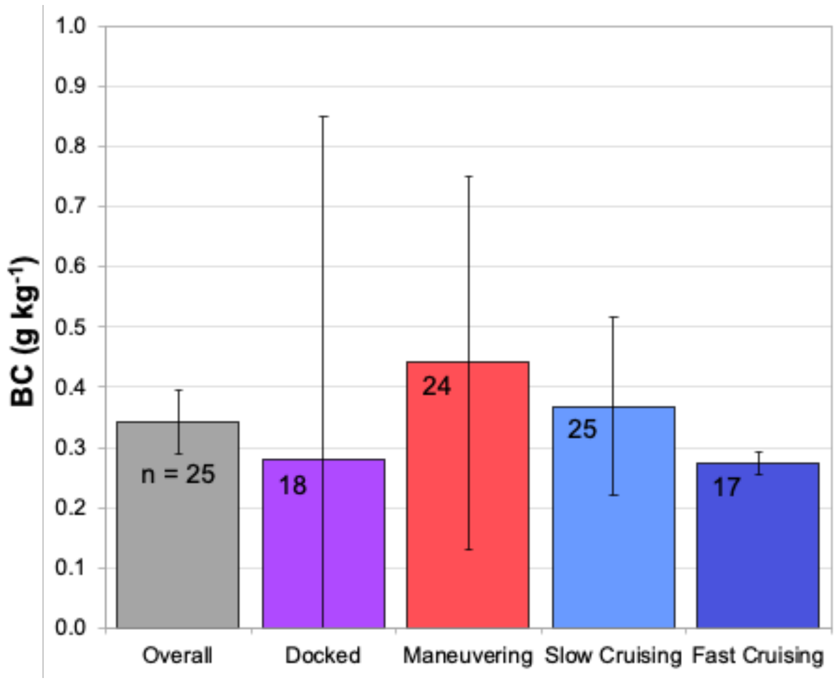
The sampled ferry and excursion vessel fleet-average BC emission factor was 0.34 ± 0.03 g kg^{-1}, (Table 12 and Figure 41). BC emission rates were highest during maneuvering and least variable during cruising. The large confidence interval on the docked emission factor is the result of one outlier (engine condition 9 = 1.09 ± 9.63 g kg^{-1}) that included only two measurements, one of which was a very high emission event while pushing the boat steady against the pier. That high emission event is likely more characteristic of maneuvering engine work; however, our field notes and speed data were not able to distinguish these two engine modes while at dock.

Table 12: Average BC Emission Rates for Each Engine Condition

Vessel #	Engine #	Engine Condition #	Engine Tier	BC ($g\ kg^{-1}$) Overall	Docked	Maneuvering	Slow Cruising	Fast Cruising
1	1	1	0	0.61 ± 0.03	0.15 ± 0.01	0.19 ± 0.08	0.35 ± 0.05	0.64 ± 0.03
	2	2		0.76 ± 0.06	—	0.26 ± 0.65	0.46 ± 0.20	0.80 ± 0.06
Tier 0				**0.68 ± 0.03**	**0.15 ± 0.01**	**0.23 ± 0.33**	**0.40 ± 0.10**	**0.72 ± 0.03**
2	3	3	2	0.33 ± 0.03	0.29 ± 0.20	0.29 ± 0.06	0.33 ± 0.03	—
		4		0.57 ± 0.04	0.55 ± 0.45	0.48 ± 0.15	0.58 ± 0.04	—
3	4	5		0.46 ± 0.16	—	0.74 ± 0.64	0.43 ± 0.17	—
4	5	6		0.81 ± 0.21	0.01 ± 0.01	1.29 ± 0.88	0.79 ± 0.22	—
5	6	7		0.20 ± 0.04	0.68 ± 0.45	0.72 ± 0.29	0.15 ± 0.03	0.05 ± 0.03
6	7	8		0.30 ± 0.07	0.44 ± 0.33	0.42 ± 0.18	0.28 ± 0.07	—
	8	9		0.63 ± 0.15	1.09 ± 9.63	0.99 ± 0.53	0.59 ± 0.16	—
7	9	10		0.39 ± 0.13	0.37 ± 0.07	0.71 ± 0.47	1.61	0.33 ± 0.11
	10	11		0.41 ± 0.17	0.52 ± 0.53	0.55 ± 0.16	1.26 ± 3.07	0.32 ± 0.14
8	11	12		0.40 ± 0.09	0.22 ± 0.02	1.09 ± 1.90	0.26 ± 1.28	0.39 ± 0.02
	12	13		0.22 ± 0.07	0.21 ± 0.02	0.19 ± 0.02	0.21 ± 0.13	0.25 ± 0.04
Tier 2				**0.43 ± 0.04**	**0.44 ± 0.97**	**0.68 ± 0.21**	**0.59 ± 0.33**	**0.27 ± 0.04**
9	13	14	3	0.44 ± 0.70	—	0.97 ± 6.94	0.38 ± 0.13	—
10	14	15		0.21 ± 0.07	—	0.19 ± 0.04	0.21 ± 0.08	—
11	15	16	3 (Retrofit SCR)	0.51 ± 0.16	—	—	0.25 ± 0.25	0.54 ± 0.17
12	16	17		0.24 ± 0.11	—	0.91 ± 1.00	0.08 ± 0.11	0.20 ± 0.06
		18		0.22 ± 0.12	0.27 ± 0.52	0.06 ± 0.03	0.32 ± 1.08	0.22 ± 0.15
	17	19		0.16 ± 0.05	—	0.18 ± 0.31	0.14 ± 0.18	0.17 ± 0.04
		20		0.13 ± 0.13	0.01	0.06 ± 0.05	0.16 ± 0.22	0.07 ± 0.04
13	18	21		0.16 ± 0.03	0.07 ± 0.08	0.09 ± 0.04	0.16 ± 0.05	0.17 ± 0.04
	19	22		0.12 ± 0.03	0.04 ± 0.04	0.06 ± 0.02	0.08 ± 0.04	0.18 ± 0.05
		23		0.16 ± 0.06	0.02 ± 0.00	0.07 ± 0.03	0.06 ± 0.03	0.21 ± 0.08
Tier 3 (No SCR)				**0.32 ± 0.35**	—	**0.58 ± 3.47**	**0.29 ± 0.07**	—
Tier 3 (Inactive SCR)				**0.22 ± 0.04**	**0.10 ± 0.18**	**0.23 ± 0.17**	**0.17 ± 0.16**	**0.22 ± 0.04**
Tier 3 (Active SCR)				**0.16 ± 0.06**	**0.02 ± 0.00**	**0.07 ± 0.03**	**0.06 ± 0.03**	**0.21 ± 0.08**
14	20	24	4 (SCR)	0.08 ± 0.01	0.03 ± 0.02	0.02 ± 0.01	0.01 ± 0.01	0.08 ± 0.01
	21	25		0.03 ± 0.00	0.06 ± 0.06	0.03 ± 0.04	0.06 ± 0.02	0.03 ± 0.00
Tier 4				**0.05 ± 0.01**	**0.05 ± 0.03**	**0.03 ± 0.02**	**0.04 ± 0.01**	**0.05 ± 0.01**
Sampled Fleet				**0.34 ± 0.03**	**0.28 ± 0.57**	**0.44 ± 0.31**	**0.37 ± 0.15**	**0.27 ± 0.02**

Summary of average BC emission factors (± 95% confidence intervals) measured in this study. The overall BC emission factor was determined by a weighted average scheme described in the text above. Not all engine conditions included docked measurements or a fast cruise and are noted with (—). Single measurements in a mode are reported without confidence intervals. Emission factors for engine condition 16 could not be categorized by docked or maneuvering operational mode.

Figure 41: Fleet-Average BC Emission Rates by Operating Mode



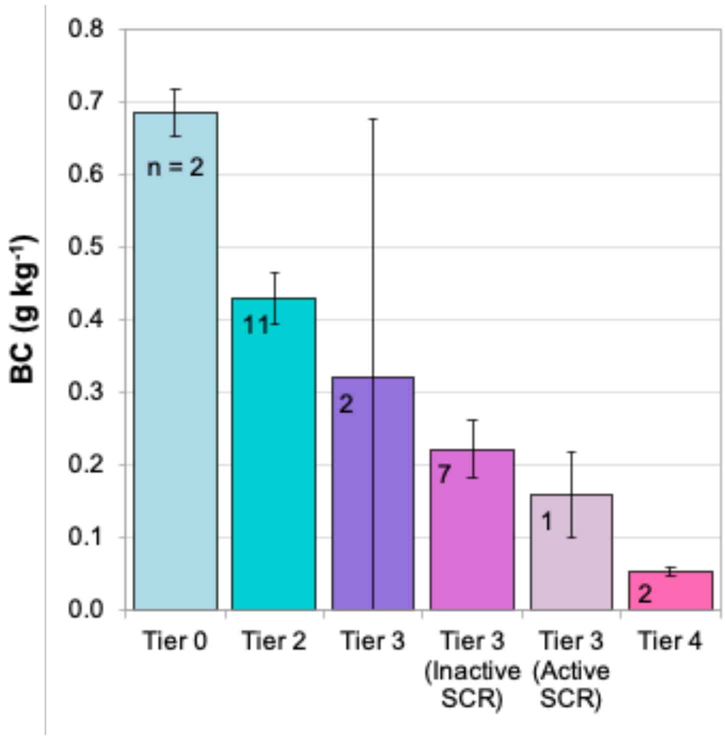
The overall and mode-specific average BC emission factors for the sampled fleet of ferry and excursion vessels. The number (n) of engine conditions included in each average value is noted in each bar. The error bars represent 95% confidence intervals about these arithmetic means. The overall BC emission factor was determined by a weighted average scheme described in the text above.

Figure 42 shows average BC emission factors by engine tier, as also summarized in Table 12. There is a downward trend in BC emissions from Tier 0 to Tier 4 engines, with Tier 4 engines emitting 92% less BC per kg of fuel burned than Tier 0 engines, on average. The SCR retrofit on Tier 3 engines leads to a reduction in emitted BC from these engines compared to the Tier 3 engine without SCR. This trend is consistent with results from the PEMS work discussed above, in which a 38% reduction in measured PM downstream of the SCR system relative to the upstream sampling point was attributed to losses in the SCR system and DOC. Based on the present plume capture measurements, this BC reduction also appears to be dependent on SCR activity: active systems emit 23% less BC per kg of fuel compared to inactive systems. Inactive systems have BC emission rates that are 31% lower than Tier 3 engines without SCR, on average, while active systems have emission factors that are 51% lower.

This trend by engine tier is largely determined by the cruising operating mode, given that ferry and excursion vessels spend a majority of their time and fuel in this mode (Table 11). The decreasing emissions by engine tier holds across all operating modes, except for the two sampled Tier 0 engines under a long-haul route (Figure 43

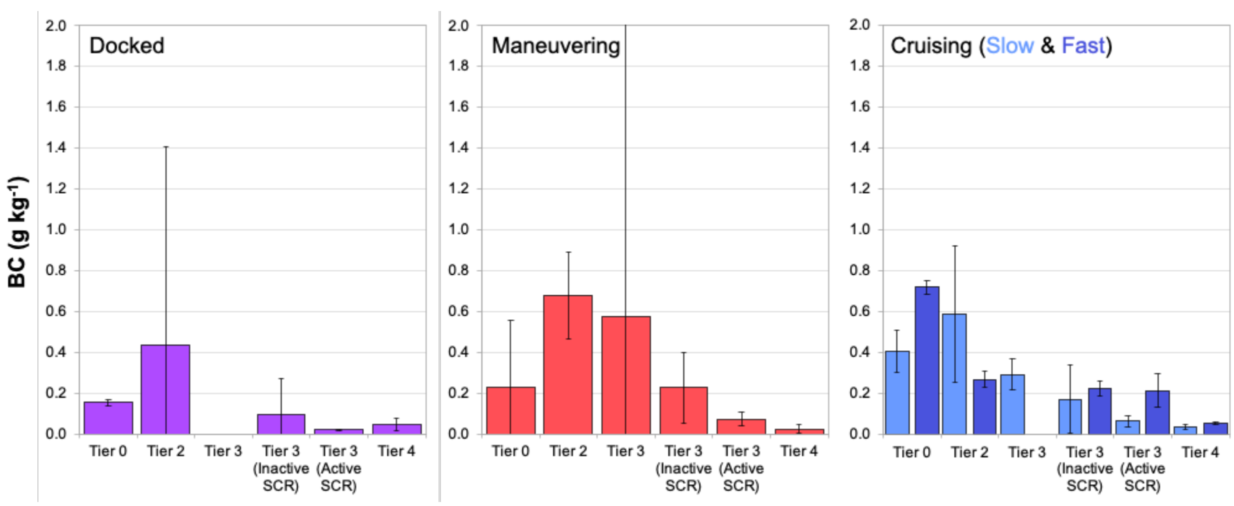
). For the Tier 0 engines sampled, the average docked and maneuvering BC emission rates are ~65% lower than Tier 2 and Tier 3 engines without SCR, while average fast cruising emissions are 2.7 times higher and weighted by 90% in the overall average.

Figure 42: Average BC Emission Rates by Engine Tier



Overall BC emission factors (± 95% confidence interval) by engine tier, as also summarized in Table 12. The number (n) of engine conditions included in each average value is noted in each bar. The overall BC emission factor was determined by a weighted average scheme described in the text above.

Figure 43: Average BC Emission Factors by Engine Tier and Operating Mode

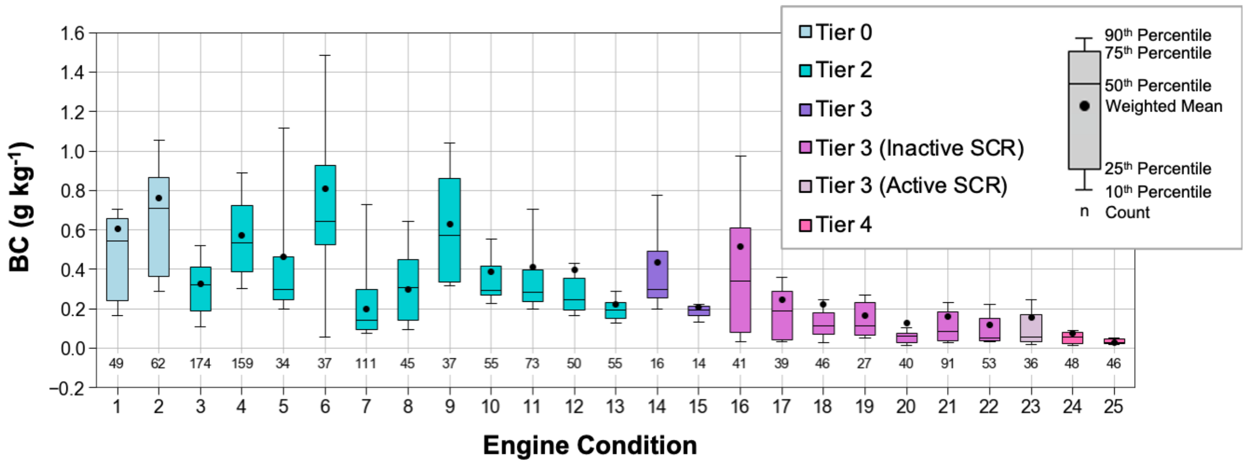


The number of engine conditions included in each tier category is summarized above in Table 12 and shown in Figure 42.

Figure 44 presents boxplot distributions of BC emission factors measured for each engine condition. The boxes show the 25th, 50th, and 75th percentiles while the whiskers represent the

10^{th} and 90^{th} percentiles of the measured distributions. The 50^{th} percentile gives the median value, while the closed circle report the weighted means (i.e., the overall averages reported in Table 12). The number of emission factors measured for each engine condition is reported at the bottom of each distribution.

Figure 44: BC Emission Factor Distributions for Each Measured Engine Condition

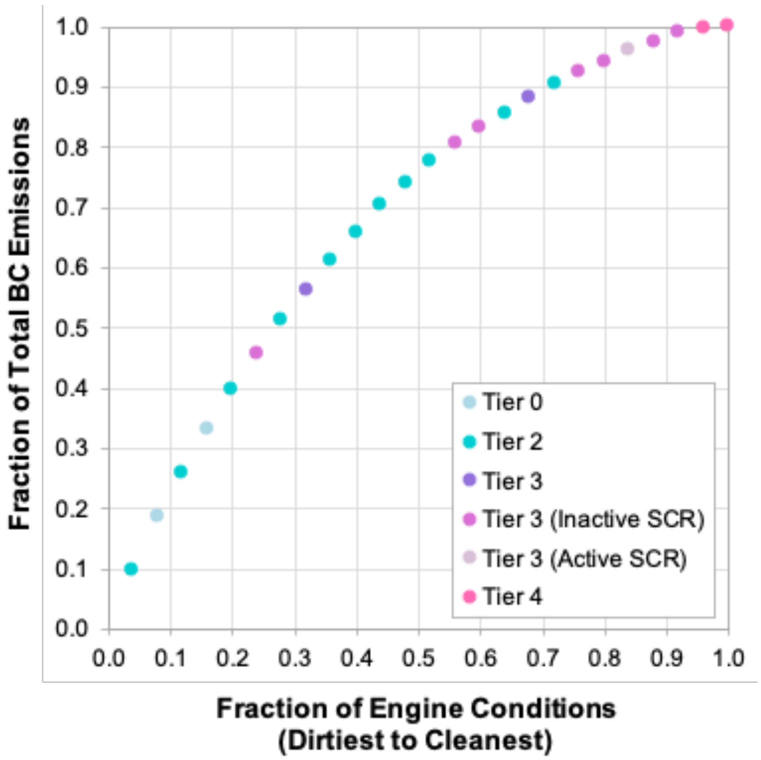


The noted sample size (n) refers to the number of plume capture event emission factors included in each distribution.

Emission rates can vary greatly during a vessel's operation. Most of the Tier 3 and Tier 4 emissions distributions are tightly constrained around a small range of emission factors (from near-zero to ~0.4 g kg^{-1}). The Tier 0 and Tier 2 distributions include a larger range of values and are less consistent from engine-to-engine. For example, some Tier 2 engines are consistently relatively low-emitting (i.e., engine condition 13), while others exhibit highly varying emissions and some of the highest emissions (i.e., engine condition 6). Some distributions are very skewed, with arithmetic means that exceed the 75^{th} or 90^{th} percentiles. These distributions emphasize the importance of making many measurements across a vessel's operation to determine characteristic real-world emission factors.

The cumulative distribution of BC emissions from the sampled fleet is shown in Figure 45. Overall emission factors for each sampled engine condition are ranked from highest to lowest on the horizontal axis, and the corresponding cumulative BC emitted is shown on the vertical axis. Engine tier is noted for each measured engine condition. If normally distributed, these data would plot in a straight, diagonal line from left-to-right.

Figure 45: Cumulative Distribution of BC Emissions



Cumulative distribution of the overall BC emission factors for the 25 engine conditions included in this study. Emission factors are ranked from highest to lowest on the horizontal axis, and the corresponding cumulative BC emitted is shown on the vertical axis. Engine tier is noted for each measured engine condition. The overall BC emission factor was determined by a weighted average scheme described in the text above.

BC emissions from the ferry and excursion fleet are somewhat skewed: the most polluting 20% of engines are responsible for nearly 40% of total BC emissions by this sampled fleet. Conversely, the cleanest 20% of engines contribute only ~5% of the total BC emitted. In comparison, BC emissions from in-use heavy-duty diesel trucks are typically much more skewed, especially as on-road fleets adopt emission control technologies like diesel particle filters (DPFs). For instance, 99% of the Port of Oakland drayage fleet in the SF Bay Area is DPF-equipped with 2007 and newer model year engines, and the most polluting 20% of trucks were responsible for 90% of the fleet's BC emissions in calendar year 2015 (Preble et al., 2018). For the ferry and excursion fleet, the highest-emitters are older engines that are Tier 0 and Tier 2 and have higher allowable PM emissions, while the lowest-emitters are Tier 3 and Tier 4 engines with more stringent PM standards (see Table 14 and discussion below). If all vessels in this fleet were instead equipped with Tier 4 engines, the fleet-average BC emission factor would be reduced by ~85% (from 0.34 to 0.05 g kg^{-1}).

NO_x Emission Rates

Table 13 summarizes the average NO_x emission factors that were measured for a subset of 10 engine conditions. NO_x emissions were measured on fewer vessels than BC emissions because the NO_x analyzers required access to electrical outlets on-board, which were unavailable to the team on most vessels. Since NO_x measurements were not possible on all vessels, the results shown in Figure 46 and Figure 47 are limited to a single Tier 2 engine condition, 7 conditions of Tier 3 engines retrofitted with SCR, and 2 conditions of Tier 4 engines equipped with original equipment SCR systems. The fleet-averages summarized in Table 13 and shown in Figure 46, therefore, are not representative of the broader ferry and excursion fleet and instead characterize a newer subset of the current in-use fleet.

Table 13: Average NO_x Emission Rates for Each Engine Condition

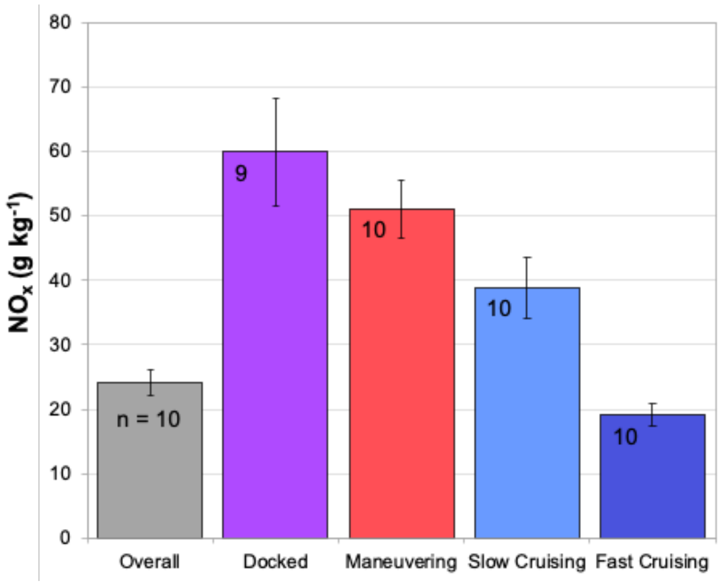
Vessel #	Engine #	Engine Condition #	Engine Tier	NO_x (g kg^{-1})				
				Overall	Docked	Maneuvering	Slow Cruising	Fast Cruising
5	6	7	2	27.2 ± 2.2	45.1 ± 9.8	42.6 ± 6.2	25.2 ± 2.6	27.9 ± 7.1
Tier 2				**27.2 ± 2.2**	**45.1 ± 9.8**	**42.6 ± 6.2**	**25.2 ± 2.6**	**27.9 ± 7.1**
12	16	17	3 (Retrofit SCR)	26.5 ± 5.6	66.4 ± 16.3	39.0 ± 10.1	45.7 ± 5.0	18.6 ± 5.8
12	16	18	3 (Retrofit SCR)	30.3 ± 3.4	44.3 ± 5.0	53.9 ± 6.8	33.9 ± 15.4	27.3 ± 4.0
12	17	19	3 (Retrofit SCR)	19.6 ± 7.0	—	40.5 ± 15.8	39.4 ± 20.3	9.0 ± 2.1
12	17	20	3 (Retrofit SCR)	36.3 ± 4.9	67.4 ± 66.7	51.9 ± 7.3	37.1 ± 6.7	28.0 ± 8.9
13	18	21	3 (Retrofit SCR)	32.3 ± 3.2	70.1 ± 70.1	45.4 ± 6.9	34.3 ± 5.6	27.3 ± 4.4
13	19	22	3 (Retrofit SCR)	34.9 ± 3.8	58.7 ± 6.9	40.3 ± 6.7	40.7 ± 5.1	24.4 ± 3.9
13	19	23	3 (Retrofit SCR)	5.1 ± 2.0	17.2 ± 19.9	13.8 ± 14.7	1.8 ± 0.8	5.1 ± 2.7
Tier 3 (No SCR)				—	—	—	—	—
Tier 3 (Inactive SCR)				**30.0 ± 2.0**	**61.4 ± 14.0**	**45.2 ± 3.9**	**38.5 ± 4.6**	**22.4 ± 2.2**
Tier 3 (Active SCR)				**5.1 ± 2.0**	**17.2 ± 19.9**	**13.8 ± 14.7**	**1.8 ± 0.8**	**5.1 ± 2.7**
14	20	24	4 (SCR)	15.2 ± 4.1	71.1 ± 23.3	72.4 ± 30.2	82.9 ± 36.6	12.6 ± 4.2
14	21	25	4 (SCR)	13.9 ± 5.4	99.3 ± 32.9	110.7 ± 15.4	47.4 ± 8.0	11.3 ± 5.6
Tier 4				**14.5 ± 3.4**	**85.2 ± 20.2**	**91.5 ± 17.0**	**65.2 ± 18.7**	**12.0 ± 3.5**
Sampled Fleet				**24.1 ± 1.4**	**59.9 ± 8.4**	**51.0 ± 4.4**	**38.8 ± 4.7**	**19.2 ± 1.7**

Summary of average NO_x emission factors (± 95% confidence intervals) measured in this study. The overall NO_x emission factor was determined by a weighted average scheme described in the text above. As described above, NO_x was included on a subset of sampling; only those engine conditions with NO_x measurements are included here. Engine conditions or operating modes without measurements are noted with (—).

The fleet-average NO_x emission factor for this subset of the sampled fleet was 24.1 ± 1.4 g kg^{-1} (Table 13 and Figure 46). The highest NO_x emission rates occurred while docked, closely followed by maneuvering operations. Fast cruising emissions were 62–68% lower than docked and maneuvering emissions, on average. Similar to BC, docked and maneuvering NO_x emissions are more variable than fast cruising emissions. Across all operational modes, though, NO_x emission rates were proportionally less variable than BC emissions (Figure 41 and Figure 46).

Note that 3 out of the 10 engine conditions included in this subset of NO_x measurements included active SCR systems (Table 10 and Table 13). SCR activity likely accounts for the lower NO_x emission rates during cruising, as engines reach the minimum exhaust temperature and load required for urea dosing.

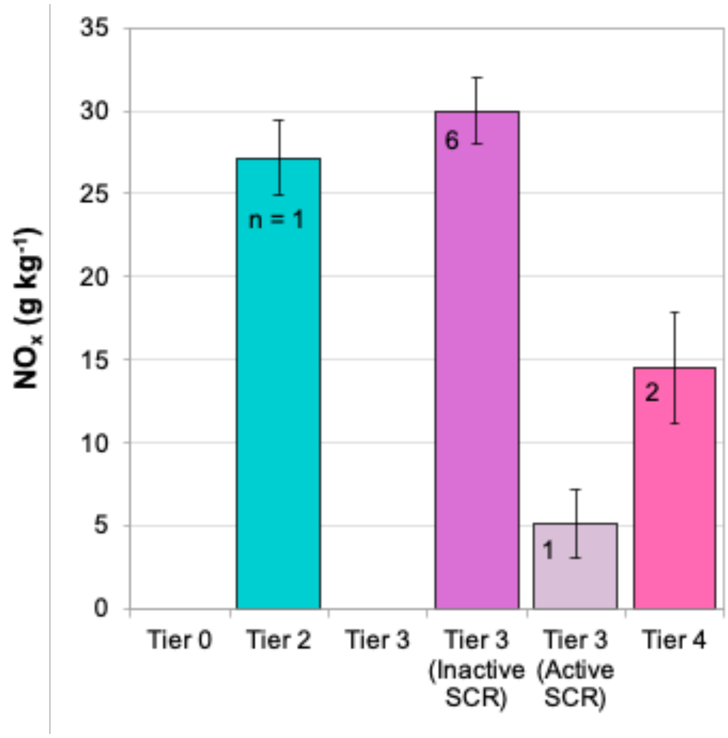
Figure 46: Fleet-Average NO_x Emission Rates



The overall and mode-specific average NO_x emission factors for the sampled fleet of ferry and excursion vessels. The number (n) of engine conditions included in each average value is noted in each bar. The error bars represent 95% confidence intervals about these arithmetic means. The overall NO_x emission factor was determined by a weighted average scheme described in the text above. Note that 9 out of 10 of the engine conditions included in the NO_x measurements are Tier 3 or higher, including SCR-equipped engines (Table 10 and Table 13).

The Tier 2 engine without SCR and Tier 3 engines with inactive SCR had comparable overall NO_x emissions, on average (Figure 47). The Tier 4 engines are equipped with original equipment SCR systems to meet the most stringent EPA emission standards. The average NO_x emissions from the Tier 4 engines were lower than emissions from Tier 3 engines with inactive SCR retrofits and the Tier 2 engines. Yet, the active retrofit SCR system on the Tier 3 engine had NO_x emissions that were lower by a factor of 2.8–5.8, compared to the other three categories. More results and discussion of SCR effectiveness is presented below.

Figure 47: Average NO_x Emission Rates by Engine Tier

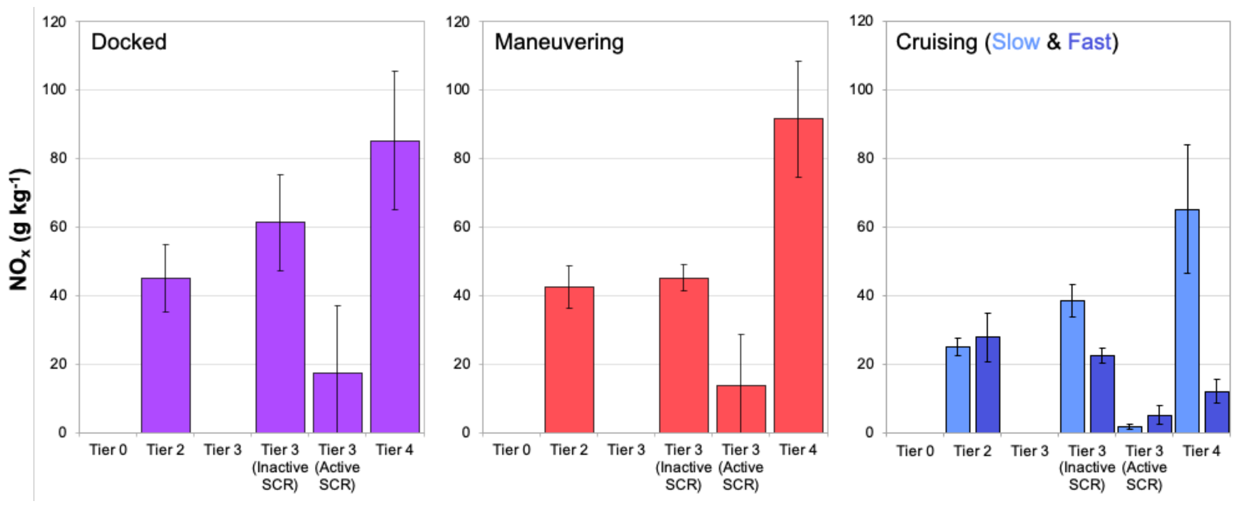


Overall NO_x emission factors (± 95% confidence interval) by engine tier, based on the subset of 10 engine conditions with NO_x measurements and as also summarized in Table 13. The number (n) of engine conditions included in each average value is noted in each bar. The overall NO_x emission factor was determined by a weighted average scheme described in the text above.

Overall emissions by engine tiers are driven by the fast cruising operating mode—where a majority of fuel is consumed during each trip—while the docked, maneuvering, and slow cruising emissions exhibit different emissions pattern (Figure 48). The active SCR retrofit on the Tier 3 engine has the lowest emissions across all four operating modes. Slow cruising NO_x emissions are ~95% lower for the active SCR retrofit system compared to Tier 2, Tier 3 with inactive SCR, and Tier 4 engines. Fast cruising conditions had smaller differences between engine tier, with active SCR systems on Tier 3 and 4 engines 57–82% lower than inactive SCR systems on Tier 3 engines or the Tier 2 vessel without SCR.

When retrofit SCR systems on Tier 3 engines are inactive, NO_x emissions are comparable to the Tier 2 engines during maneuvering and higher while docked. Maneuvering, docked, and slow cruising emission factors are highest for Tier 4 engines with original equipment SCR. Compared to the Tier 2 engines, for example, average emissions by the Tier 4 engines are 1.9–2.6 times higher in those three operating modes. The differences are larger when comparing the Tier 4 and Tier 3 engine with an active retrofit SCR system—Tier 4 emissions are 5.0–6.6 times higher during maneuvering and docked operation and 36.2 times higher when slow cruising, on average. This difference may be due to engine tuning. For example, Tier 4 engines may be intentionally tuned towards lower engine-out PM and higher engine-out NO_x, similar to the case for trucks with original equipment SCR (Preble et al., 2018). If that SCR system is inactive because of insufficient exhaust temperature or engine load—conditions that may exist during maneuvering, while docked, and under slow cruising—then tailpipe NO_x emissions may be higher than those from a non-Tier 4 engine that is tuned towards lower engine-out NO_x and higher PM. There is no clear explanation for why the original equipment SCR systems on the Tier 4 engines were less effective at reducing emitted NO_x than the active Tier 3 retrofit system during fast cruising, when both systems were confirmed as operational. An analysis of these measured emission factors compared to corresponding engine certification values and EPA exhaust limits is presented below, as are two case studies of SCR activity.

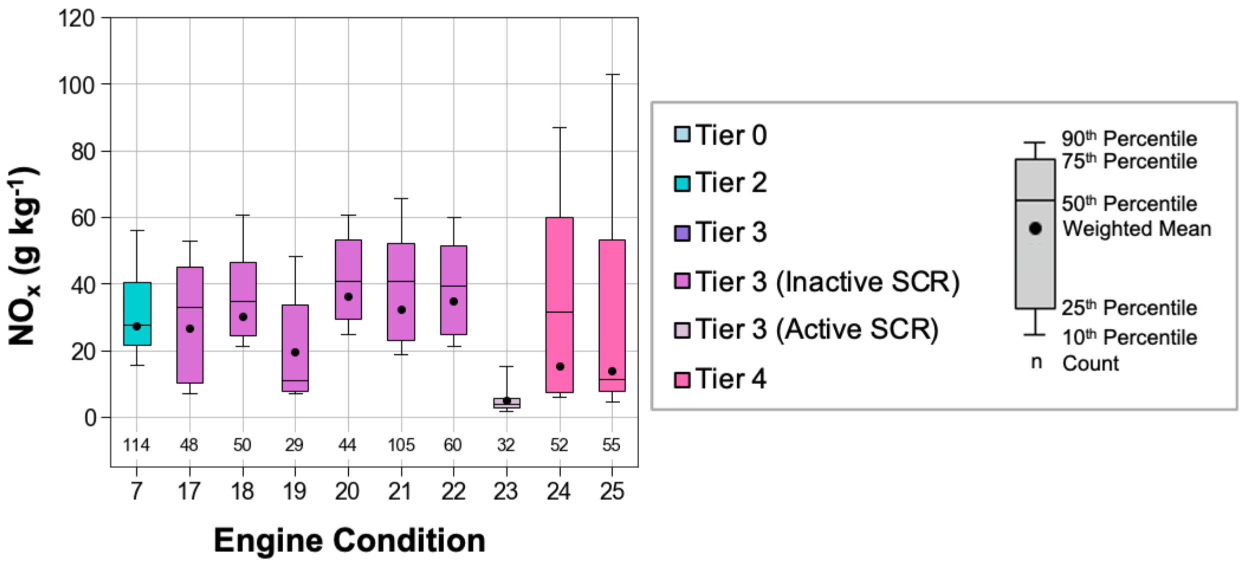
Figure 48: Average NO_x Emission Factors by Engine Tier and Operating Mode



Note that NO_x was not measured for all engine conditions, as described in the text. The number of engine conditions included in each tier category is summarized above in Table 13.

Distributions of NO_x emission factors measured for each engine condition are shown in Figure 49. Emissions from the active SCR retrofit (engine condition 23) were tightly constrained between near-zero and 20 g kg^{-1}, but skewed with an average value that exceeded the 75th percentile. Distributions for the Tier 2 engine and the inactive SCR retrofits were consistently similar across engine conditions, ranged between ~10 and ~70 g kg^{-1}, and did not exhibit much skewness. The distributions for the two Tier 4 engines covered the largest range, with measured emission factors extending across an order of magnitude (~10 to ~100 g kg^{-1}) and broadly extending 90th percentile whiskers.

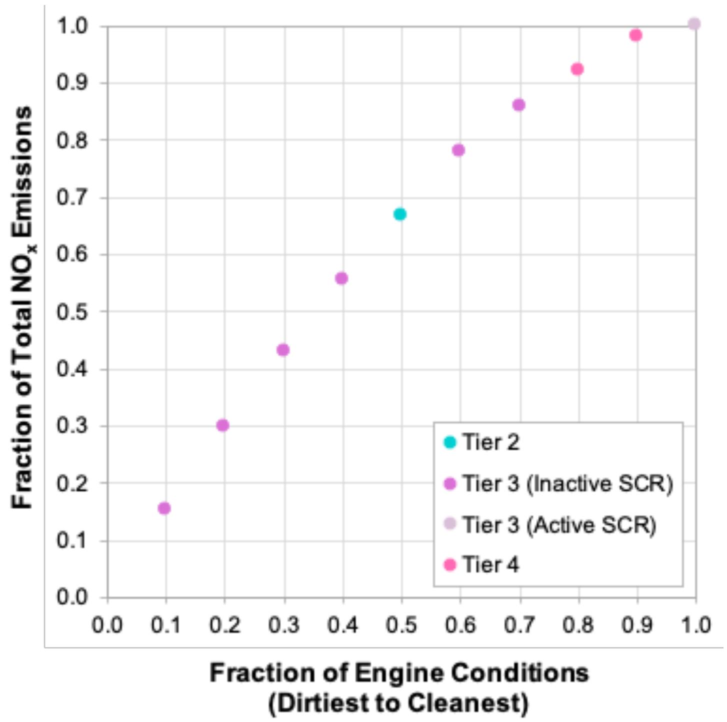
Figure 49: NO_x Emission Factor Distributions for Each Measured Engine Condition



Note that NO_x was not measured for all engine conditions, as summarized in Table 13. The noted sample size (n) refers to the number of emission factors included in each distribution.

The cumulative distribution of NO_x emissions for the sampled fleet is shown in Figure 50. Emissions are very slightly skewed for this subset of the fleet, less so than was found for BC. The highest-emitting 20% of engine conditions is responsible for 30% of total emissions, while the cleanest 20% of the fleet contributed <10% of total NO_x emissions. As discussed above, it is important to note that this subset is not fully representative of the broader ferry and excursion vessel fleet. If our sampling had been able to include additional Tier 0, 1, and 2 engines with higher allowable NO_x emission limits set by EPA standards, it is likely that these engines would be the highest emitters that contribute more to total emissions. In on-road studies of heavy-duty diesel truck exhaust, though, BC emissions are typically more skewed than NO_x emissions (Dallmann et al., 2012; Preble et al., 2015). If this subset of the fleet had effective and active SCR systems like engine condition 23, then the overall average NO_x emission factor would be ~80% lower, around 5 g kg^{-1} rather than the 24 g kg^{-1} measured in this study.

Figure 50: Cumulative Distribution of NO_x Emissions



Cumulative distribution of overall NO_x emission factors for the subset of 10 engine conditions with NO_x measurements. The overall NO_x emission factor was determined by a weighted average scheme described in the text above. Emission factors are ranked from highest to lowest on the horizontal axis, and the corresponding cumulative NO_x emitted is shown on the vertical axis. Engine tier is noted for each measured engine condition.

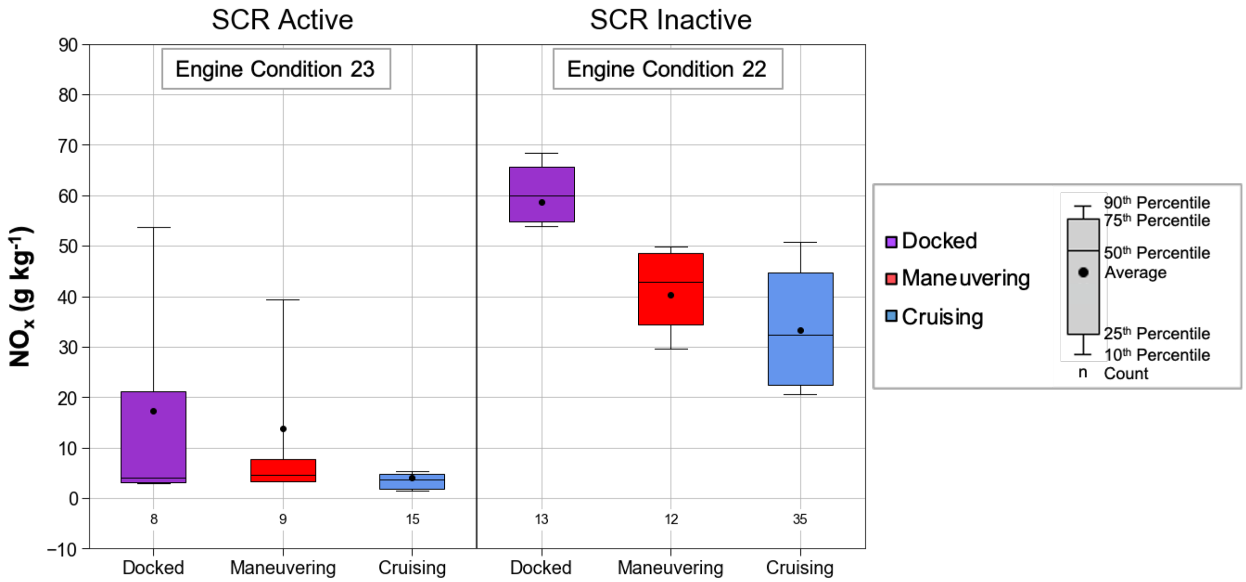
SCR Effectiveness: Two Case Studies

Here, we focus on two case studies that offer insights into SCR effectiveness. For both case studies, we conducted intentional experiments where we sampled from a given engine under two SCR conditions: (1) when the SCR system was enabled, and (2) when the SCR system was deliberately turned off. During the first case study, the SCR system was active and operated without any errors during the first part of the experiment. During the second case study, the SCR system was on, but the operating conditions for a majority of sampling were insufficient for the system to be active. For this second case, the engine condition was classified as "inactive SCR" in the above analysis, as that was the dominant emissions characteristic.

Case Study #1

Over a single morning, we sampled the exhaust from engine 19 while the SCR was on and active (condition 23) and when it was intentionally disabled (condition 22). From these two sets of measurements, we can directly compare the effectiveness of a given SCR system at reducing tailpipe NO_x emissions under similar operating conditions. Figure 51 summarizes the results of this experiment with boxplots of emission factors by experimental state and engine operating mode.

Figure 51: Case Study of SCR Effectiveness with Engine 19 Experiment



For Engine 19, the SCR system was intentionally disabled during sampling of engine condition 22. This experiment allows for a direct comparison of SCR effectiveness at reducing NO_x emissions from a given engine when the system is active under similar operating states (engine condition 23). The noted sample size (n) refers to the number of emission factors (i.e., plume capture events) included in each distribution. The cruising distribution includes emission factors from either slow or fast cruising.

For both experimental states, average emissions tend to be highest when the vessel is docked, followed by maneuvering and then cruising operations. The distributions of these general trends differ by experimental condition, however. When the SCR system is active, cruising emissions are tightly constrained below ~5 g kg^{-1}, whereas maneuvering and docked emissions are much more variable and skewed. During these latter two modes, half of the distribution is also low and tightly constrained, with median values below ~5 g kg^{-1}. The 75th and 90th percentiles of these distributions are much greater and exceed the median values by up to an order of magnitude, with docked emissions varying more than maneuvering. These distributions indicate that SCR systems are active and effectively reducing emitted NO_x around half of the time vessels are maneuvering or docked, but that SCR dosing may cease during these operations and lead to high emission events that skew the average emission rate high.

When the SCR system is inactive, NO_x emissions are less variable and less skewed during docked and maneuvering. There is no overlap in the distributions for these two operating modes, with docked emissions between 1.3 and 1.8 times higher than maneuvering emissions. Cruising emissions are lower on average than docked and maneuvering operations, but there is a significant amount of overlap in the cruising and maneuvering distributions. Cruising emissions are much more variable when the SCR system is inactive than when it is active, extending from

20–50 g kg^{-1}. On average, the active SCR system effectively reduces emitted NO_x by ~70% while docked and maneuvering and ~90% while cruising.

Case Study #2

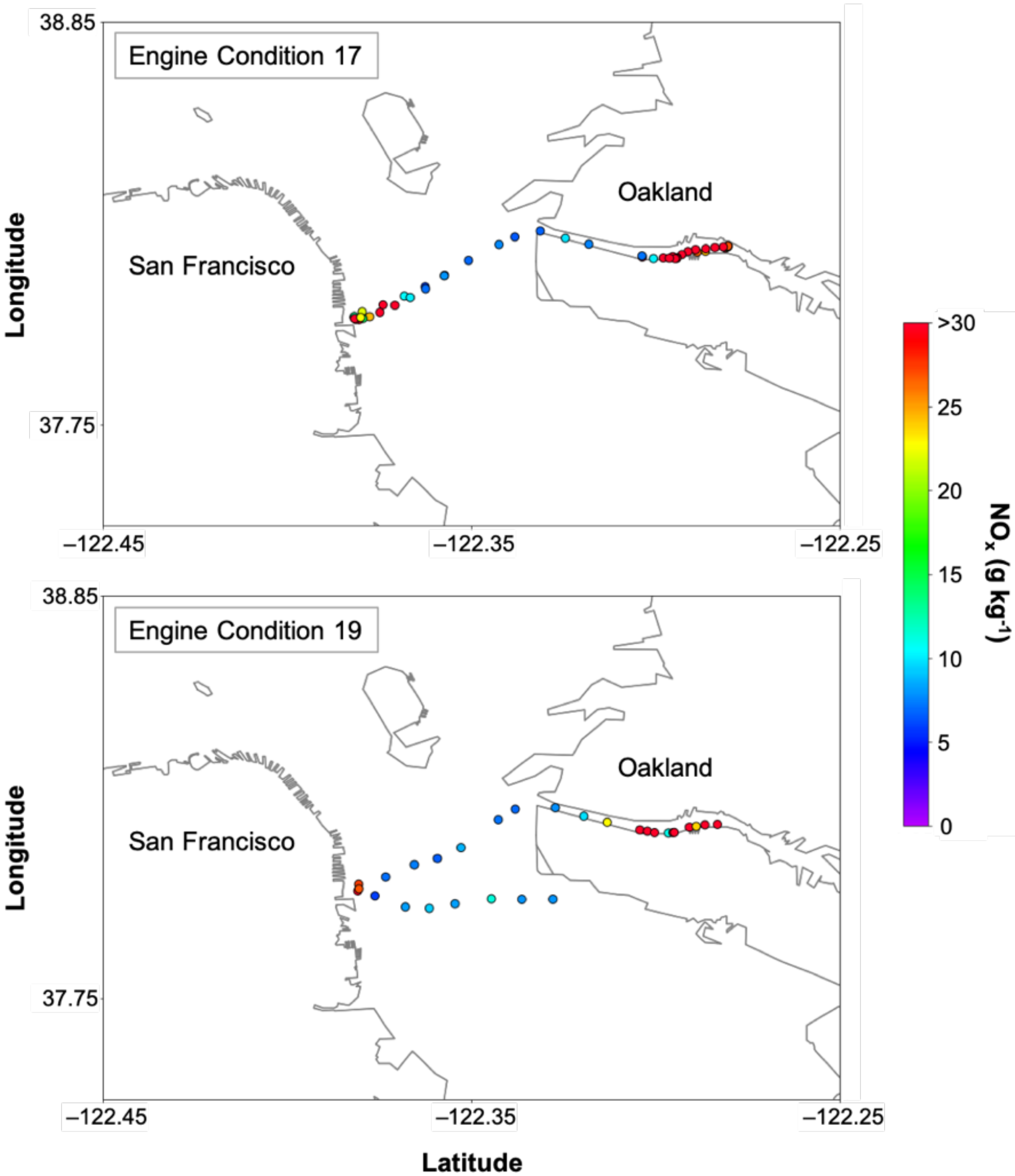
We conducted the same experiment on vessel 12. Each main engine was sampled while its SCR system was enabled (engine conditions 17 and 19) and after we intentionally disabled the SCR system (engine conditions 18 and 20). The distributions shown above in Figure 49, however, do not show the difference between the two SCR scenarios that was observed in the first case study. This suggests that the SCR system was not active during the SCR experiments on these two engines. While there were no system errors during sampling, data downloaded from the SCR system confirmed that urea was not dosing for a majority of the sampling period.

Even without system errors, it is possible that an SCR system can be operational but not functional. According to the vessel operator, these SCR systems are both exhaust temperature and engine load dependent. If either of those requirements is not met, urea dosing is deliberately stopped and the catalyst is flushed for ~5 minutes. If the exhaust temperature or engine load return to minimum threshold values, urea dosing does not start again until after the flushing cycle is complete. As such, during intermittent low-load operation, these flushing cycles could prevent the SCR system from being functional.

The SCR system data confirms that urea dosing occurred intermittently during the active SCR experiments on vessel 12 (engine conditions 17 and 19). Moreover, the emission factor distributions for these measurements are slightly shifted down towards a lower range of emission factors than their SCR-disabled counterparts (Figure 49). These suggest that the SCR system was potentially functional during some of the vessel's operation.

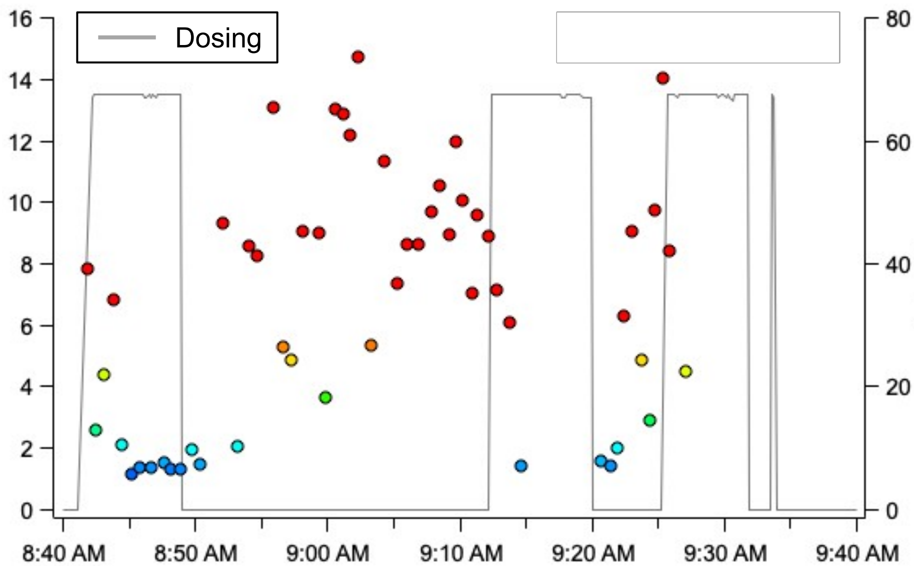
The vessel route during these measurements included slow cruises down the Oakland Inner Harbor, with intermittent maneuvering and docking at two ferry docks that are a short distance across the harbor from each other. Once out of the harbor, the vessel traveled at a fast cruise (based on the speed distinction detailed above) straight across the San Francisco Bay. Figure 52 shows a map of this route and the location of each emission factor measurement. NO_x emissions are elevated along the Oakland Inner Harbor and near the three ferry stops, and lower along the faster cruise stretch leading out the harbor and across the bay. Figure 53 shows an example time series of urea dosing rate by the SCR system and the corresponding NO_x emission factors (engine condition 17, or the top map in Figure 52). While urea is dosing, emission factors are low and steady below 10 g kg^{-1}. When urea dosing stops, NO_x emissions quickly increase to 40–80 g kg^{-1}. The SCR system was functional during the fast cruises but nonoperational during the slow cruise, maneuvering, and docked modes.

Figure 52: Example of Operating Mode-Dependence of SCR Activity



Map of NO_x emission factors measured during engine conditions 17 and 19, in which the SCR was turned on but showed driving mode dependence for functionality. During the slow cruises in the Oakland Inner Harbor and maneuvering and docking at the three ferry docks, NO_x emissions are elevated. During the steady cruises heading out of the harbor and across the SF Bay, emissions are lower.

Figure 53: SCR Dosing Rate and Corresponding NO_x Emission Factors



Time series of the urea dosing rate (grey line) and the corresponding NO_x emission factors measured at the exhaust tailpipe for engine condition 17. The SCR system was not dosing consistently. Emission factors are high when dosing is stopped, and these high emission factors occurred during slow cruise, maneuvering, and docked operating modes (Figure 52).

Figure 52 and Figure 53 indicate that an SCR system's functionality is dependent on the vessel's operating mode. Over this route on this day, we noted that the water was especially calm, such that the vessel coasted into most docks and the engines were not working as hard to accelerate as days with stronger, more turbulent currents. The operating modes within the harbor and the water conditions on this particular day likely meant low engine loads prevented the SCR system from operating effectively. While the data indicates that there were periods when the SCR system was active on these two engines, a majority of the NO_x emission factors from engine conditions 17 and 19 were elevated and characteristic of inactive systems. Hence, we included these two conditions in the inactive SCR category.

Measured Emission Rates Relative to EPA Values

Table 14 summarizes the overall (fuel-weighted, mode average) emission factor measured for each engine condition and the corresponding EPA certification value and emission standard for each engine provided by CARB. Overall emission factors were converted from units of g kg^{-1} to g kWh^{-1} using a brake specific fuel consumption informed from in-use engine performance data (bsfc = 176.5 g bhp-h^{-1} = 236.6 g kWh^{-1}), as described above. It is important to note that the EPA values reported here are generated by operating engines over a range of loads according to the ISO 8178 E3 cycle for main propulsion engines, which the real-world operation of these ferries and excursion vessels may not mirror. As such, the comparisons of emission factors measured in this study to EPA certification levels and emission standards are illustrative, but should not be used to determine the emissions compliance of these vessels.

Table 14: Emission Factors Measured in this Study and Corresponding EPA Values

Vessel #	Engine #	Engine Condition #	Engine Tier	Measured Overall Emission Factor (g kWh^{-1})		Certification Value (g kWh^{-1})		EPA Standard (g kWh^{-1})	
				BC	NO_x	PM	NO_x	PM	NO_x
1	1	1	0	0.14 ± 0.01	—	0.50	9.80	N/A	N/A
	2	2		0.18 ± 0.01					
2	3	3	2	0.08 ± 0.01		0.08	6.44	0.20	7.20
		4		0.14 ± 0.01					
3	4	5		0.11 ± 0.04		0.10	6.85		
4	5	6		0.19 ± 0.05					
5	6	7		0.05 ± 0.01	6.43 ± 0.53	0.07	6.12		
6	7	8		0.07 ± 0.02	—	0.12	7.00		
	8	9		0.15 ± 0.04					
7	9	10		0.09 ± 0.03					
	10	11		0.10 ± 0.04					
8	11	12		0.09 ± 0.02		0.15	6.50		
	12	13		0.05 ± 0.02					
9	13	14	3	0.10 ± 0.17		0.08*	N/A	0.11	5.80
10	14	15		0.05 ± 0.02					
11	15	16	3 (Retrofit SCR)	0.12 ± 0.04		0.08	4.66	0.11	5.80
12	16	17		0.06 ± 0.03	6.26 ± 1.33				
		18		0.05 ± 0.03	7.16 ± 0.81				
	17	19		0.04 ± 0.01	4.66 ± 1.66				
		20		0.03 ± 0.03	8.60 ± 1.15				
13	18	21		0.04 ± 0.01	7.63 ± 0.76		4.36		
	19	22		0.03 ± 0.01	8.27 ± 0.91				
		23		0.04 ± 0.01	1.22 ± 0.48				
14	20	24	4 (SCR)	0.02 ± 0.00	3.60 ± 0.96	0.02	1.57	0.04	1.80
	21	25		0.01 ± 0.00	3.29 ± 1.27				

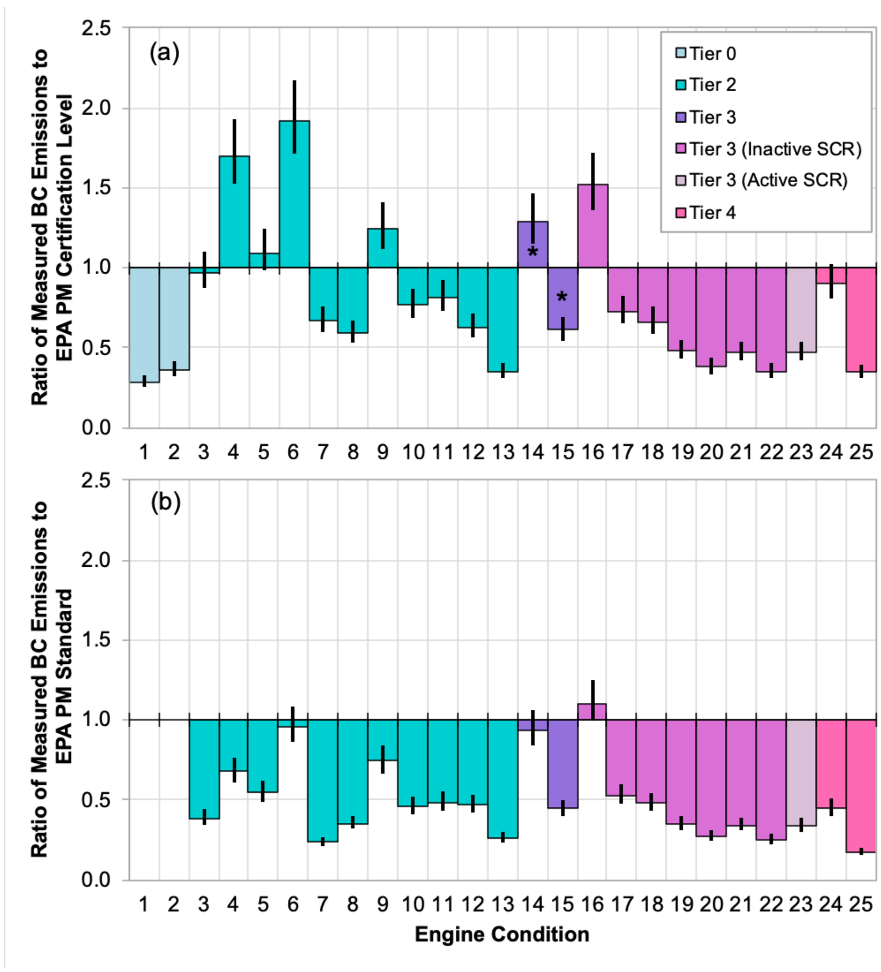
Overall BC and NO_x emission factors (± 95% confidence interval) measured for each engine condition, and the corresponding EPA certification value and emission standard. The fuel-based emission factors measured in this study were converted from units of g kg^{-1} to g kWh^{-1} using a brake specific fuel consumption informed from in-use engine performance data. See text for more details. Note that BC is a major but not sole component of PM emitted from diesel engines. EPA certification values were not available for engine conditions 14 and 15, so the value for the other Tier 3 engines was assumed for this analysis (noted by the *). Note that Tier 0 engines are not EPA certified, so the values reported here are from CARB's off-road inventory.

Allowable PM and NO_x emissions decrease from Tier 0 to Tier 4 engines, such that the newest engines have the most stringent emission standards. Engine certifications can vary slightly from engine-to-engine but all engines are required to meet the EPA exhaust emission standards during laboratory certification testing. In this engine sample, NO_x certification limits varied by ~10%

for Tier 2 and 3 engines and PM limits varied by a factor of ~2 for Tier 2 engines, ranging 0.07–0.15 g kWh^{-1} (0.26–0.56 g kg^{-1}).

Figure 54 and Figure 55 respectively show the ratio of the overall BC and NO_x emission factor measured for each engine condition and corresponding EPA engine certification level and emission standard, respectively. Given potential uncertainties in actual bsfc for each engine condition, vertical lines are shown to represent the ratio range if the minimum and maximum bsfc values reported in Table 11 were used instead of the average value when converting from fuel- to power-based emission units.

Figure 54: Ratio of Measured BC and EPA Values

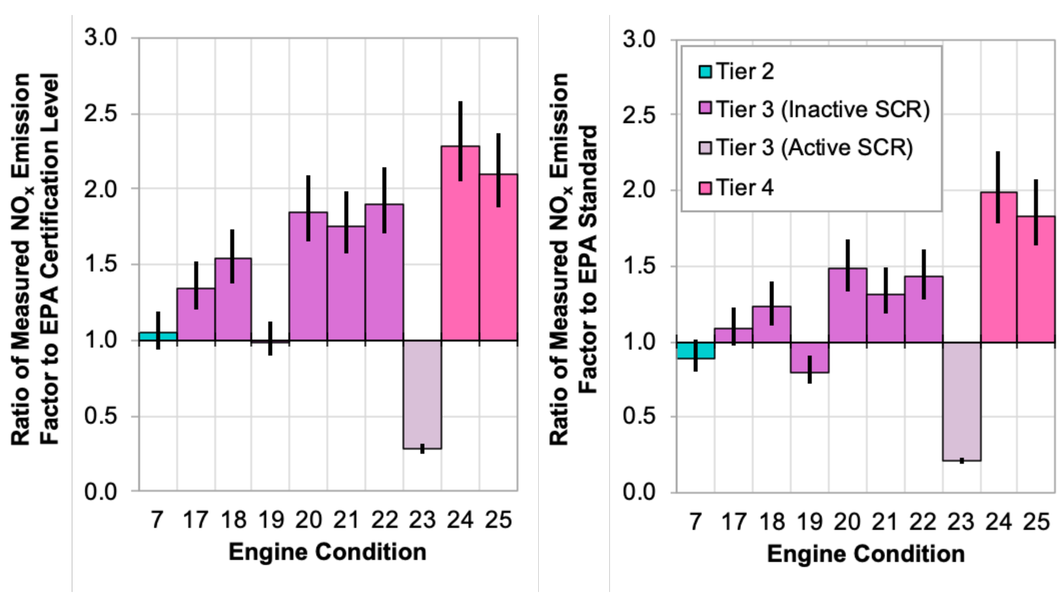


Ratio of the overall BC emission factor measured for each engine condition in this study and the corresponding EPA PM (a) certification value for that engine and (b) emission standard. Values less than one indicate real-world BC emission rates that meet the certification value or PM standard, whereas values greater than one represent measured emissions that exceeded the engine's PM certification value or standard. Note that BC is a major but not sole component of PM emitted from diesel engines. EPA certification values were not available for engine conditions 14 and 15, but the value for the other Tier 3 engines was assumed for this analysis (noted by the *). Note that Tier 0 engines are not EPA certified, so the values reported here are from CARB's off-road inventory.

While the two Tier 0, most of the Tier 3, and both Tier 4 engines sampled in this study have BC emissions that are below their corresponding PM certification levels by 10–70%, a third of the Tier 2 engines have average BC emissions that are 1.1–2.0 times higher than their corresponding certification values (Figure 54a). Relative to the EPA emission standard, all but one engine had average BC emission factors that met the PM exhaust limit (Figure 54b). The single engine that exceeded the standard had an average BC emission rate within 10% of the limit. It is important to note that BC is a major but not sole constituent of diesel PM. Thus, PM emission rates may be larger than the BC emission factors reported here.

Relative to NO_x certification levels, only the Tier 3 engine with active SCR had appreciably lower average in-use emissions in this study; a Tier 3 engine with inactive SCR and the Tier 2 engine had in-use emissions comparable to their certification levels, while the remaining Tier 3 and Tier 4 engines sampled had elevated NO_x emissions (Figure 55). The ratios are slightly smaller in magnitude when the emission standard is considered, but the overall trends are the same. All but one of the Tier 3 engines with inactive SCR retrofits have NO_x emissions that are 1.4–1.9 times higher, highlighting the importance of functional SCR systems. The Tier 4 engines with original equipment SCR systems must meet the most stringent emission standard (Table 14), but the measured emission factors in this study were ~2.2 times higher than the certification level and ~1.9 times the emission standard.

Figure 55: Ratio of Measured NO_x and EPA Values



Ratio of the average NO_x emission factor measured for each engine condition in this study and the corresponding EPA (a) certification value for that engine and (b) emission standard. Values less than one indicate real-world NO_x emission rates that meet the certification value or exhaust standard, whereas values greater than one represent measured emissions that exceeded the engine's certification value or standard.

These results indicate that the real-world operation of these engines may not be well described by the prescribed duty cycle tests for engine certification. It further suggests that the impact of real-world emissions and operation should be considered for emission inventory development; this could include assuming emission control deterioration factors or real-world emission rates instead of directly applying only emission factors derived from certification levels or standards without any further adjustment. Since these measurements represent a small subset of the in-use fleet, more measurements would increase the confidence of this result, including off-cycle emissions, repeat measurements of the vessels sampled in the present study, and additional measurements of the broader fleet to capture a larger total sample size.

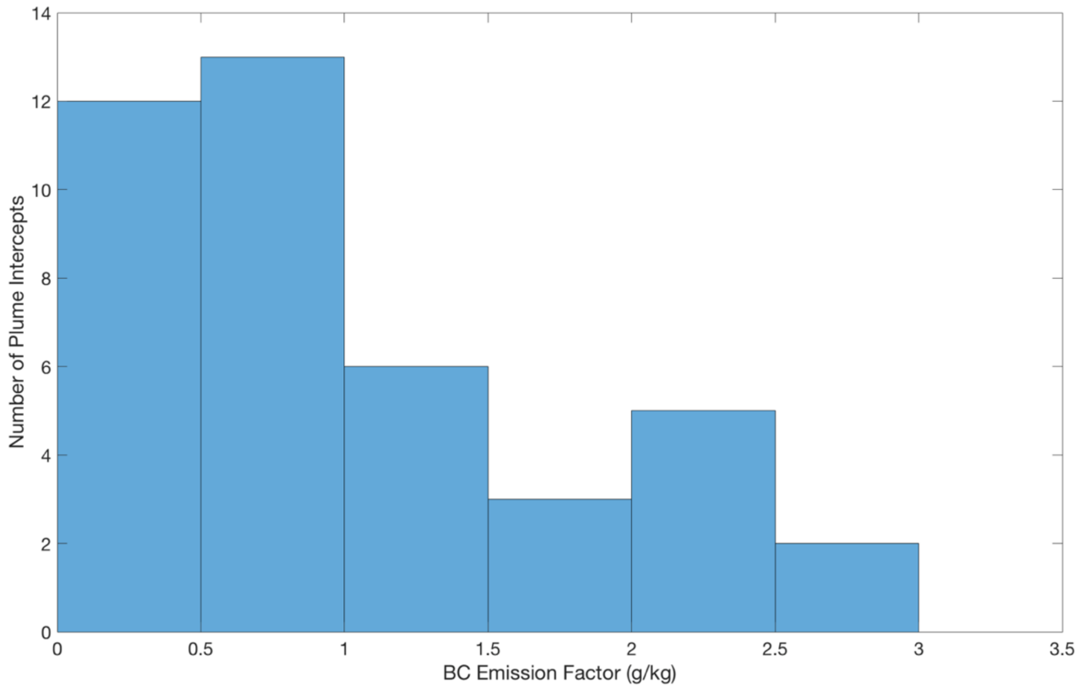
South Coast Measurements of a Passenger Boat & Charter Fishing Boat

Additional plume capture measurements were made in Southern California on-board a Tier 2 passenger boat (i.e., excursion vessel) with a wet exhaust system and a Tier 1 charter fishing boat with dry exhaust. As with the SF Bay Area sampling, measurements were conducted during normal boat operation. For both South Coast vessels, the exhaust stacks from the main and auxiliary engines were sampled together. Therefore, emission factors from these on-board measurements should be considered as a composite of main and auxiliary engine emissions unless otherwise noted. Operating modes were also noted during sampling, but with slightly different definitions than presented above for the SF Bay Area results. In the South Coast, three modes were noted: idling with both engines turned on, idling with auxiliary engine only, and moving. Idling was defined as times the engine was on while the boat was stationary. The moving operating mode includes measurements made while the vessel was speeding up, slowing down, and cruising at a steady speed. On the passenger boat, transition periods between idling and moving were also noted. Because of these differences in vessel categories and operating mode definitions, and the combined sampling of main and auxiliary engine exhaust, the South Coast results are presented separately from the SF Bay Area.

BC emission factor distributions for each vessel are shown in Figure 56 and Figure 57. While the distribution of 41 emission factors measured on-board the Tier 1 fishing boat with dry exhaust is skewed with a long tail of higher-emitting instances, the 58 emission factors measured on the Tier 2 passenger boat with wet exhaust follow an approximately normal distribution.

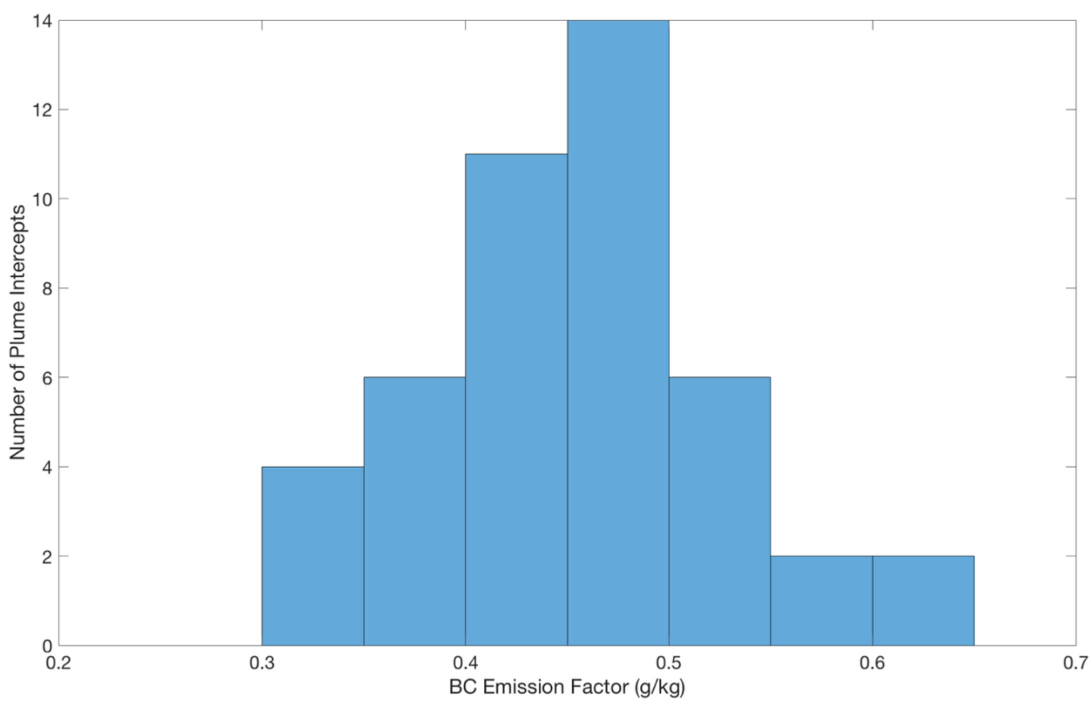
Table 15 and Figure 58 summarize emissions by operating mode. For the fishing boat, the moving operating mode had the highest average BC emission factor, with a geometric mean of 0.82 g/kg. The wide range of emission factors observed in this mode likely reflects a wide range of operational variability. In contrast, idling with the auxiliary engine only resulted in the highest BC emissions for the passenger boat (0.59 g/kg). Emission factors from all operating modes on-board the passenger boat with wet exhaust were less variable within each mode than those from the fishing boat with dry exhaust. The standard deviation for all measurements on the passenger boat was 0.12 g/kg and very little variability was observed in emission factors between operating modes where both engines were turned on. This may be due to differences in engine maintenance or rated loads between the two vessels.

Figure 56: Dry Exhaust Fishing Boat Emission Factor Distribution



Distribution of BC emission factors (n = 41) measured on-board a Tier 1 fishing boat with dry exhaust.

Figure 57: Wet Exhaust Passenger Boat Emission Factor Distribution

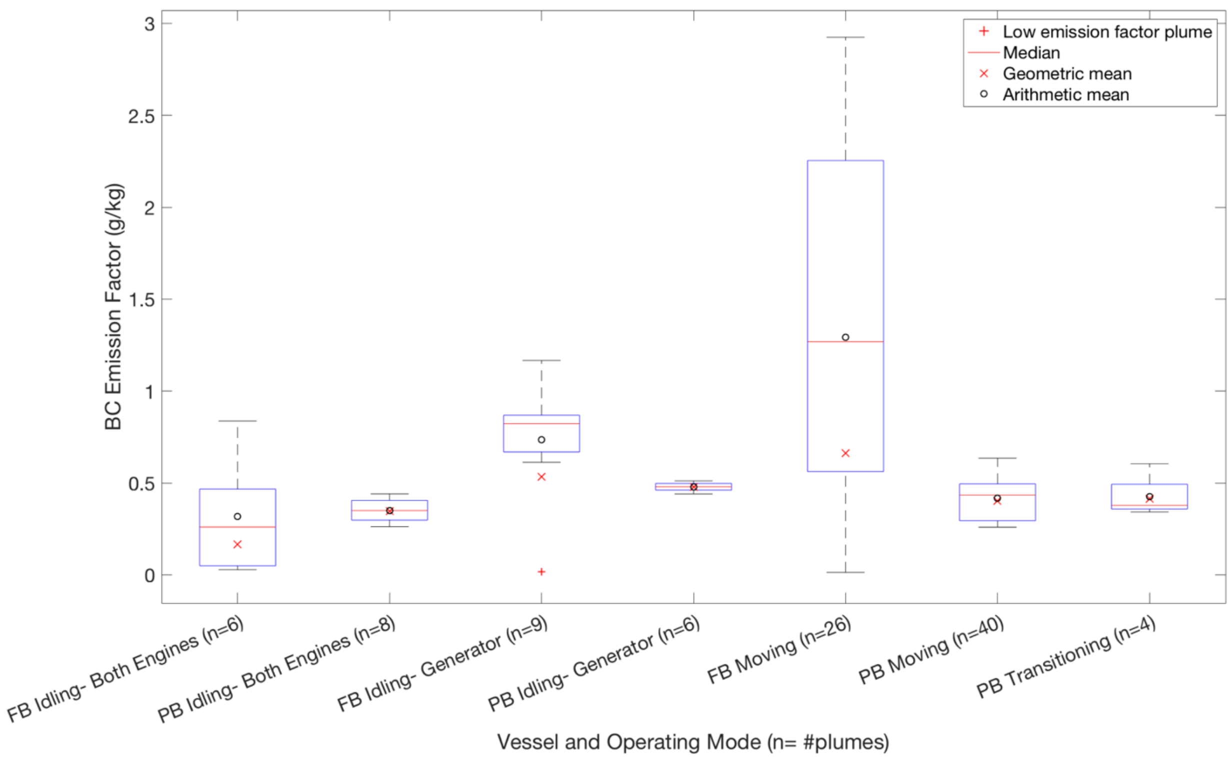


Distribution of BC emission factors (n = 58) measured on-board a Tier 2 passenger boat with wet exhaust.

Table 15: BC Emissions by Operating Mode

Vessel	Operating Mode	Geometric Mean BC Emission Factor (g/kg)	Arithmetic Mean BC Emission Factor (g/kg)	Standard Deviation (g/kg)
Fishing boat with dry exhaust		0.64	1.27	1.04
	Idling- both engines	0.21	0.39	0.40
	Idling- generator only	0.66	0.91	0.39
	Moving	0.82	1.60	1.15
Passenger boat with wet exhaust		0.50	0.51	0.12
	Idling- both engines	0.43	0.44	0.08
	Idling- generator only	0.59	0.59	0.03
	Moving	0.50	0.52	0.13
	Transitioning	0.51	0.53	0.15

Figure 58: Emission Factor Distributions by Vessel and Operating Mode



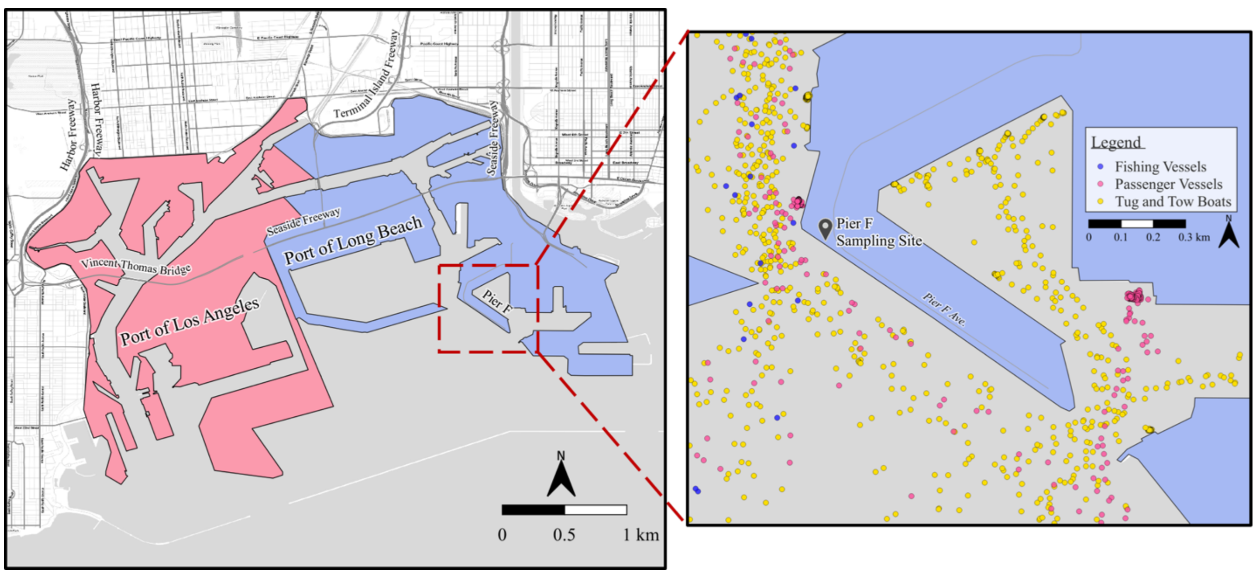
Boxplots of emission factors from on-board measurements separated by vessel and operating mode. Fishing boat box plots are labeled FB and passenger boat box plots are labeled PB. Low emission factor plumes are statistical outliers. Outliers were identified when an emission factor was less than the 25th percentile of emission factors in that category minus 1.5 times the interquartile range.

In-Use Emissions Measurements: Onshore Plume Capture

Methods

Tug and tow boats represent a critical source of harbor craft emissions, and boarding these types of vessels during their normal revenue service is more challenging than standard passenger-carrying vessels. Onshore plume capture measurements of passing vessels were conducted in the San Pedro Bay Port Complex in the South Coast Air Basin to diversify the categories of sampled harbor craft. This complex is made up of the Ports of Los Angeles and Long Beach, which together form the busiest port in North America and one of the busiest port facilities in the world (Figure 59; Port of Los Angeles, 2018). Characterizing harbor craft emissions is especially important in this area because air quality in the surrounding communities is significantly impacted by port emissions (Mousavi et al., 2018; Mousavi et al., 2019).

Figure 59: Map of San Pedro Bay Port Complex



The San Pedro Bay Port Complex (left) and twenty-four hours of harbor craft activity near the Pier F sampling site (right).

Emissions from passing vessels were measured from shore at Pier F in the Port of Long Beach over the course of nine days. This area was selected for the majority of sampling because of the frequent, close-to-shore harbor craft traffic, as determined from AIS data. In addition, the onshore sea breeze from the southwest facilitated advection of exhaust plumes to the shore sampling location. Vessels were observed cruising and accelerating at this location. Exhaust samples of tugboats that were idling with both auxiliary and main engines turned on while docked in the Port Complex were also collected. Vessel types and names were identified through real-time AIS data using the smart-phone application *Marine Traffic* (Marine Traffic, 2019) and vessel operating modes were recorded during sampling.

A nondispersive infrared analyzer (LI-COR model LI-840A) was used to measure CO_2 concentrations at 1 Hz frequency. An external pump with a flow rate of 100 cc/min drew air through a ~6 m long sample line made of Teflon tubing and through a 1-micron filter before reaching the sample chamber of the LI-840A. The CO_2 peak concentrations captured with the onshore measurements were small in magnitude and unaffected by the overshoot behavior described above and shown in Figure 37. As such, the correction factor applied to the on-board measurements was not applied to these onshore emission factors. BC mass concentrations were measured using a filter-based light absorption photometer (custom-built UC Berkeley ABCD). These BC concentrations were post-processed to include adjustments for the filter loading artifact, as discussed above.

Since onshore measurements were taken seconds to minutes down wind of vessels, BC concentrations were sometimes low compared to background concentrations and relative to instrument noise. A 40-second moving average was applied to the 1 Hz CO_2 and BC data. Further information on the application of a moving average can be found in Appendix C. Fuel-based BC emission factors were calculated via carbon balance, using the same method described above.

Results & Discussion

Inventory of Sampled Vessels

A total of 78 plumes were intercepted from 42–46 unique vessels operating in San Pedro Bay using the onshore method. Note that we report a range of unique vessels because four tugboats were not identifiable through field observations and AIS data. Based on the average engine count of each category of harbor craft from the 2018 Port of Los Angeles emissions inventory, these measurements represent BC emissions contributed by an estimated ~158 engines (Port of Los Angeles Emissions Inventory, 2019). Most of the plumes measured, 64%, came from 25–29 unique tug/tow boats. This corresponds to 34–39% of tug and tow boats operating out of San Pedro Bay according to the 2018 vessel inventories conducted by the ports of Los Angeles and Long Beach (2018 Port of Long Beach Emissions Inventory, 2019; 2018 Port of Los Angeles Emissions Inventory, 2019). Following these same vessel inventories, the relative proportions of vessel categories measured are not representative of the harbor craft fleet in the San Pedro Bay Port Complex, but rather reflect the vessel activity in this area of the Port of Long Beach.

Table 16: Summary of Onshore Vessel Sampling

Vessel Category	Number of Plume Intercepts	Number of Unique Vessels Sampled	San Pedro Bay Harbor Craft Population (2018)
Tug/Tow Boats	50	25-29 [1]	74
Pilot Boats	12	6	40
Passenger Boats	7	5	20
Fishing Vessels	6	3	102
Other [2]	3	3	63
All Onshore Measurements	78	42-46 [1]	299

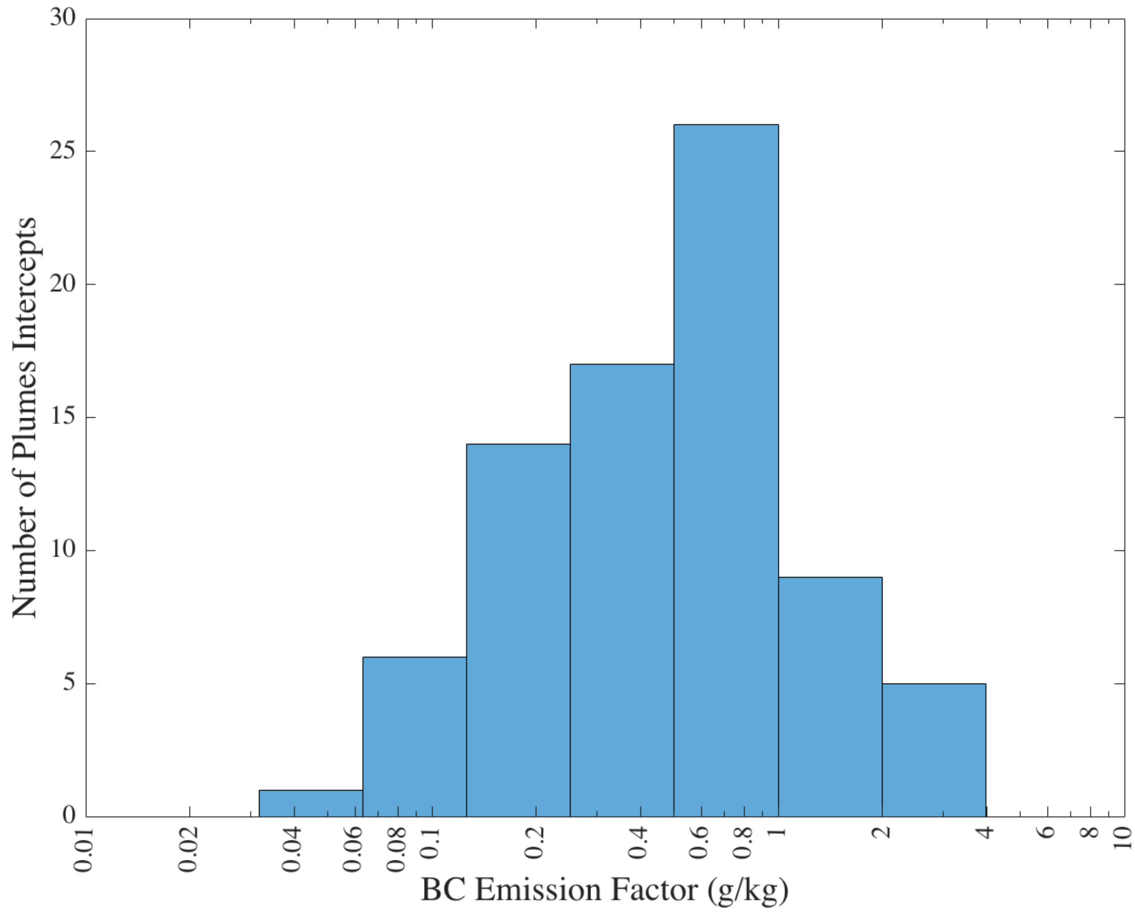
Number of plume intercepts and unique vessels observed for each category of commercial harbor craft during onshore measurements compared to the inventory of the broader fleet. Note that the passenger boat vessel category includes both excursion boats and ferries. [1]A range of unique vessels is given because four tug/tow boats were not identifiable through field observations and AIS data. [2]The category "other" includes excursion vessels, supply boats, work boats, and government vessels.

Emission Factors for Sampled Fleet

Emission factors from all onshore measurements had an approximately lognormal distribution (Figure 60). A summary of average BC emission factors for each vessel type observed is shown in Table 17. The geometric mean of BC emission factors for all onshore measurements was 0.45 g/kg. Passenger boats had the highest geometric mean BC emission factor of 0.54 g/kg. This agrees well with the geometric mean of BC emission rates observed on-board the Southern California passenger boat with wet exhaust during the moving operating mode, 0.50 g/kg. The higher variability observed in the onshore measurements likely reflects vessel-to-vessel variability, which was absent in the on-board measurements.

Fishing vessels had the highest arithmetic mean BC emission factor and the highest variability, or standard deviation, of all vessel categories observed during onshore measurements (0.88 ± 1.18 g/kg). This is mostly due to observations of high emitters, which here are defined as emission factors greater than the 75^{th} percentile of all emission factors from onshore measurements plus 1.5 times the interquartile range (Figure 61). Onshore observations of fishing vessels were significantly lower than those from the on-board measurements of the fishing boat with dry exhaust during the moving operating mode. This might suggest that the on-board measurements captured more operational variability than the onshore measurements, or that the fishing boat sampled on-board is more representative of a high emitter.

Figure 60: Emission Factor Distribution for All Onshore Measurements



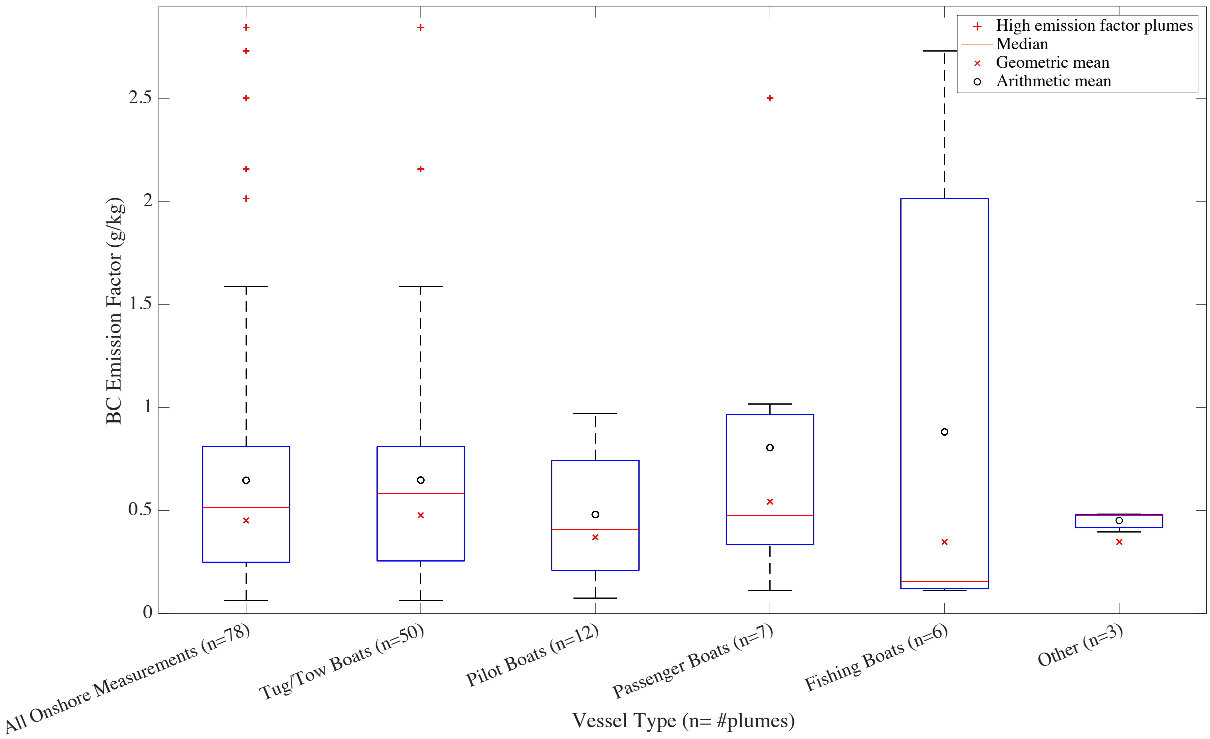
Distribution of BC emission factors from all onshore measurements. Note the log scale of the x-axis.

Table 17: Average Onshore Emission Factors by Vessel Type

Vessel Type	Geometric Mean BC Emission Factor (g/kg)	Arithmetic Mean BC Emission Factor (g/kg)	Standard Deviation (g/kg)
Tug/Tow Boats [1]	0.51	0.68	0.53
Pilot Boats	0.37	0.48	0.32
Passenger Boats	0.54	0.81	0.81
Fishing Vessels	0.35	0.88	1.18
Other	0.45	0.45	0.05
All Onshore Measurements	0.45	0.65	0.59

[1]Averages for tug and tow boats exclude idling measurements so that they are more directly comparable to the emission factors reported for other vessel types, which did not include idling measurements.

Figure 61: Onshore Emission Factor Distributions by Vessel Type



Box plots of all onshore measurements separated by vessel type. High emission factor plumes are statistical outliers defined as emission factors greater than the 75th percentile of emission factors from that vessel type plus 1.5 times the interquartile range.

Tug/Tow Boat Emissions by Operating Mode

Emission factors from tug and tow boats were further analyzed based on the three operating modes observed: without load, with load, and idling. Observations were categorized as "without load" when tug/tow boats were travelling without pushing a barge or when no tow line was attached to a ship, "with load" when tug/tow boats were pushing barges or had tow lines attached to ships, and "idling" when tug/tow boats were turned on (both auxiliary and main engines) and stationary. Idling measurements were taken during the two days of dock measurements described above.

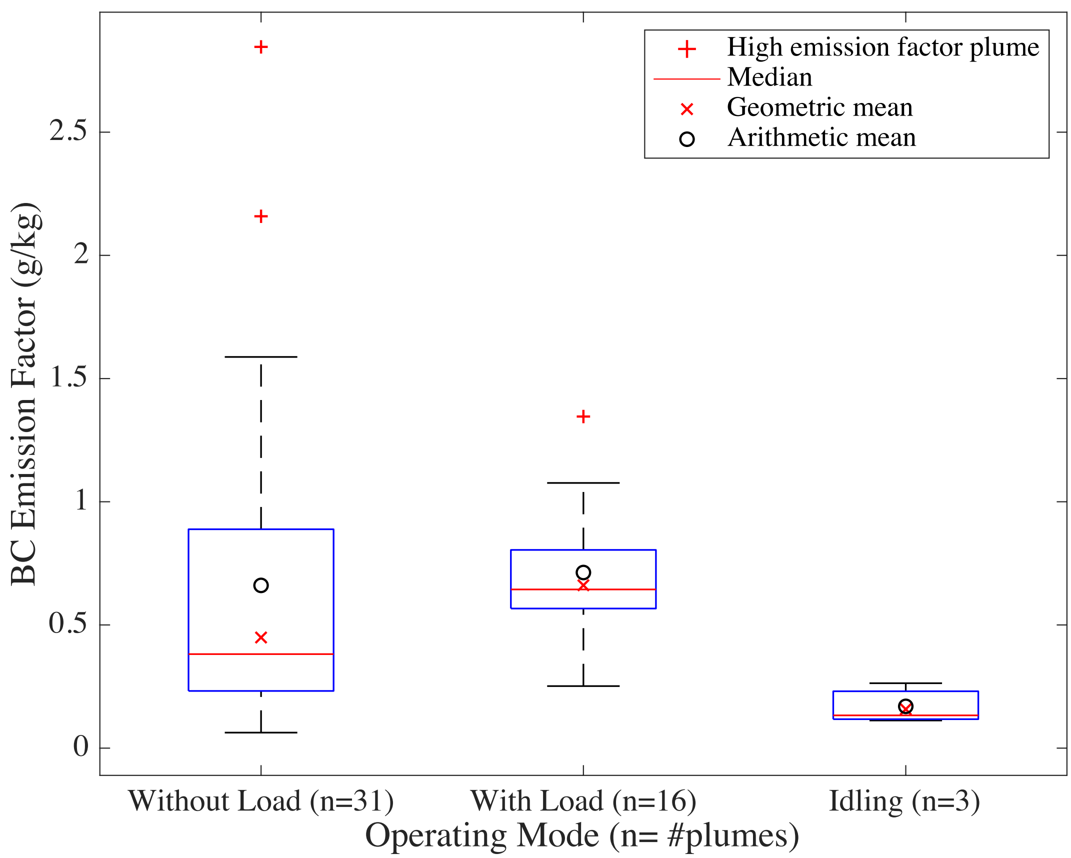
BC emission factors of tug and tow boats separated by operating mode are shown in Figure 62 and Table 18. Geometric mean emission factors were highest when tug and tow boats were operating with load (0.66 ± 0.28 g/kg), second highest without load (0.45 ± 0.63 g/kg), and lowest while idling (0.16 ± 0.08 g/kg). However, the statistical power of these differences is limited due to the small sample size of with load and idling observations. The largest amount of variability was observed in the without load operating mode. This variability likely reflects both vessel-to-vessel and operating variability, such as observations made while vessels are accelerating versus cruising.

Table 18: Average Tug/Tow Boat Emission Factors by Operating Mode

Operating Mode	Geometric Mean BC Emission Factor (g/kg)	Arithmetic Mean BC Emission Factor (g/kg)	Standard Deviation (g/kg)
Without Load	0.45	0.66	0.63
With Load	0.66	0.71	0.28
Idling	0.16	0.17	0.08
All Tug/Tow Boat Measurements	0.48	0.65	0.53

Summary of average emission factors from onshore measurements of tug and tow boats separated by operating mode.

Figure 62: Tug/Tow Boat Emission Factor Distributions by Operating Mode



Boxplots of BC emission factors measured from tug and tow boats separated by operating mode. High emission factors are statistical outliers defined as emission factors greater than the 75th percentile of emission factors from that operating mode plus 1.5 times the interquartile range.

Engine Tier Analysis

Engine information was provided by CARB for 27 of the ~45 vessels sampled using the onshore measurement method. The vessels with engine information consisted of tugboats, pilot boats, passenger boats, and fishing boats (Table 19). EPA engine tier ratings of the observed harbor craft ranged from Tier 0 (i.e., pre-Tier 1) to Tier 3.

Table 19: Inventory of Vessels with Engine Tier Information Provided by CARB

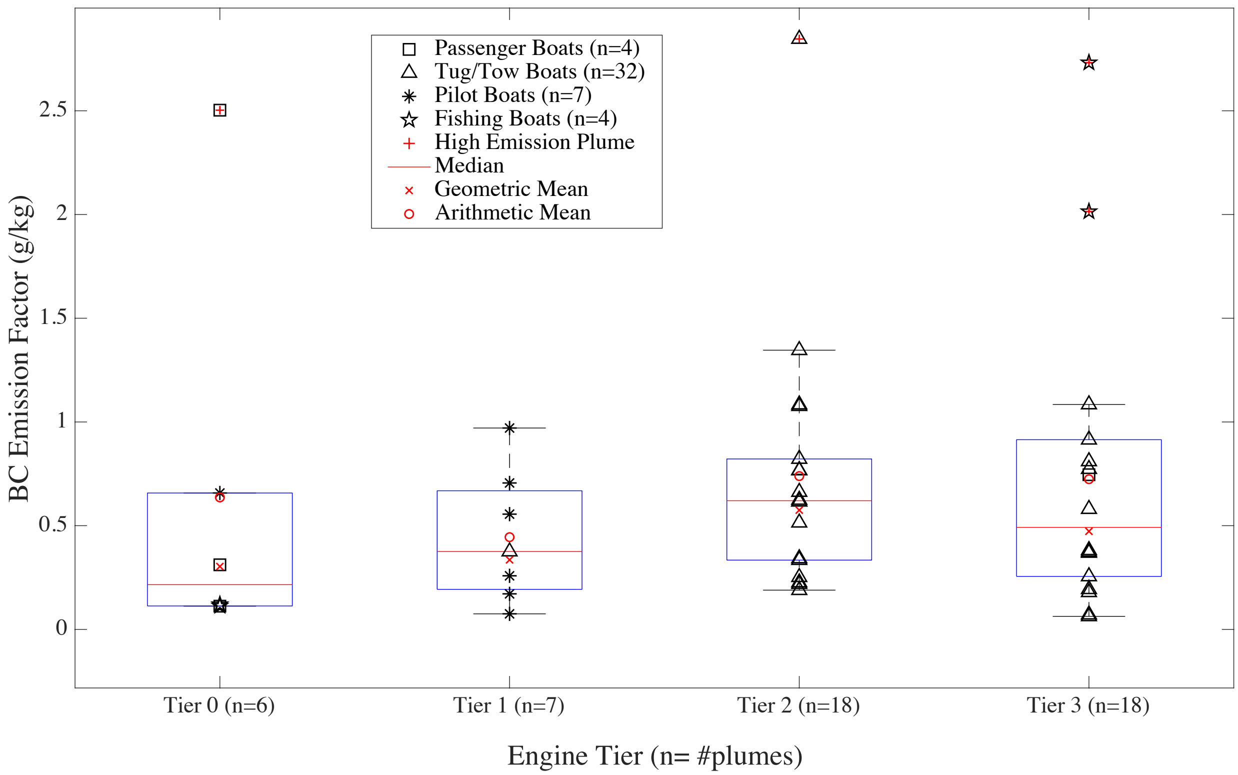
	Number of Unique Vessels			
Engine Tier	Tug Boats	Pilot Boats	Passenger Boats	Fishing Boats
Tier 0	0	1	3	1
Tier 1	1	1	0	0
Tier 2	12	0	0	0
Tier 3	6	0	1	1

Summary table of the vessels sampled using the onshore measurement method with engine information provided by CARB.

Figure 63 shows the distribution of non-idling BC emission factors by engine tier. Vessels with Tier 2 engines had the highest median BC emission factor of 0.62 g/kg followed by those with Tier 3 engines which had a median emission factor of 0.49 g/kg. Despite having less stringent PM certification levels (discussed in more depth below), Tier 0 and Tier 1 vessels had the lowest median BC emission factors of 0.22 g/kg and 0.38 g/kg, respectively. This may be partly explained by the heterogeneity of vessel types being compared between engine tiers. Tier 2 and Tier 3 vessels mostly consisted of tug and tow boats, whereas Tier 0 and Tier 1 observations mostly consisted of pilot boats, passenger boats, and fishing boats (Table 19). In this study and previous studies (Buffalo et al., 2014; Lack et al., 2008), tug and tow boats had higher average BC emission factors when compared to other categories of harbor craft (Table 17 and Table 20). Indeed, when comparing only Tier 2 and Tier 3 observations of tug and tow boats, the statistics are as expected: the Tier 2 arithmetic mean emission factor was 0.74 g/kg ± 0.62, which is higher than that for Tier 3, 0.47 ± 0.34 g/kg.

A second source of variability between engine tiers is operating mode. Tier 2 and Tier 3 tug and tow boats were observed moving with and without load, whereas Tier 0 and Tier 1 vessels were only observed moving. On average, tug and tow boats had higher median emission factors when operating with load than when operating without load (Figure 62), which likely contributed to the higher average BC emission factors observed in Tier 2 and Tier 3 vessels compared to Tier 0 and Tier 1. These results suggest that there are additional sources of variability beyond engine tier that contributed to the range of BC emission factors observed in onshore measurements.

Figure 63: Onshore Measurement Distributions by Engine Tier



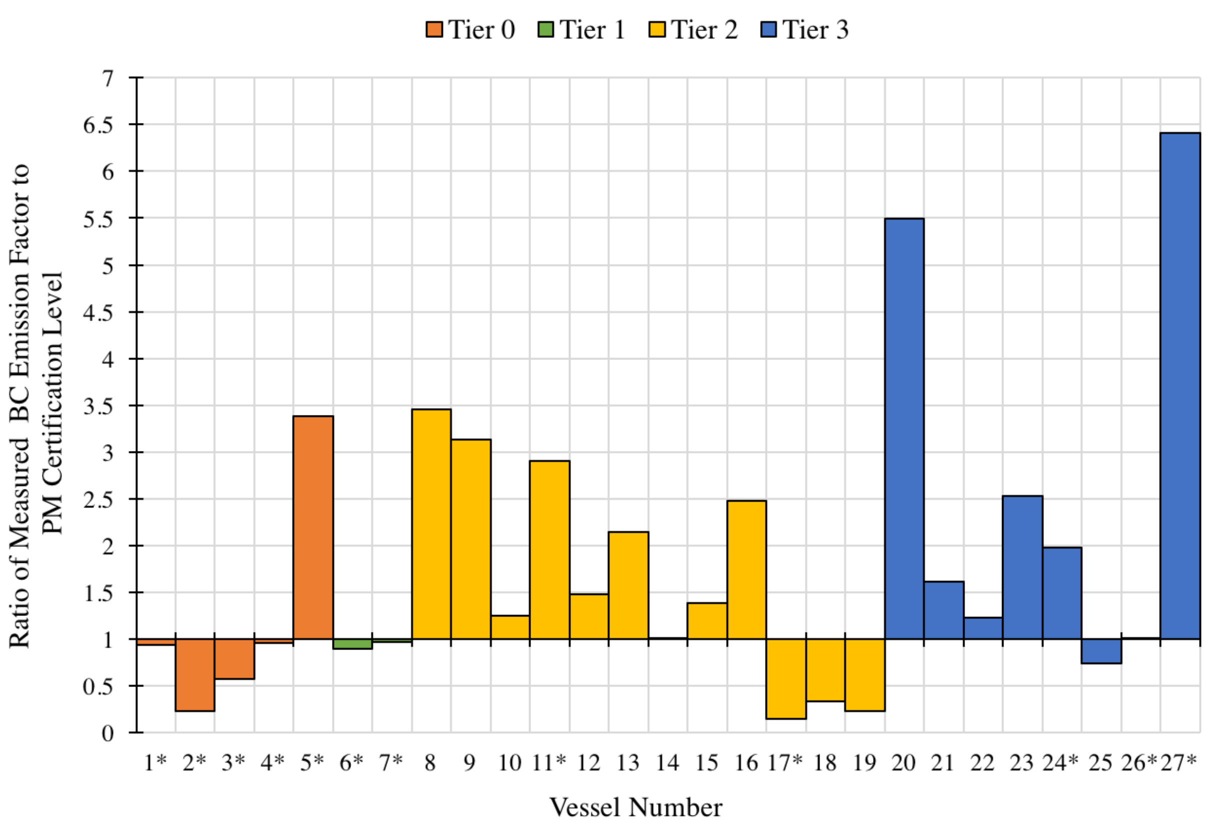
Boxplots of non-idling onshore measurements of the 27 vessels with engine information provided by CARB. Black symbols indicate vessel types and red symbols indicate statistics.

Comparison to Engine Certification Levels and EPA Standards

Arithmetic mean BC emission factors of non-idling observations were compared to EPA PM certification levels and emission standards that were provided by CARB for the 27 vessels mentioned in the previous section. For some vessels, denoted by asterisks in Figure 66 and Figure 67, engine family information was not available and PM certification levels were estimated using CARB's emission inventory. It should be noted that the EPA certification levels reported reflect only EPA certification level data for engines of the same engine family, whereas CARB inventory estimates are averages of EPA certification levels from multiple engine families. A brake specific fuel consumption value of 270 g/kWh was used to convert EPA PM certification values from g/kWh to g/kg; note that this value is slightly higher than the average value assumed above (237 g/kWh) and instead captures the high end of bsfc reported in Table 11. Again, this assumption adds uncertainty to the analysis since detailed engine information (e.g., annual engine hours, engine load during plume capture), was not available for vessels observed from shore. Further, the emission snapshots considered in the following analyses are not representative of the duty cycles used to define EPA PM certification values. Due to these assumptions, the results presented below and shown in Figure 64 and Figure 65 should not be used to interpret compliance with EPA PM standards.

The ratios of average BC emission factors to the EPA PM certification levels provided by CARB are shown for each vessel in Figure 64. In general, average BC emission factors of Tier 0 and Tier 1 vessels were lower than the estimated PM certification levels from CARB's emission inventory model. Over half of the Tier 2 and Tier 3 vessels had average BC emission factors that were higher than their certification levels by a factor of 1.5 or greater. As discussed above, Tier 2 and Tier 3 vessels were mostly tug and tow boats and the high average BC emission factors observed may partly be explained by operational variability. More measurements are needed to: (1) determine if these emissions snapshots are indicative of these vessels emitting higher than their PM certification levels, and (2) if the duty cycles used to set PM certification values are representative of typical tug/tow boat operation.

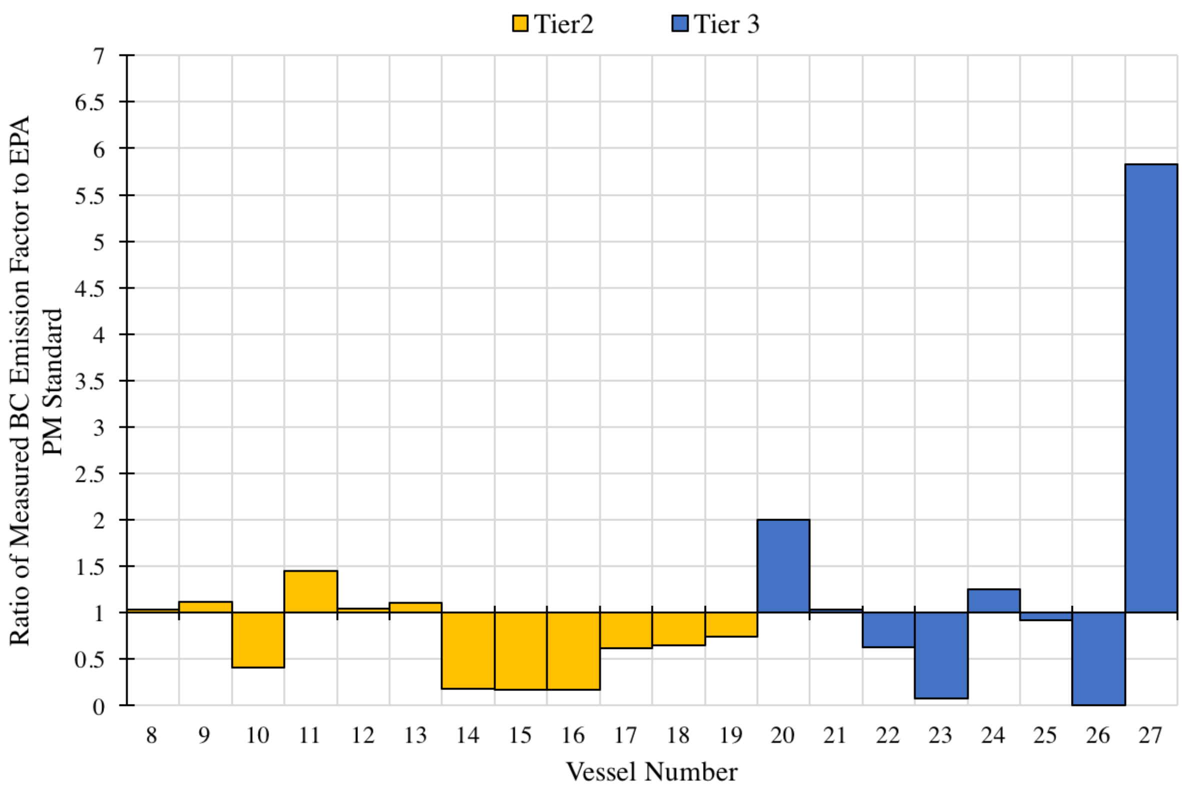
Figure 64: Ratio of Measured BC Emissions Factors to PM Certification Levels



EPA PM certification levels were provided by CARB when available and estimated from CARB's emission inventory (denoted by asterisks) when engine information was missing. These data were compared to the arithmetic mean of non-idling BC emission factors. Ratios greater than 1 indicate vessels with average BC emission factors that are greater than their PM certification level and ratios less than 1 indicate vessels with average BC emission factors lower than their PM certification level.

Figure 65 compares arithmetic mean BC emission factors from Tier 2 and Tier 3 vessels to their corresponding PM standards. The ratio of average BC emission factor to PM standard ranged from 0.26 to 1.5 for Tier 2 vessels, with only 3 of these 11 vessels exceeding their PM standards by more than 10%. For Tier 3 vessels, ratios of BC emission factors to PM standards were between 0.09 and 5.8. Only 3 of the 8 Tier 3 vessels had average BC emission factors that exceeded their PM standards by more than 10%. These results show that BC emission snapshots of Tier 2 and 3 vessels generally exceeded PM emission levels reported to EPA during certification, and were below EPA PM standards.

Figure 65: Ratio of Measured BC Emission Factors to EPA PM Standards



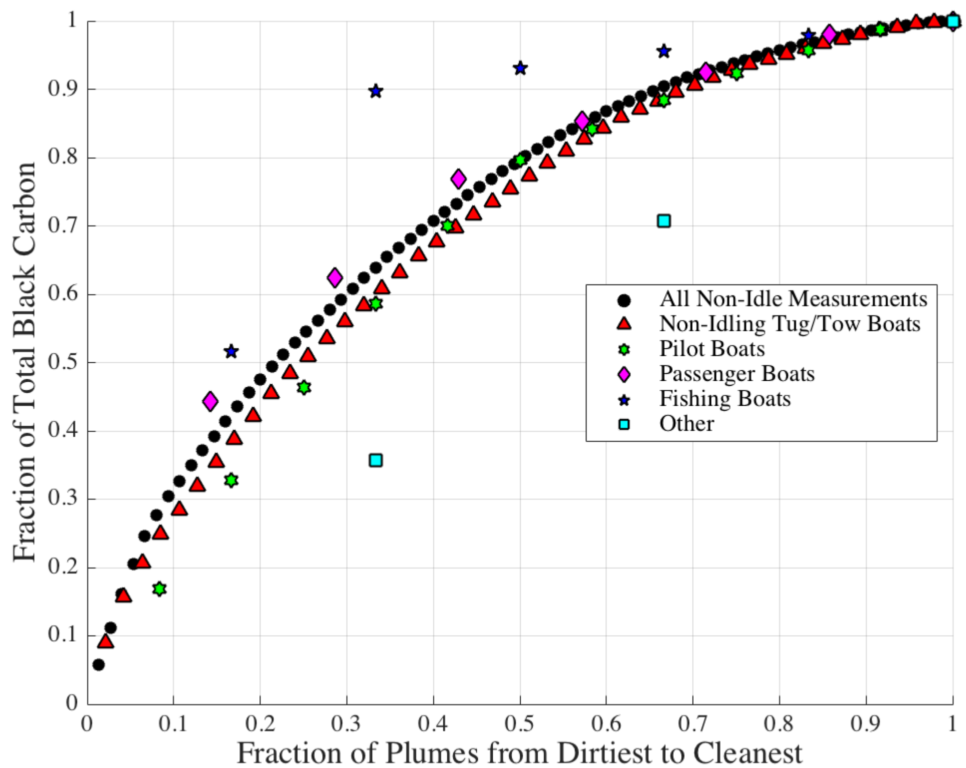
EPA PM standards were provided by CARB for Tier 2 and Tier 3 vessels. Results shown here compare the arithmetic mean of non-idling BC emission factors to EPA PM emission standards. Ratios greater than 1 indicate vessels with average BC emission factors that are greater than their EPA PM standards and ratios less than 1 indicate vessels with average BC emission factors lower than their EPA PM standards. Due to the assumptions discussed above, these emission snapshots should not be used to interpret compliance with EPA PM standards.

Vessel 27, a Tier 3 fishing vessel with two plume intercepts, had an average BC emission factor that was greater than its PM certification level and emission standard by a factor of 6.4 and 5.8, respectively (Figure 64 and Figure 65). BC emission factors measured from this vessel were statistical outliers when compared to other Tier 3 emission factors (Figure 63) and when compared to all emission factors measured using the onshore method (Figure 61). This suggests that Vessel 27 is likely a high emitter, possibly due to an engine maintenance issue or design flaw, although engine information was not available to elucidate the cause of these high BC emissions. Ideally, additional measurements would be made to determine if the two emission snapshots presented here are characteristic of BC emissions from this vessel.

BC Emissions Skewness

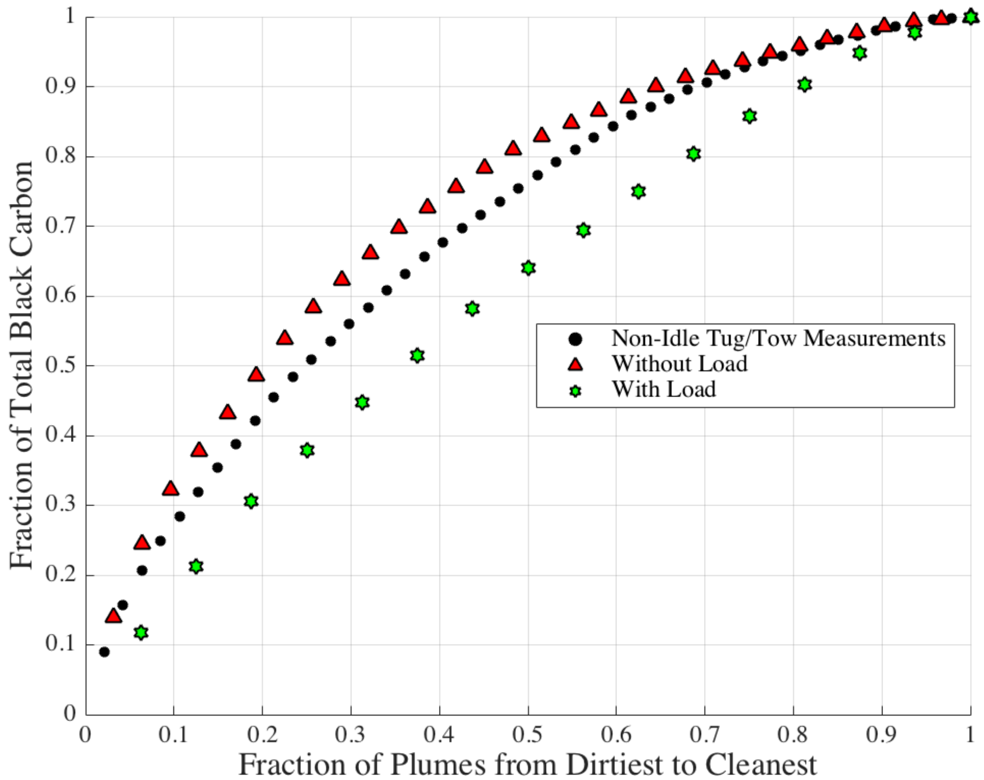
BC emission factors from all non-idle, onshore measurements are skewed, with the dirtiest 20% of plume intercepts contributing ~47% of BC emissions (Figure 66). Emission factors from fishing boats are the most skewed with the single highest BC emission factor capture observed accounting for over 52% of BC emissions from this vessel category. For tug and tow boat emission factors, skewness was highest while vessels were moving without load, with the dirtiest 20% of plume intercepts contributing nearly 50% of total BC emissions from vessels moving without load (Figure 67).

Figure 66: Cumulative Emissions Distributions from All Onshore Measurements



Cumulative BC emission factor distributions of onshore measurements of harbor craft. The fraction of cumulative BC emissions is shown on the y-axis and the fraction of plumes, from dirtiest to cleanest, is shown on the x-axis. For example, 20% of the dirtiest plumes from all harbor craft contribute to ~47% of total black carbon (black circles) and 25% of the dirtiest plumes from pilot boats contribute ~48% of total black carbon from pilot boats (green hexagons). If normally distributed, these data would plot in a straight line. Note that the distribution shown here only changes minimally when repeated measurements are averaged to show the fraction of vessels from dirtiest to cleanest.

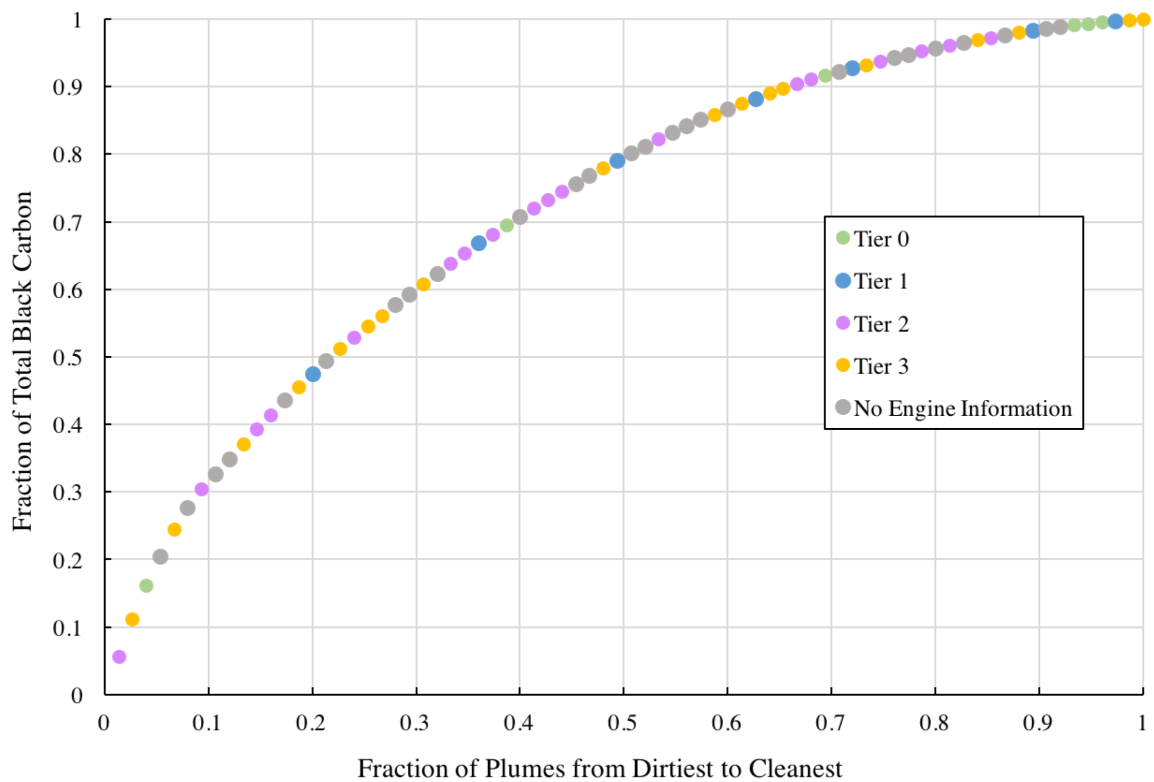
Figure 67: Cumulative Emissions Distributions for Tug/Tow Boats



Cumulative BC emission factor distributions of onshore measurements of tug and tow boats separated by operating mode.

Figure 68 shows skewness of non-idling BC emission factors measured from shore with observations labeled by engine tier. Unlike Figure 45, engine tiers do not cluster together when BC emission factors are ranked from dirtiest to cleanest. This may be due to the vessel-type variability in each tier, which was not seen during the SF Bay Area on-board measurements. Information from operators on engine specifics such as engine age and operating hours would be needed to determine if high emitters are the result of malfunctioning emission control technologies or other maintenance issues. This figure suggests that engine tier variability alone does not account for the skewness observed in the harbor craft fleet in the San Pedro Bay Port Complex.

Figure 68: Cumulative Emissions Distribution by Engine Tier



Cumulative BC emission factor distribution of onshore measurements with EPA engine tiers labelled when available.

Comparison of Onshore Measurements to Prior Studies

There are two previous measurement campaigns that measured BC emission factors from multiple harbor craft. The first is the Texas Air Quality Study (TexAQS), where light absorption techniques were used to measure vessel emissions near Galveston Bay and the Houston shipping channel during the 2006 Texas Air Quality Study (Lack et al., 2008). This study focused on cargo vessels, but tugboats and passenger boats were also encountered. A summary of relevant emission factors from this study is included in Table 20.

The geometric mean BC emission factor for tugboats in TexAQS was significantly higher than that of non-idling tug and tow observations in this study (Table 18). This may be in part because the average fuel sulfur content in the TexAQS study, determined by measuring sulfur emissions, was 0.4 ± 0.6% by weight for tugboats. In California, ultra-low sulfur fuel (0.0015% sulfur by weight) is required within 24 nautical miles of the coastline. Since most of the tugboats observed in this study have "home ports" in the ports of Los Angeles and Long Beach, it is reasonable to assume that the vessels encountered during onshore measurements were burning ultra-low sulfur fuel. This finding supports previous work where lower fuel sulfur content was found to decrease BC emissions (Khan et al., 2012; Lack et al., 2011; Lack and Corbett, 2012). Another factor that may contribute to the differences observed in these studies is the proportion of observations made while tug and tow boats were moving with loads versus without. In the current study, 34% of non-idling tug/tow observations were operating with load, while the TexAQS study does not report a corresponding value. Lastly, disparities in reported emission factors could be due to differences in the measured fleets.

The geometric mean BC emission factor for passenger boats is higher in the current study than in TexAQS. Disparities in reported BC emission factors between the two studies are likely similar to those for tug and tow boats, though operating with/without load would not be expected to play a role.

A second measurement campaign with multiple harbor craft observations is the 2010 California Nexus campaign (CalNex; Buffalo et al., 2014). In this study, plumes were intercepted from vessels operating within 24 nautical miles of California's coastline, wherein vessels were required to use low sulfur fuels at the time of this study. Relevant emission factors from CalNex are summarized in Table 20. The geometric mean BC emission factor for tug and tow boats was somewhat lower during CalNex than those of non-idling tug and tow observations from the current study. This is likely due to the small proportion of vessels moving with load during CalNex (Buffalo et al., 2014). Indeed, the geometric mean emission factor from the current study of tug and tow boats moving without load (0.45 g/kg) agrees much better with the CalNex tug/tow boat average (0.43 g/kg). Pilot boat emission factors agree well with CalNex. Passenger boat and fishing vessel geometric mean BC emission factors were significantly lower in CalNex than in the current study; likewise, the variability observed in passenger boat and fishing vessel emission factors was much lower in CalNex. This is likely due to observations of high emitters in the current study. Indeed, median BC emission factors, which are less sensitive to outlying data points than the geometric mean, agree very well for the current study versus CalNex (i.e., for passenger boats and fishing vessels).

Table 20: Summary of Previous Studies of CHC BC Emission Factors

Vessel Type	No. of Intercepts			Geometric Mean BC Emission Factor (g/kg)			Median BC Emission Factor (g/kg)		
	This Study	CalNex [1]	TexAQS [2]	This Study	CalNex [1]	TexAQS [2,3]	This Study	CalNex [1]	TexAQS [2]
Tug/Tow Boats [4]	50	13	54	0.51 ± 0.53	0.43 ± 0.46	0.74 ± 0.66	0.59	0.33	0.85
Pilot Boats	12	5		0.37 ± 0.32	0.33 ± 0.28		0.41	0.27	
Passenger Boats	7	9	8	0.54 ± 0.81	0.30 ± 0.41	0.32 ± 0.20	0.48	0.47	0.29
Fishing Vessels	6	6		0.35 ± 1.18	0.22 ± 0.18		0.26	0.25	

[1]CalNex data are from Buffalo et al. (2014) and [2]TexAQS data are from Lack et al. (2008). [3]Geometric means reported for TexAQS were not provided in Lack et al. (2008). The values reported here are those from Buffalo et al. (2014). [4]Tug/tow boat average BC emission factors reported for the current study exclude idling measurements, and those reported for CalNex are averages of the tugboat and tow boat emission factors reported in Buffalo et al. (2014).

Conclusions

This study characterized in-use pollutant emissions from commercial harbor craft operating in California. A portable emissions measurement system (PEMS) measured emissions aboard two vessels in the San Francisco Bay. An on-board plume capture measurement system collected more than 1,400 emission snapshots yielding average BC and NO_x emission factors for 25 and 10 engine conditions, respectively, for ferry and excursion vessels operating in the San Francisco Bay Area. Additionally, the same on-board plume capture system was used on a passenger and fishing vessel operating in the South Coast Air Basin. An onshore plume capture approach measured 78 exhaust plumes from ~45 in-use harbor craft, which can each include exhaust from two main engines and an auxiliary engine, in the San Pedro Bay Port Complex in the South Coast Air Basin.

The following are key findings under five areas of significance: BC emissions, NO_x emissions, effect of SCR on NO_x emissions, effect of SCR on particle emissions, and comparison to emission certification levels.

BC Emissions

- BC emissions from the in-use fleet are somewhat skewed: the most polluting 20% of engines are responsible for nearly 40% of total BC emitted by the ferry and excursion fleet in the SF Bay and nearly 50% of the BC emitted by the fleet dominated by tug and tow boats in the San Pedro Bay Port Complex. Conversely, the cleanest 20% of engines contribute only ~5% of the total BC emitted by both fleets.
- Amongst the ferry and excursion fleet, the highest BC emitters are Tier 0 and Tier 2 engines, while the lowest-emitters are Tier 3 and Tier 4 engines. Tier 4 engines emitted 92% less BC per kg of fuel burned than Tier 0 engines, on average.
- Non-idling tug and tow boats had the highest median BC emission factor when compared to the other vessel types observed at the San Pedro Bay location. Moreover, tug and tow boats had higher BC emission factors when operating with load than when operating without load.
- The average BC emission factor measured for tow and tugboats was two times greater than that measured for ferry and excursion vessels. This difference may be due to the snapshot measurement of a limited number of operating conditions by onshore measurements compared to the measurements on-board ferries and excursion vessels that captured multiple vessel operating modes. The difference could also reflect true operational distinctions between these vessel categories.

NO_x Emissions

- As measured by PEMS, both Vessel A and Vessel B have higher NO_x emissions per passenger than driving a single-occupancy vehicle or riding a public transit bus.

- On-board plume capture NO_x emissions were very slightly skewed, though the subset of the San Francisco Bay ferry and excursion vessel fleet on which NO_x emissions were measured was relatively new and not fully represented of the entire fleet. The highest-emitting 20% of engine conditions is responsible for 30% of total NO_x emissions, while the cleanest 20% of the fleet contributed <10% of total NO_x emissions. Tier 2 engines and Tier 3 engines with inactive SCR had comparable NO_x emission factors, on average.

Effect of SCR on NO_x Emissions

- PEMS NO_x emission rates from the SCR-retrofitted Vessel B were nearly the same before and after the SCR, suggesting that the SCR system was not properly functional during the test period.
- The active retrofit SCR system on the Tier 3 engine sampled in this on-board plume capture portion of this study reduced emitted NO_x than by nearly a factor of 6, while the average NO_x emissions from the Tier 4 engines with original equipment SCR only reduced emitted NO_x by a factor of 2 compared to those from Tier 3 engines with inactive SCR and Tier 2 engines.
- A case study comparing emissions from a Tier 3 ferry when its SCR system was active to when it was intentionally disabled shows that, on average, the active SCR system effectively reduces emitted NO_x by ~70% while the vessel is docked and maneuvering and ~90% while it is cruising.
- Analysis of NO_x emission factors measured along a ferry route suggests that SCR systems may not always yield the intended NO_x emission reductions; SCR functionality can depend on vessel operation, where systems are active and dosing with urea during fast cruise but urea dosing may cease during low-load conditions like slow cruise and docking.

Effect of SCR on Particle Emissions

- The PEMS PM emission rate was 38% lower after the SCR, suggesting that the SCR system removes some particles.
- The on-board plume capture measurements further indicated that the BC reduction appears to be dependent on SCR activity: active systems emit 23% less BC per kg of fuel compared to inactive systems.
- Relative to a Tier 3 engine with active SCR, average BC emissions from the two Tier 3 engines without SCR and the eleven Tier 2 engines were, respectively, 2.0 and 2.7 times higher.

Comparison to Certification Levels and EPA Standards

- PEMS NO_x emissions from both vessels and PM emissions from Vessel B were below engine certification values. The SCR system on Vessel B could have made it a Tier 4-equivalent vessel, however the SCR system did not function properly. This result emphasizes the importance of maintaining and operating SCR systems so that they can effectively reduce real-world NO_x emissions. Additional measurements are needed to quantify the reduction capabilities of the SCR system on this vessel.

- On-board and onshore plume-capture fuel-normalized emission factors were compared to engine-power-normalized certification levels and EPA emission standards for PM and NO_x using a brake specific fuel consumption that was derived from engine data. It is important to note that BC is a major but not sole constituent of diesel PM. Thus, PM emission rates may be larger than the BC emission factors reported here. It is also important to note that these EPA values are based on specific duty-cycle tests, which the real-world operation of these ferries and excursion vessels may not mirror. As such, these comparisons should not be used to determine compliance with EPA limits.
- For the on-board measurements of ferry and excursion vessels in the SF Bay Area, the two Tier 0 and most of the Tier 3 engines sampled in this study have BC emissions below their corresponding PM certification levels, but many of the Tier 2 engines have average BC emissions that are 1.1–2.0 times higher than their corresponding values.
- Relative to the EPA emission standard, all but one in the SF Bay Area on-board measurements had average BC emission factors that met the PM exhaust limit. The single engine that was higher than the standard had a BC emission rate that was within 10% of the limit.
- For the subset of engines with NO_x measured on-board in the SF Bay Area, only the Tier 3 engine with active SCR had appreciably lower average emissions than its certification level and standard, a Tier 3 engine with inactive SCR and a Tier 2 engine had comparable real-world emissions, and all remaining Tier 3 and Tier 4 engines had elevated NO_x emissions. The Tier 4 engines with original equipment SCR systems have the most stringent emission standard and exceed their certification limits by a factor of ~2.
- For the onshore measurements in San Pedro Bay, over half of the Tier 2 and Tier 3 vessels had average BC emission factors that were 1.5–6.5 times higher than their PM certification levels. Most of these vessels were tug and towboats and the high average BC emission factors observed may be partly explained by operational variability.
- With the exception of one vessel that may be a high emitter, most of these vessels in San Pedro Bay had average BC emissions below or within 10% of their corresponding PM standard, as was also observed for the SF Bay Area ferry and excursion fleet.

Next Steps and Recommendations

This study presents BC and NO_x emission factors for commercial harbor craft that are currently in-use. These new data can be used to evaluate emission inventories and guide CARB's rulemaking process. This work has also uncovered many new relevant questions, some of which could be addressed with additional sampling that includes larger numbers of vessels and multiple measurements of individual vessels.

While emissions from more than 60 vessels were captured in this study, there were few repeat measurements of the same vessel. Repeat measurements would help evaluate whether elevated BC and NO_x emission rates measured in the present study for some vessels are typical of normal operation or are transient and due to a potential mechanical issue. Repeat measurements and a large total sample size are also needed for evaluating the high emitter problem, characterizing off-cycle emissions for SCR-equipped engines, and determining general trends across the fleet.

Though this study produced information with a considerable amount of granularity, additional measurements that include a broader cross-section of the in-use commercial harbor craft fleet would be more informative. For example, the present study included only two Tier 4 engines with original equipment SCR systems. The limited sample size prevents a generalization of these specific results, especially in terms of projecting future fleet emissions. A limited number of measurements indicate that fishing boats have the highest and most variable BC emissions compared to other vessel categories. This may be cause for further study of this vessel category, as CARB projects that fishing vessels will emit a significant portion of the diesel particulate matter from CHC in 2023.

The on-board plume capture method deployed for the first time in this study overcomes one of the main limitations of static plume capture measurements that collect only a single snapshot of engine exhaust. In a sense, the method deployed here that captures ~100 exhaust snapshots throughout normal operation is PEMS-like, but is without direct acquisition of engine operating data. Since the on-board plume capture approach is less invasive and less costly, it can be deployed on large numbers of vessels. A recommendation for future studies is to obtain engine-specific information, such as engine load or speed, during on-board plume capture measurements. If applied on many vessels, this combination would help to develop confidence in operating-mode-specific emission factors. If these measurements are made in coordination and collaboration with vessel operators and include specific details about the engine and maintenance practices, it would be possible to better understand the conditions that lead to high emissions. Such assessments could include SCR performance variability as a function of different operating modes, malfunction, and vessel types. For instance, on the vessel where we conducted experiments with the SCR system (engine conditions 17–19), we were able to gain important insight into SCR activity by operational mode with SCR system data provided by the operator.

References

AVL. *AVL Micro Soot Sensor Operating Manual*. **2013**, Document AT1861E.

Ban-Weiss, G. A., et al. Long-Term Changes in Emissions of Nitrogen Oxides and Particulate Matter from On-Road Gasoline and Diesel Vehicles. *Atmos. Environ.* **2007**, *42*, 220–232.

Ban-Weiss, G. A., et al. Measurement of Black Carbon and Particle Number Emission Factors from Individual Heavy-Duty Trucks. *Environ. Sci. & Tech.* **2009**, *43*, 1419–1424.

Buffalo, G. M., et al. Black Carbon Emissions from In-Use Ships: A California Regional Assessment. *Atmos. Chem. Phys. Disc*. **2013**, *13*, 24675–24712.

California Air Resource Board (CARB). *Overview of Commercial Harbor Craft Regulation*. **2016**. ww2.arb.ca.gov/sites/default/files/2019-03/chcfactsheet0516.pdf.

California Air Resource Board (CARB). Draft CHC Emission Inventory, as Presented on March 5, 2020. *Webinar: Overview of Proposed Concepts for Amendments to the Commercial Harbor Craft Regulation*. **2020**. https://ww2.arb.ca.gov/sites/default/files/2020-03/CHC%20Webinar% 20Presentation %20March%202020_1.pdf.

Caubel, J.J., et al. A Distributed Network of 100 Black Carbon Sensors for 100 Days of Air Quality Monitoring in West Oakland, California. *Environ. Sci. & Tech.* **2019**, *53*, 7564–7573.

Corbett, J. J., et al. Mortality from Ship Emissions: A Global Assessment. *Environ. Sci. & Tech.* **2007**, *41*, 8512–8518.

Dallmann, T.R., et al. On-Road Measurement of Gas and Particle Phase Pollutant Emission Factors for Individual Heavy-Duty Diesel Trucks. *Environ. Sci. & Tech.* **2012**, *46*, 8511–8518.

Environmental Protection Agency (EPA) *Method 2—Determination of Stack Gas Velocity and Volumetric Flow Rate (Type S Pitot Tube)* **2019**. https://www.epa.gov/sites/production/files/ 2017-08/documents/method_2.pdf. (Accessed 2019.10.08).

Fuglestvedt, J., et al. "Shipping Emissions: From Cooling to Warming of Climate—and Reducing Impacts on Health." *Environ. Sci. & Tech.* **2019**, *43*, 9057–9062.

Golden Gate Bridge Highway & Transportation District. **2019**, https://www.goldengate.org/bus/history-research/statistics-ridership/ (Accessed 2019.08.07).

Government Publishing Office (GPO). **2019**, https://www.govinfo.gov/content/pkg/CFR-2010-title40-vol19/pdf/CFR-2010-title40-vol19-sec86-1342-94.pdf. (Accessed 2019.10.16).

Johnson, K., et al. *Validation Testing for the PM-PEMS Measurement Allowance Program*. **2010**, CARB Contract No. 07-620.

Jung, H., et al. The Influence of Engine Lubricating Oil on Diesel Nanoparticle Emissions and Kinetics of Oxidation. **2003**, SAE Technical Paper No. 2003-01-3179.

Khan, M. Y., et al. Benefits of Two Mitigation Strategies for Container Vessels: Cleaner Engines and Cleaner Fuels. *Environ. Sci. & Tech.* **2012**, *46*, 5049–5056.

Kirchstetter, T.W., Novakov, T. Controlled Generation of Black Carbon Particles from a Diffusion Flame and Applications in Evaluating Black Carbon Measurement Methods. *Atmos. Environ.* **2007**, *41*, 1874–1888.

Lack, D. A., et al. Light Absorbing Carbon Emissions from Commercial Shipping. *Geophys. Res. Lett.*, **2008**, *35*, L13815.

Lack, D. A., et al. Particulate Emissions from Commercial Shipping: Chemical, Physical, and Optical Properties. *J. of Geophys. Res.* **2009**, *114*, D00F04.

Lack, D. A., et al. Impact of Fuel Quality Regulation and Speed Reductions on Shipping Emissions: Implications for Climate and Air Quality. *Environ. Sci. & Tech.* **2011**, *45*, 9052–9060.

Lack, D. A., Corbett, J. J. Black Carbon from Ships: A Review of the Effects of Ship Speed, Fuel Quality and Exhaust Gas Scrubbing. *Atmos. Chem. Phys. Disc*. **2012**, *12*, 3509–3554.

Lobo, P., et al. Measurement and Analysis of Aircraft Engine PM Emissions Downwind of an Active Runway at Oakland International Airport. *Atmos. Environ.* **2012**, *61*, 114–123.

Marine Cadastre. **2019**, https://marinecadastre.gov/ais/

Marine Exhaust. **2019**, https://www.marineexhaust.com/index.cfm?fuseaction=home.main. (Accessed 2019.07.13).

Marine Traffic. **2019**, https://www.marinetraffic.com/en/ais/home/centerx:117.903/centery: 33.606/zoom:17. (Accessed 2019.11.11).

Mousavi, A., et al. Impact of Particulate Matter (PM) Emissions from Ships, Locomotives, and Freeways in the Communities near the Ports of Los Angeles (POLA) and Long Beach (POLB) on the Air Quality in the Los Angeles County. *Atmos. Environ.* **2018**, *195*, 159–169.

Mousavi, A., et al. Impact of Emissions from the Ports of Los Angeles and Long Beach on the Oxidative Potential of Ambient $PM_{0.25}$ Measured across the Los Angeles County. *Sci. Total Environ.* **2019**, *651*, 638–647.

Port of Long Beach. *Port of Long Beach Emissions Inventory*. **2018**, www.polb.com/ environment/ air/emissions.asp.

Port of Los Angeles. *Port of Los Angeles Air Emissions Inventory (2018)*. **2019**, www.portoflosangeles.org/ environment/air-quality/air-emissions-inventory

Port of Los Angeles. *Facts and Figures*. **2018**, www.portoflosangeles.org/ business/statistics/ facts-and-figures.

Preble, C. V., et al. Effects of Particle Filters and Selective Catalytic Reduction on Heavy-Duty Diesel Drayage Truck Emissions at the Port of Oakland. *Environ. Sci. & Tech.* **2015**, *49*, 8864–8871.

Preble, C. V., et al. In-Use Performance and Durability of Particle Filters on Heavy-Duty Diesel Trucks. *Environ. Sci. & Tech.* **2018**, *52*, 11913–11921.

Schauer, J. J., et al. Measurement of Emissions form Air Pollution Sources. 2. C1 through C30 Organic Compounds from Medium Duty Diesel Trucks. *Environ. Sci. & Tech.* **1999**, *33*, 1578–1587.

Sensors, Inc. *On-Vehicle Diesel Emission Analyzer SEMTECH-DS User Manual*. **2007**, Document #9510-086.

Tang, N. W., et al. Measurement of Black Carbon Emissions from In-Use Diesel-Electric Passenger Locomotives in California. *Atmos. Environ.* **2015**, *115*, 295–303.

United States Coast Guard. **2019**, https://www.dco.uscg.mil/OurOrganization/ AssistantCommandantforPreventionPolicy(CG-5P)/InspectionsCompliance(CG-5PC)/OfficeofInvestigationsCasualtyAnalysis/MerchantVesselsoftheUnitedStates.aspx

VesselFinder. **2019**, https://www.vesselfinder.com/historical-ais-data.

Wang, J. M., et al. Plume-based Analysis of Vehicle Fleet Air Pollutant Emissions and the Contribution from High Emitters. *Atmos. Meas. Tech.* **2015**, *8*, 3263–3275.

West Marine. **2019**, https://www.westmarine.com/WestAdvisor/Exhaust-System-Basics. (Accessed 2019.07.13).

Appendix A: Activity Characterization Questionnaire

Vessel Identification Information

Name of company that owns this vessel:

Name of company that operates this vessel (if different than above):

Name of this vessel:

Type of vessel (Please use category name from the list below):

United States Coast Guard identification number:

IMO number:

MMSI number:

Study Questionnaire

1. What is the engine make, model (or type / kind), and year?
2. What is the emissions Tier of the engine? Tier 1, Tier 2, Tier 3, or Tier 4?
3. Please add any additional details on modifications that have been made to the propulsion engine(s) or emissions control systems since purchase.
4. Where does this boat typically travel to and from?
5. Please describe the vessel's primary use.
6. How many days per week is this vessel in use?
7. Which days per week is this vessel in use?
8. Which hours of the day is this vessel in use?
9. Is this vessel used year-round, or just during part of the year?
10. If just during part of the year, which months is it used?
11. Is this vessel operated more or less regularly during any part of the year?
12. Are you willing to allow us to place a GPS logger on your vessel for one month?

For the vessels that are selected for GPS-tracking, we ask you to record the following on a daily basis (if possible):

1. Total time that each engine operated (i.e., the difference of initial and final readout on a given non-resettable hour meter)
2. Total fuel consumed (gallons) during the logged time period. (An estimate of total fuel will be acceptable)

Vessel Types

Ferry: A harbor craft having provisions only for deck passengers or vehicles, operating on a short run, on a frequent schedule between two points over the most direct water route, and offering a public service of a type normally attributed to a bridge or tunnel.

Excursion: A self-propelled vessel that transports passengers for purposes including, but not limited to, dinner cruises; harbor, lake, or river tours; scuba diving expeditions; and whale watching tours. "Excursion Vessel" does not include crew and supply vessels, ferries, and recreational vessels.

Crew and Supply Vessels: A self-propelled vessel used for carrying personnel and/or supplies to and from offshore and in-harbor locations (including, but not limited to, offshore work platforms, construction sites, and other vessels).

Barge: A vessel having a flat-bottomed rectangular hull with sloping ends and built with or without a propulsion engine.

Dredge: A vessel designed to remove earth from the bottom of waterways, by means of including, but not limited to, a scoop, a series of buckets, or a suction pipe. Dredges include, but are not limited to, hopper dredges, clamshell dredges, or pipeline dredges.

Fishing Vessel: A self-propelled vessel that is either: (a) a Commercial Fishing Vessel dedicated to the search for, and collection of, fish for the purpose of sale at market or directly to a purchaser(s); or (b) a Charter Fishing Vessel used for hire by the general public and dedicated to the search for and collection of, fish for the purpose of general consumption.

Work Boat: Vessels used to perform duties such as fire/rescue, law enforcement, hydrographic surveys, spill/response research, training, and construction.

Pilot Vessel: A vessel designed for, but not limited to, the transfer and transport of maritime pilots to and from ocean-going vessels while such vessels are underway.

Tugboat: Any self-propelled vessel engaged in, or intending to engage in, the service of pulling, pushing, maneuvering, berthing, or hauling alongside other vessels, or any combination of pulling, pushing, maneuvering, berthing or hauling alongside such vessels in harbors, over the open seas, or through rivers and canals. Tugboats generally can be divided into three groups: harbor or short-haul tugboats, ocean-going or long-haul tugboats, and barge tugboats. "Tugboat" is interchangeable with "towboat" and "push boat" when the vessel is used in conjunction with barges.

Push Boat/Towboat: Any self-propelled vessel engaged in or intending to engage in the service of pulling, pushing, or hauling alongside barges or other vessels, or any combination of pulling, pushing, or hauling alongside barges or other vessels. "Push boats" is interchangeable with "towboats."

Appendix B: PEMS

Table 21: Field-Calibration Values for the Sensors SEMTECH

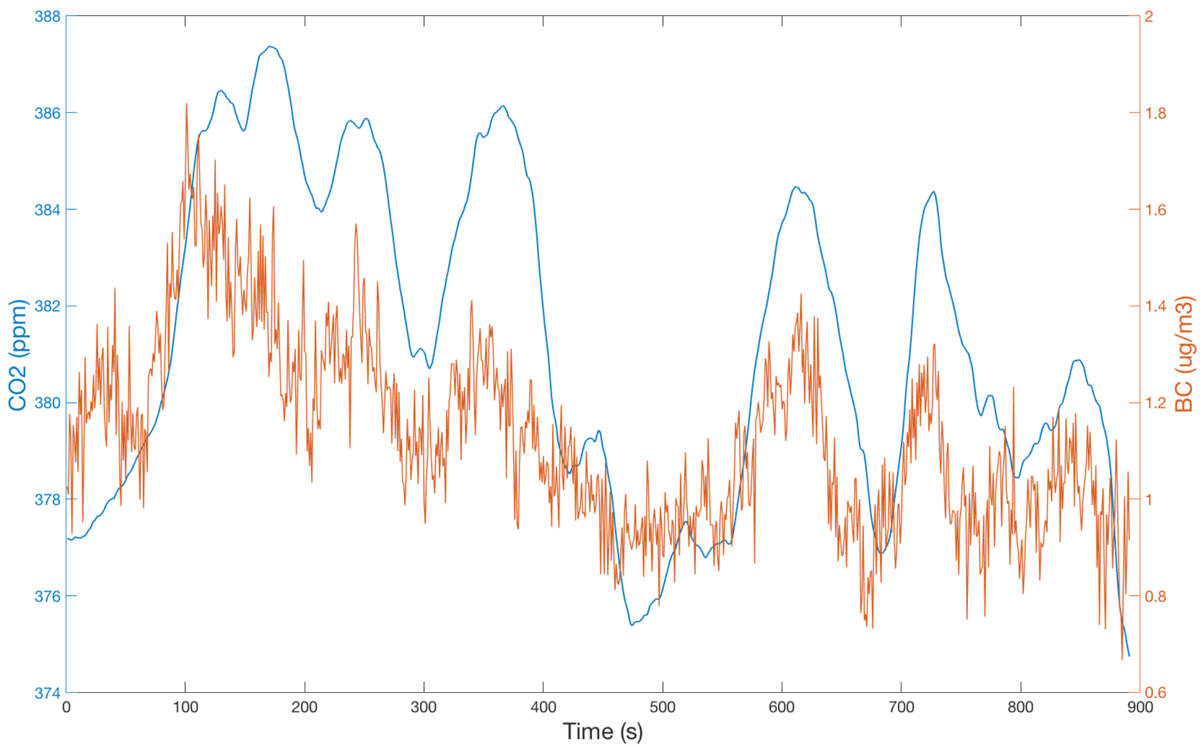
Date	Gas	Reference for Span (ppm)	Initial Zero (ppm)	Initial Span (ppm)	Final Zero check (ppm)	Final Span check (ppm)	Span Initial to Refernce Difference (%)	Span Final to Inital Difference (%)
1/21/2019 Cold Start Vessel A	CO	10080	0	9988.66667	10	9987.333333	-0.906084653	-0.013348468
	CO2	151200	0	150913.33	0	150913.33	-0.189596561	0
	NO	1030	0.293333	1031.89333	5.9	1040.246667	0.183818738	0.80951526
	NO2	250.8	-0.053333	252.186667	2.966667	260.14	0.552897528	3.15374841
	THC	237	-3.266667	238.086667	11.686667	235.451111	0.458509283	-1.106973369
1/22/2019 Vessel A	CO	10080	-10	10005	4.666667	10029.33333	-0.744047619	0.243211724
	CO2	151200	0	151210	-0.004667	151026.67	0.006613757	-0.121241981
	NO	1030	-0.0933	1030.9	4.953333	1037.513333	0.087378641	0.641510622
	NO2	250.8	-0.7	251.39	4.613333	249.86	0.235247209	-0.608616095
	THC	237	18.167	237.4	-2.253333	231.208889	0.168776371	-2.607881634
1/23/2019 Vessel A	CO	10080	-10	9982	15.12	9979	-0.972222222	-0.030054097
	CO2	151200	0	151160	0	151080	-0.026455026	-0.052924054
	NO	1030	0.4267	1029.9	8.3667	1044.3	-0.009708738	1.398193999
	NO2	250.8	0	251.72	3.52	253.58	0.366826156	0.738916256
	THC	237	12.107	237.44	7.2867	226.71	0.185654008	-4.519036388
1/28/2019 Idle and cold start Vessel B	CO	10080	0	10015	0	10021	-0.64484127	0.059910135
	CO2	151200	0	150950	0	150970	-0.165343915	0.01324942
	NO	1030	0.7	1031.4	5.38	1036.2	0.13592233	0.465386853
	NO2	250.8	0	250.8	2.2	252.67	0	0.745614035
	THC	237	8.953	236.67	9.5867	232.47	-0.139240506	-1.774622893
1/28/2019 Post SCR Morning Vessel B	CO	10080	0	9985.3	10	9966.7	-0.939484127	-0.186273823
	CO2	151200	0	150710	-0.001	150760	-0.324074074	0.033176299
	NO	1030	5	1036.9	16.44	1056	0.669902913	1.842029125
	NO2	250.8	1.98	254	2.06	261.9	1.275917065	3.11023622
	THC	237	N/A	N/A	N/A	N/A	N/A	N/A
1/28/2019 Post SCR Evening Vessel B	CO	10080	0	9988.7	2.67	10020	-0.905753968	0.31335409
	CO2	151200	0	150900	6.058	150290	-0.198412698	-0.404241219
	NO	1030	0.0133	1030.7	-5.11	1021.1	0.067961165	-0.931405841
	NO2	250.8	0	250.67	-6.47	243.88	-0.051834131	-2.708740575
	THC	237	N/A	N/A	N/A	N/A	N/A	N/A
1/29/2019 Pre SCR Cold Start Vessel B	CO	10080	0	9989.3	-10	9994	-0.899801587	0.047050344
	CO2	151200	0	150850	-0.06	151310	-0.231481481	0.304938681
	NO	1030	0.147	1030.7	3.1	1034.5	0.067961165	0.368681479
	NO2	250.8	-0.1	250.47	-0.83	250.67	-0.131578947	0.079849882
	THC	237	9.33	237.3	7.03	235.36	0.126582278	-0.817530552
1/29/2019 Pre SCR Morning Vessel B	CO	10080	-6.67	9954.7	-10	9953.3	-1.243055556	-0.014063709
	CO2	151200	-0.06	151030	-0.066667	151060	-0.112433862	0.019863603
	NO	1030	4.25	1036.6	13.08	1052.7	0.640776699	1.553154544
	NO2	250.8	0.29	251.33	6.56	255.93	0.211323764	1.830263001
	THC	237	N/A	N/A	N/A	N/A	N/A	N/A

Calibration values for the Sensors SEMTECH. N/A values during Vessel B testing correspond to non-cold start tests. FID fuel for THC measurement was not allowed on the vessel while it was in operation due to public safety.

Appendix C: South Coast Onshore Plume Capture Measurements

BC concentrations from onshore measurements were often low relative to baseline concentrations and instrument noise, so data were smoothed using a centered, moving average. In this smoothing approach, each individual data point was replaced by the arithmetic mean of the neighboring data points within a given window. Smoothed BC plumes matched well with corresponding CO_2 plumes when superimposed, even in instances where peak BC concentrations were very low (Figure 69). To determine an optimal window size (i.e., the number of data points used for the moving average), we performed statistical and graphical analyses.

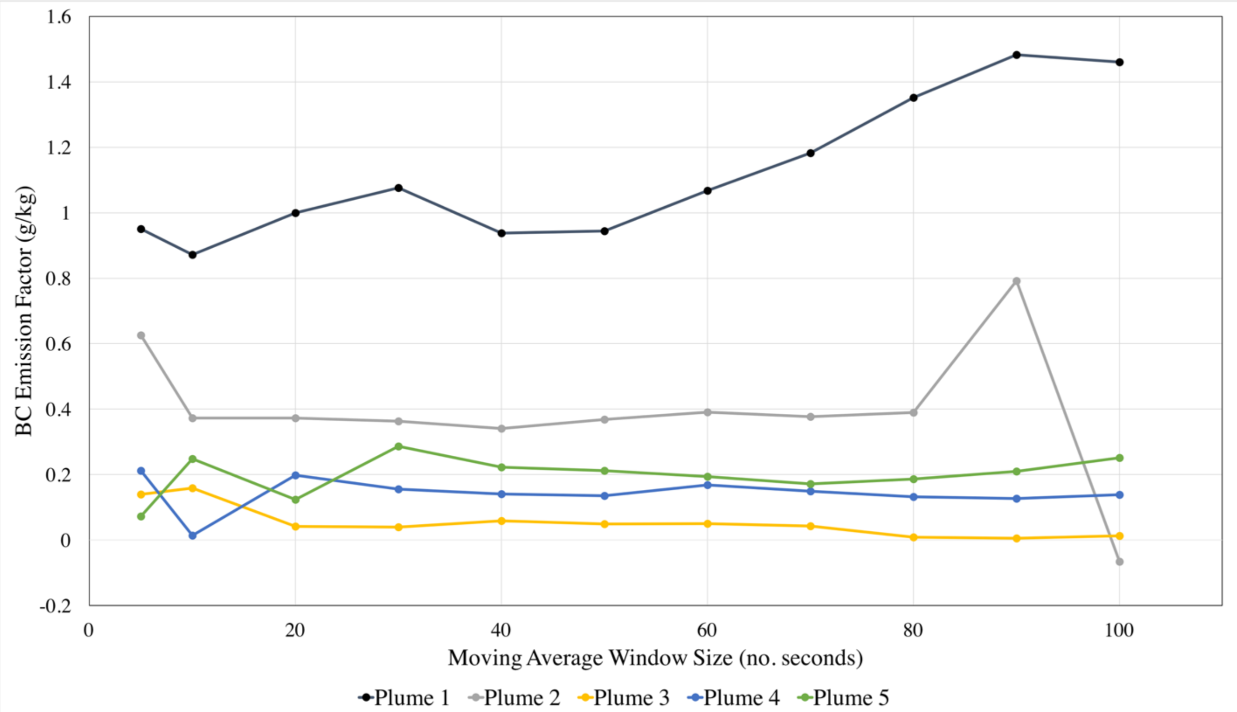
Figure 69: Example of Low Concentration BC Peak and Corresponding CO_2 Signal



Plume 4 ABCD data that has been smoothed with a 40-second moving average (orange) and matched to the corresponding CO_2 plume (blue).

BC emission factors were calculated for five plumes sampled during onshore measurements using smoothed data with window widths ranging from 5 to 100 seconds (Figure 70). Note that the measurements were made at 1 Hz, so each second of sampling corresponds to one data point. BC emission factors for each plume showed the most variability by window width for widths less than 30 seconds and greater than 50 seconds. Explanations for the observed variability are discussed below.

Figure 70: Impact of Different Moving Average Windows on Calculated Emission Factors

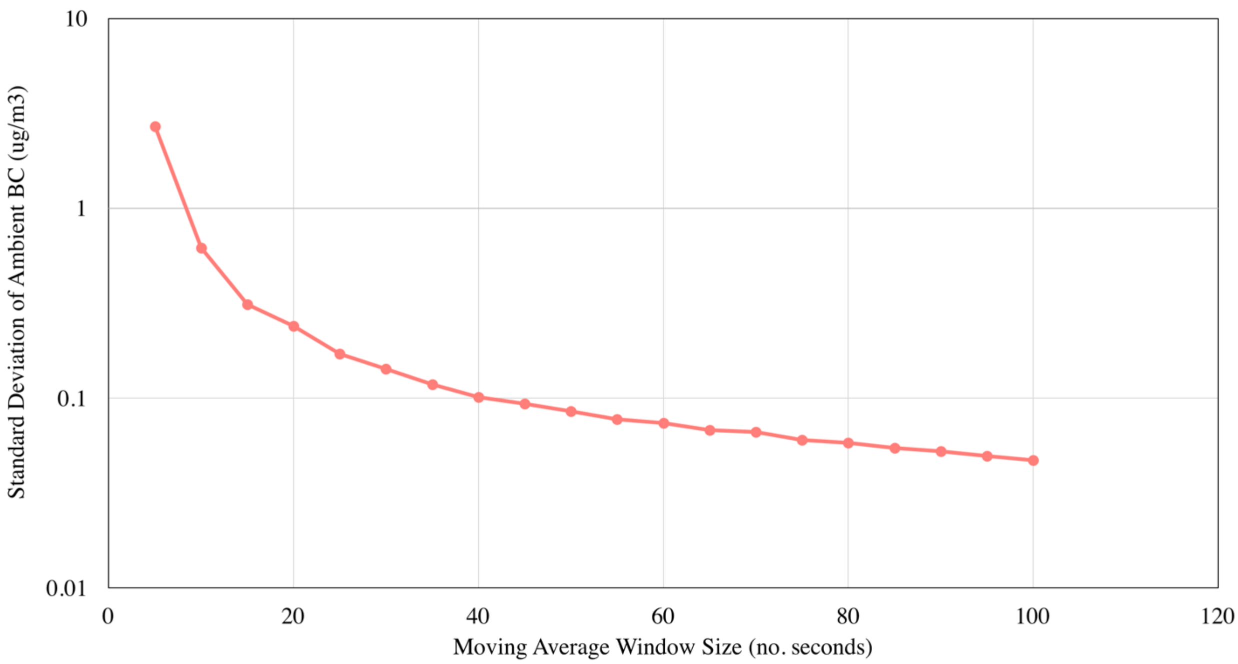


BC emission factors for five different plumes that were computed using smoothed data with varying window widths. The moving average window size corresponds to the number of data points used to smooth the BC data.

Noise in the measurements was analyzed by smoothing 200 seconds of ambient ABCD measurements (i.e., without a plume present) using window widths of 2 to 100 seconds and calculating the resulting standard deviation (Figure 71). The standard deviation decreased exponentially until window size reached 45 seconds. When window widths were increased beyond 45 seconds, the standard deviation of the ambient ABCD measurements responded approximately linearly to increased window size. Therefore, the greatest reduction in noise per increase in window width was achieved at window widths less than 45 seconds long.

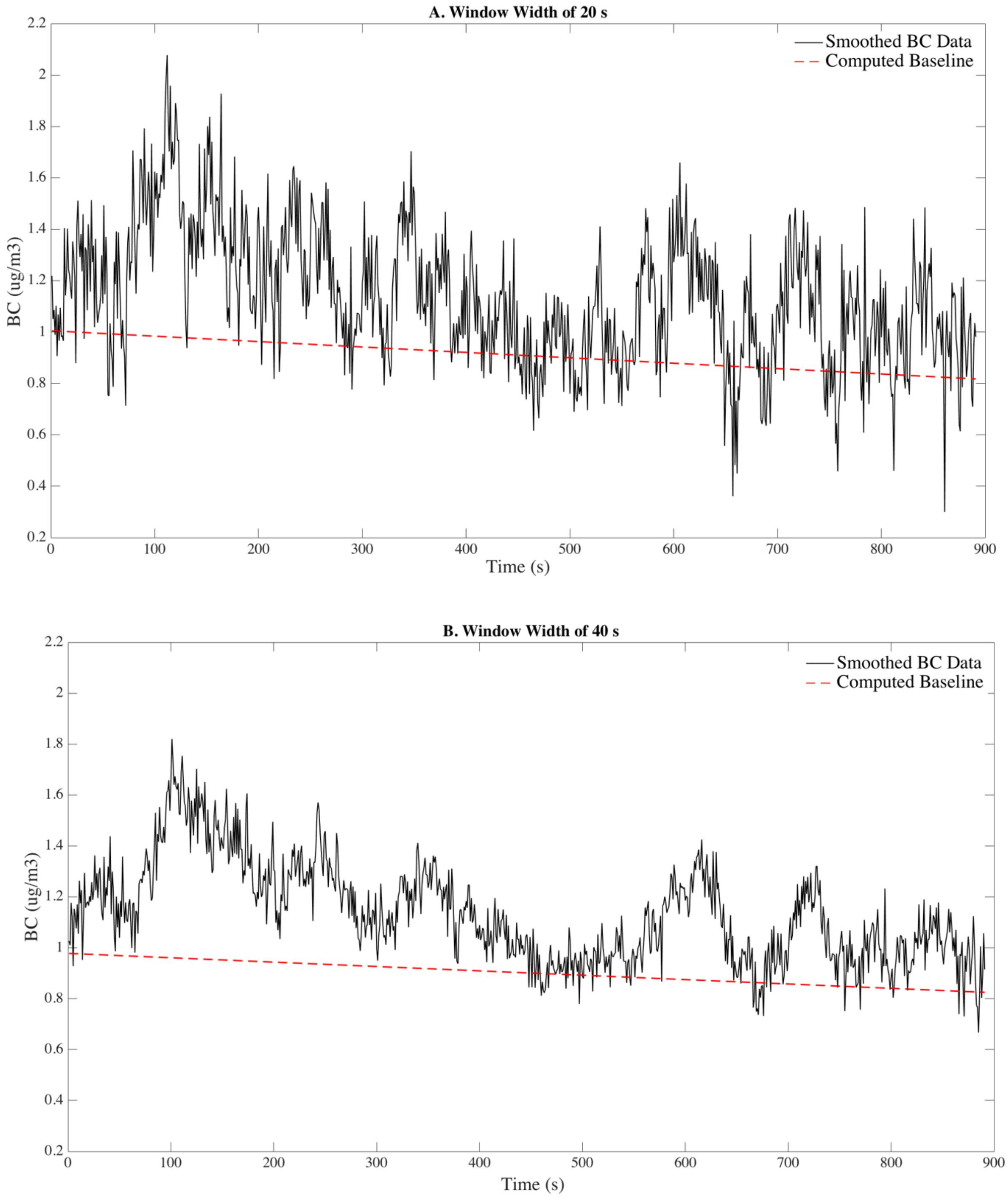
Recall that the moving baseline BC concentrations used to compute emission factors were determined by linearly interpolating between the 10 second averages preceding and following each plume capture (see the Methods section in the main body). By definition, the baseline concentration should be lower than the plume capture concentration, and hence the baseline subtraction should result in only positive BC concentrations. The effect of instrument noise on this baseline subtraction was analyzed by smoothing individual plume captures using window widths that ranged from 10 to 100 seconds. Smoothed plumes and their corresponding baseline BC concentrations were plotted for each window size, as is illustrated by the example comparison shown in Figure 72. When plumes were smoothed using window widths less than 30 seconds, BC concentrations (black line) were occasionally lower than the computed baseline (red dashed line). As window width increased, the noise observed in BC data decreased and fewer BC concentrations fell below the computed baseline. Increasing the window width did not significantly affect the baseline computed for each plume, further corroborating the analysis on smoothing ambient measurements that was discussed above and is shown in Figure 71. Taken together, these results suggest that the variability observed in emission factors for plumes smoothed with narrow window widths (see Figure 70) is likely due to instrument noise influencing the baseline subtraction in the emission factor calculations.

Figure 71: Noise in ABCD Measurements as a Function of Moving Average Window Size



Noise observed in 200 seconds of ABCD measurements of ambient BC after smoothing data with different window widths.

Figure 72: Example of Moving Baseline Calculated with Different Smoothing Windows

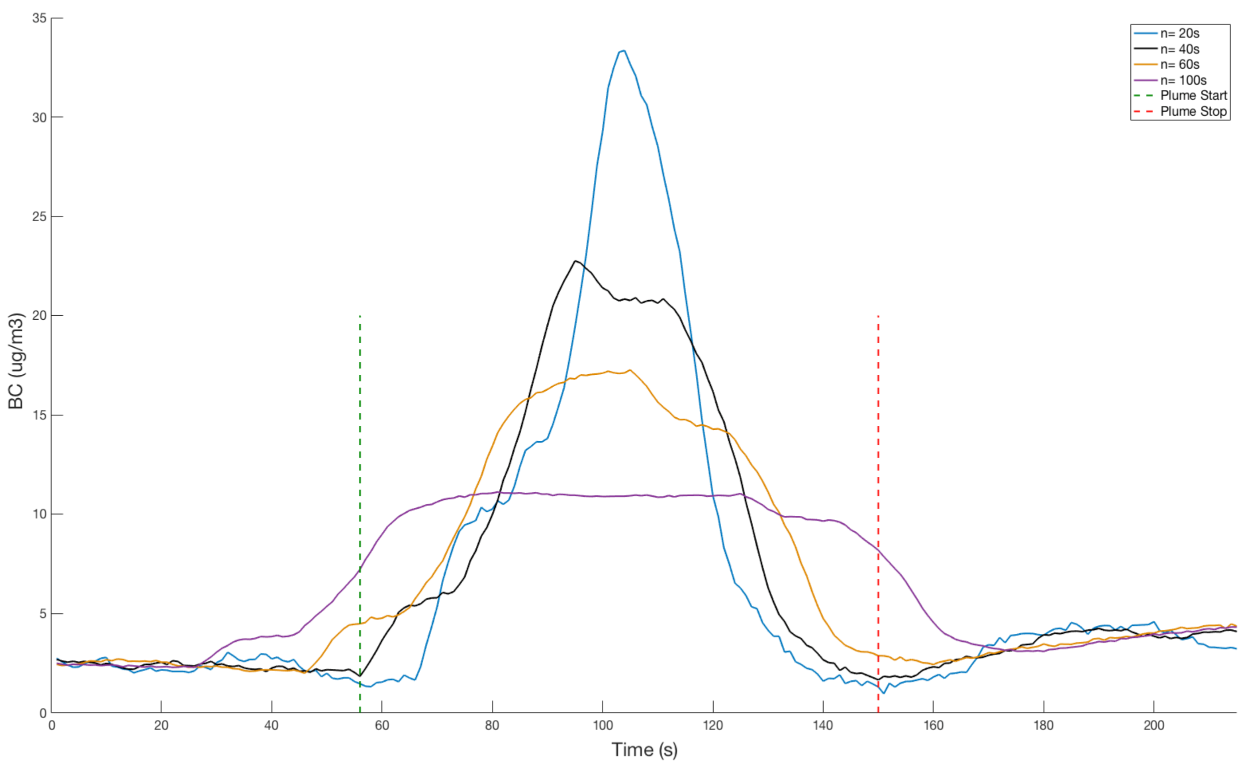


Comparison of the moving BC baseline (red dashed line) calculated for Plume 4 (black) when data were smoothed using a 20-second moving average (A) versus a 40-second moving average (B).

BC plumes from onshore measurements were analyzed graphically after data were smoothed using window widths of 15 to 100 seconds (Figure 73). As window widths became wider, BC plumes became broader. At wide window widths greater than 60 seconds, plumes became so broad that they intersected with nearby plumes such that individual emission factors could not be calculated. At mid-range window widths, plumes did not "spread" enough for nearby plumes to affect the emission factor calculation. This at least partly explains the variability observed in the emission factors for plumes smoothed with broad window widths in Figure 69.

From these analyses, a 40-second moving average was selected for smoothing onshore data. At this window width, a significant amount of instrument noise is reduced (Figure 71) without merging adjacent plumes (Figure 73). BC data smoothed at this window width are graphically similar to corresponding CO_2 plumes, even in cases where peak BC concentrations are very low (Figure 69). This observation suggests that a 40-second moving average is an effective window size to differentiate the measured BC signal from instrument noise.

Figure 73: Effect of Different Moving Average Windows on BC Peaks



Comparison of Plume 2 smoothed with different window widths.