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Authors
Sugrue, Rebecca A
Preble, Chelsea V
Tarplin, Anna G
et al.

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In-Use Passenger Vessel Emission Rates of Black Carbon and Nitrogen Oxides

Rebecca A. Sugrue[1,2], Chelsea V. Preble[1,2], Anna G. Tarplin[1,2,a], Thomas W. Kirchstetter[1,2,*]

[1]Department of Civil and Environmental Engineering, University of California, Berkeley, CA, 94720, USA.

[2]Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA.

[a]Current: Department of Civil and Environmental Engineering, Stanford University, Palo Alto, CA, 94305, USA.

*Corresponding author: twkirchstetter@lbl.gov

Abstract

This study quantified emission factors of black carbon (BC) and nitrogen oxides (NO_x) from 21 engines on in-use excursion vessels and ferries operating in California's San Francisco Bay, including EPA uncertified and Tier 1–4 engines and across engine operating modes. On average, ~60 fuel-based emission factors per engine were measured using a novel combination of exhaust plume capture combined with GPS location and speed data that can be more readily deployed than common portable emissions measurement systems. BC and NO_x emission factors (g kg^{-1}) were lowest and least variable during fast cruising and highest during maneuvering and docked operation. Selective catalytic reduction (SCR) reduced NO_x emissions by ~80% when functional. However, elevated NO_x emissions that exceeded corresponding exhaust standards were measured on most Tier 3 and Tier 4 engines sampled, which can be attributed to inactive SCR during frequent low engine load operation. In contrast, BC emissions exceeded the PM emission standard for only one engine, and SCR systems employed as a NO_x reduction technology also reduced emitted BC. Using these measured emission factors to compare commuting options, we show that the CO_2-equivalent emissions per passenger-kilometer are comparable when commuting by car and ferry, but BC and NO_x emissions can be several to more than ten times larger when commuting by ferry.

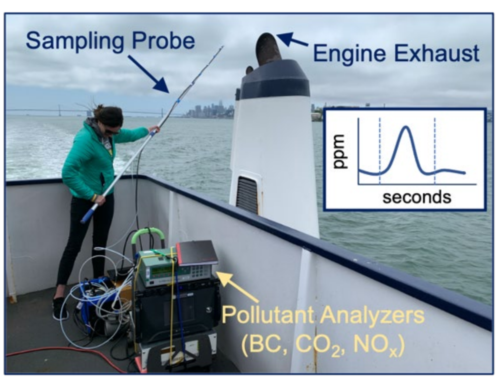
Keywords

selective catalytic reduction, pollutant emission inventory, carbon footprint, diesel exhaust, air pollution, commercial harbor craft, transportation

Synopsis

This study uses a novel approach to quantify pollutant emission rates from in-use passenger vessels and the effectiveness of selective catalytic reduction of nitrogen oxides to support emission inventory development and inform air pollution policy decision-making.

Graphic for Table of Contents (TOC)/Abstract Art



Introduction

Diesel engines are an important source of air pollutants that degrade air quality and contribute to climate change, including nitrogen oxides (NO_x), particulate matter (PM), and black carbon (BC), a major component of diesel PM.[1–3] While most diesel fuel is consumed by on-road vehicles, stricter regulations and broader use of emission control technologies by the on-road fleet mean that off-road engines increasingly contribute a larger portion of remaining emissions.[4–10]

Marine vessels are an off-road source that cause an estimated 60,000 cardiopulmonary and lung cancer deaths each year globally.[11,12] Commercial harbor craft (CHC), including ferries and excursion vessels, are a subset of marine vessels that operate particularly close to shore and nearby communities, unlike other categories of ocean-going vessels. Recognizing these impacts, California has accelerated the adoption of higher tier marine engines that meet more stringent PM and NO_x emission standards set by the U.S. Environmental Protection Agency (EPA).[13,14] Since 2009, all newly purchased vessels must meet the standards for Tier 2 or better engines, and select in-use vessel categories operating in Regulated California Waters must meet Tier 2 or Tier 3 engine standards by the end of 2022 via engine replacement or certification.

As efforts to control CHC emissions continue, it is noteworthy that pollutant emissions rates from in-use CHC have not been well characterized and only a few studies have related emissions to engine operating conditions.[15–22] Additionally, as Tier 4 engines are originally equipped and other engines can be retrofitted with selective catalytic reduction (SCR) to reduce NO_x emissions, it is critical to verify the effectiveness of SCR on in-use vessels. Emission inventories used for air pollution hazard assessments currently rely heavily on outdated datasets and older, controlled engine certification tests.[23] These inventories need be updated with newly measured emission factors that include in-use engine and emission control system operation and performance.

This study measured BC and NO_x emission rates from excursion vessels and ferries operating in California's San Francisco (SF) Bay. Engines on the vessels met a range of emission standards (EPA uncertified and Tier 1–4) and included Tier 3 engines retrofitted with SCR, as described in Table S1 of the Supporting Information (SI). For simplification, we refer to EPA uncertified engines as Tier 0. While the sampled fleet was based in the SF Bay, these vessels comply with national engine emission standards. Therefore, the results of this study are informative of what can be expected as CHC fleets outside of California modernize. The scope of this study was made possible through a novel application of an exhaust plume capture method that had previously been extensively applied to measure pollutant emission rates from on-road heavy-duty diesel trucks.[5,6,24] Owing to the low cost, size, and power consumption of modern sensors and the noninvasive approach of exhaust plume capture, the method is more readily deployable than a traditional portable emission measurements system (PEMS) and enables access to a greater number of engines. More than 1400 short-duration exhaust samples were captured on-board in-use vessels to characterize the influence of operating mode on emission rates and effectiveness of SCR systems. On three vessels, engine data was provided by either the manufacturer or another research team that concurrently deployed PEMS. This data provided fuel consumption rates that informed the weighting of the snapshot emission factors measured in the present study across engine operating modes for each sampled engine. These in-use, operating-mode-weighted emission rates are also compared to EPA emission standards and used to compare the carbon and air pollution footprints associated with commuter travel by ferry and passenger vehicle.

Materials and Methods

Concentrations of carbon dioxide (CO_2), BC, and NO_x were measured in the diluted exhaust from the main engines of ferries and excursion vessels. In total, 25 tests were conducted on 21 engines on 14 vessels, as summarized in Table S2. Emissions from one engine were measured while testing two different fuel types, and three engines were measured under two emission control modes (enabled or disabled SCR) for a total of 25 engine tests.

During all tests, an Aerosol Black Carbon Detector (ABCD)[25] and SBA-5 (PP Systems) were used to measure BC and CO_2, respectively. Both analyzers are relatively low cost, report concentrations at a frequency of 1 Hz, and are small and battery powered. These features made them convenient to carry aboard and use in this application, especially when compared to a traditional PEMS method that is more invasive and, therefore, more difficult to deploy on a large number of vessels. A NO_x analyzer meeting those requirements does not currently exist. Therefore, NO_x was measured on a subset of the vessels where plug-in power was available, using a research-grade EcoPhysics CLD64. For this subset of 10 tests, research-grade CO_2 (LI-7000, LI-COR) and BC (Aethalometer AE33, Magee Scientific) analyzers were used in addition to the corresponding lower cost analyzers. Analyzer specifications are provided in Table S3.

Prior to sampling onboard, CO_2 and NO_x analyzers were calibrated with certified zero and span concentration gases, and the zero-response of BC analyzers was verified by sampling with a particle filter on their inlets. Post sampling, concentration data was corrected for sampling artifacts and instrumental errors, as described in the SI.

During sampling, a pole was used to extend gas and particle sample lines into the engine exhaust for approximately 5–10 seconds per minute throughout the course of each ferry and excursion vessel trip, as shown in Figure S1. When not extended into the exhaust plume, the sample lines were oriented so that clean ambient air was sampled. This plume capture method generates peaks in the concentration time series related to the pollutants emitted and fuel burned by the engine.

Pollutant concentration peaks that correspond to each short-duration plume sample were integrated to calculate fuel-based BC and NO_x emission factors using a carbon balance method (Equation 1). The emission factor for pollutant P (EF_P) has units of g of pollutant emitted per kg of fuel burned and is calculated over the time interval $t_1 \leq t \leq t_2$, which corresponds to the onset and end of the rise above baseline concentration of each pollutant. 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, the weight fraction of carbon in diesel fuel (w_c = 0.87) converts that ratio to a per mass of fuel burned basis, and the factor of 10^3 converts units from g to kg of fuel. This method assumes that all fuel carbon is oxidized to CO_2 during combustion, such that carbon monoxide and volatile organic compounds are comparatively negligible in the total carbon balance.[24,26]

$$EF_P\ [g\ kg^{-1}] = \frac{\int_{t_1}^{t_2}([P]_t - [P]_{t_1})}{\int_{t_1}^{t_2}([CO_2]_t - [CO_2]_{t_1})} \cdot \frac{44}{12} \cdot w_c \cdot 10^3 \qquad (1)$$

The vessels in this study fell within two main types of travel routes, short-haul and long-haul (noted in Table S2). Excursion vessels tended to operate at slower speeds as they traveled short-haul routes in a loop between tourist attractions (e.g., SF to the Golden Gate Bridge and Alcatraz Island). Commuter ferries included shorter routes between Oakland and SF and longer routes between SF and Vallejo, with some vessels specifically noted as high-speed ferries.

Pollutant emission factors were averaged within four different engine operating modes: docked, maneuvering, slow cruising, and fast cruising. When docked, engines were either idling or pushing the vessel against the dock to allow passengers to board and disembark. Maneuvering operation occurred when the vessel was entering or exiting the harbor or moving around tourist attractions. These activities were recorded in an experimental log during each trip. Cruising encompasses all other times when the vessel was moving at a steady speed between destinations; slow cruising occurred while traveling along corridors, in harbors, or between tourist destinations, and fast cruising occurred on long stretches between destination points. The distinction between slow and fast cruising for all vessels was based on field notes and vessel speed, with slow cruising defined as 12.4–31.0 km h^{-1} and fast cruising as >31.0 km h^{-1} (see Figure 1 and SI for additional details). Vessel speeds were measured at 0.2 Hz using a GPS logger (GlobalSat DG-500).

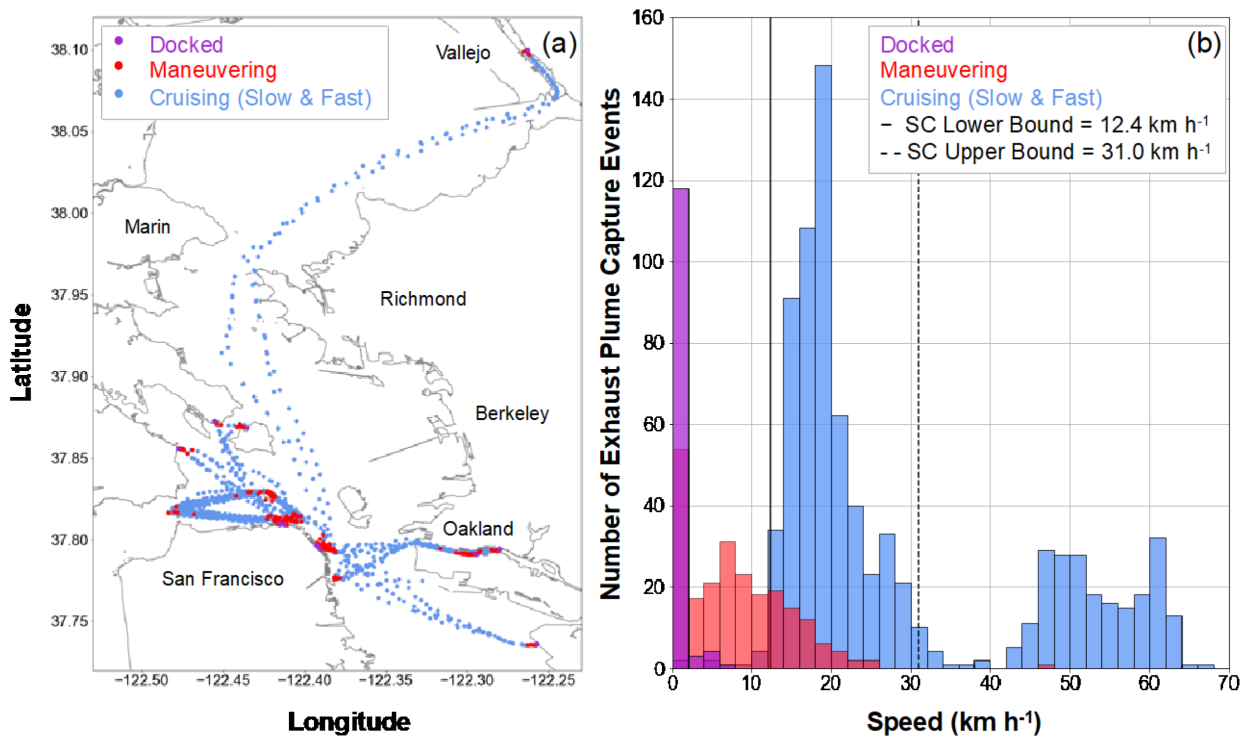


Figure 1. (a) Map of San Francisco Bay overlaid with points depicting locations of on-board exhaust plume measurement locations and (b) distribution of vessel speeds during all exhaust plume measurements (n = 1438) categorized by engine operating mode (docked, maneuvering, or cruising). Cutoffs for slow and fast cruising are shown as the solid and dashed lines, respectively.

Using Equation 2, individual emission factors characterized by operating mode were averaged and then weighted based on the amount of fuel consumed in each mode over the course of a trip to compute a single mode-weighted pollutant emission factor (EF_{wtd}) for each vessel. Fuel consumption rates for each operating mode were assumed based on engine data concurrently collected by other teams from three representative vessels: (i) a short-haul (SH), Tier 2 excursion vessel; (ii) a long-haul (LH), Tier 3 commuter ferry; and (iii) a long-haul, high-speed (LH/HS), Tier 4 commuter ferry. See Table S4 in the SI for additional details and data sources. The engine data showed that most of the fuel is consumed in the cruising mode, so those mode-average emission factors were weighted more heavily. For short-haul excursion tours and ferry commutes, slow and fast cruising (SC + FC) together accounted for 90% of fuel consumption during a trip and all other modes (docked and maneuvering, D + M) combined were weighted by 10%. Long-haul ferry commutes follow a different fuel consumption pattern that is dominated by fast cruise operation under high engine loads (Table S4), so slow cruise emission factors were combined with those measured during docked and maneuvering operation for these vessels. Fast cruising (FC) values were weighted by 90% for the long-haul ferries and by 96% for designated high-speed, long-haul ferries, while docked, maneuvering, and slow cruising modes (D + M + SC) were together weighted by the remaining 10% and 4%, respectively.

$$EF_{wtd} = \left\{ \begin{array}{c} 0.90\left(\overline{EF}_{SC\,+\,FC}\right) + 0.10\left(\overline{EF}_{D\,+\,M}\right),\ \ SH \\ 0.90\left(\overline{EF}_{FC}\right) + 0.10\left(\overline{EF}_{D\,+\,M\,+SC}\right),\ LH \\ 0.96\left(\overline{EF}_{FC}\right) + 0.04\left(\overline{EF}_{D\,+\,M\,+\,SC}\right),\ \ LH/HS \end{array} \right\} \qquad (2)$$

Another objective of this study was to evaluate the performance of SCR systems that have been installed as retrofits on Tier 3 engines or as original equipment on Tier 4 engines. In this study, the SCR system on a subset of Tier 3 engines was manually disabled such that the impact of SCR operation on NO_x and BC emission factors could be directly evaluated (Table S2). The other engines equipped with SCR systems were sampled under their normal operation, without any intervention. None of the vessels in this study were equipped with diesel particle filters.

Results and Discussion

Between January and November 2019, 1438 BC and 589 NO_x emission factors were measured during the 25 tests of 21 engines on 14 vessels in the SF Bay. Approximately 65% of these plume capture events were during slow and fast cruising, 25% during maneuvering, and 10% while docked. Details of this sampling, including route type, engine tier, fuel type, SCR activity, orientation of engine exhaust, and auxiliary engine operation, are specified in Table S2. The present study focuses on emissions differences due to engine tier, operation mode, and SCR activity, as urea dosing depends on engine operation. For the results below, engine tests are categorized as Inactive when there is evidence that urea was not dosing for a majority of the vessel trip or when SCR systems were manually disabled. All other SCR engine tests are noted as Active. Other factors such as fuel type showed comparatively minimal impact on the emission trends. Emission factors reported below are average values ± 95% confidence intervals, unless otherwise noted.

In-Use Emissions Trends

Mode-weighted and mode-specific average BC and NO_x emission factors measured on vessels with Tier 0–4 engines are shown in Figure 2 and reported in Tables S5 and S6. Across the mode-weighted averages determined for each of the 25 engine tests in the present study, the mean BC emission factor for the sampled vessel fleet is 0.34 ± 0.03 g kg^{-1}. This result is similar to average BC emission factors reported for passenger vessel fleets measured in Texas (0.36 g kg^{-1}) and California (0.30 g kg^{-1}) in 2006 and 2010, repsectively.[15,18] BC emission factors were highest during maneuvering (0.44 ± 0.31 g kg^{-1}) and lowest during fast cruising (0.27 ± 0.02 g kg^{-1}). Docked and maneuvering BC emissions were more variable than during cruising. It is important to note that much of the docked mode variability is driven by a single test with only two plume capture events (engine test 9, equal to 1.09 ± 9.63 g kg^{-1}).

NO_x emissions were measured on a subset of engines (tests 7, 17–25): Tier 2 without SCR, Tier 3 with retrofit SCR, and Tier 4 that were originally equipped with SCR. The average NO_x emission factor of this subset—not including the Tier 0 and non-SCR Tier 3 engines sampled in this study—was 24.1 ± 1.4 g kg^{-1}. Average NO_x emission rates were highest when docked (59.9 ± 8.4 g kg^{-1}) and lowest and least variable during fast cruising (19.2 ± 1.2 g kg^{-1}), as shown in Figure 2b. Further, NO_x emission factors during slow and fast cruising were lower than when docked and maneuvering. As discussed in further detail below, this difference is most likely attributable to SCR operation, as it is expected that engine exhaust temperatures exceed the minimum requirement for SCR system urea dosing with the high engine load and power conditions typical of cruising operation.[27]

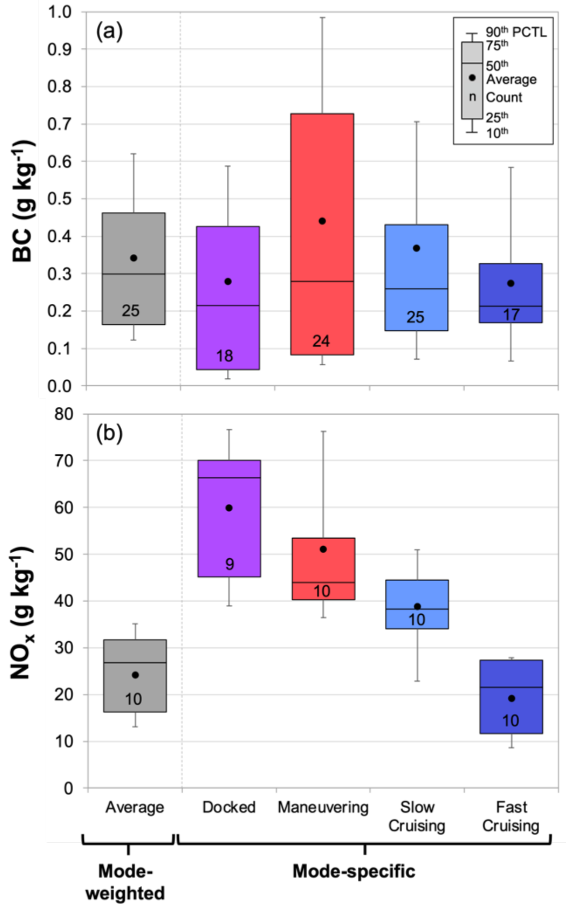


Figure 2. Distributions of average mode-weighted and mode-specific (a) BC and (b) NO_x emission factors from the sampled engine tests. Mean values are shown as a closed circle and the number of engine test averages included in each distribution is listed. PCTL refers to percentile.

Average BC and NO_x emission factors by engine tier are shown in Figure 3 and reported in Tables S5 and S6. The trend in BC emission rates followed the increasingly more stringent exhaust standards set by the EPA for each engine tier, which were highest for Tier 0 engines (engine tests 1–2) and progressively lower for each subsequent tier (Table S1, Figure 3a). On average, Tier 4 engines (engine tests 24–25) emitted 92% less BC per kg of fuel than Tier 0 engines. BC emission factors from SCR-equipped Tier 3 engines were 29% lower when the SCR system was active (engine test 23) rather than inactive (engine tests 17–22). Relative to Tier 3 engines without SCR (engine tests 14–15), BC emissions from those with SCR retrofits were

31% lower with inactive SCR and 51% lower with active SCR. Thus, presence of SCR appears to offer a co-benefit of reducing BC emissions in addition to the primary intention of reducing NO_x emissions.

Unlike the BC trend, NO_x emission factors did not decrease with engine tier and increasingly stringent EPA emission standards (Figure 3b). Rather, the main feature that stands out is the marked reduction in NO_x emissions with active SCR. This effect is most pronounced for the active SCR system on the Tier 3 engine, which reduced NO_x emissions by 83% compared to Tier 3 engines with inactive SCR; this is similar to the 95% reduction seen on an SCR-retrofitted Tier 2 tugboat previously studied.[20] SCR systems on the Tier 4 engines were much less effective, reducing NO_x emissions by only 52% relative to the inactive SCR on Tier 3 engines. Though these differences in SCR performance warrants further study, they may be related to engine tuning. Similar to how heavy-duty diesel truck engines with diesel particle filters and SCR are tuned, Tier 4 engines with original SCR systems may be tuned for higher engine-out NO_x and lower engine-out PM compared to Tier 3 engines.[6] In use, however, SCR is less effective under low engine load conditions like docked or maneuvering modes, when engine exhaust temperatures likely fall below the minimum temperature required for urea injection (Figure S4).[21]

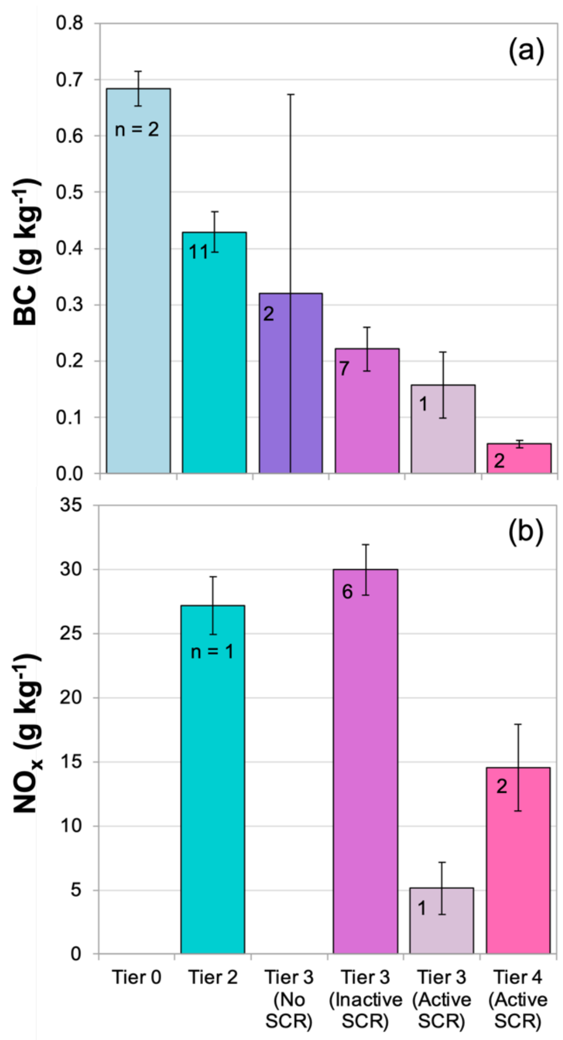


Figure 3. Average (a) BC and (b) NO_x emission factors for each sampled engine tier. The number (n) of engine tests included each average is noted. The error bars represent the 95% confidence intervals about the mean value.

SCR Effectiveness

The NO_x reduction performance of Tier 3 engines retrofitted with SCR was explicitly evaluated using two different approaches. First, emissions were measured during a vessel trip when the SCR system was manually disabled and then again with the same SCR system enabled, while all other factors like route and operating modes remained the same. Second, SCR data was provided by the vessel operator and used to evaluate SCR operation relative to measured NO_x emission factors.

Figure 4 shows the NO_x emission factor distributions for two engine tests during the docked, maneuvering, and cruising (combined slow and fast) operating modes with the SCR system enabled (engine test 23) and intentionally disabled (engine test 22). On average, tailpipe exhaust NO_x emission factors were ~70% lower in the docked and maneuvering modes and ~90% lower while cruising when the SCR system was enabled. However, the SCR performance was not uniformly effective throughout the docked and maneuvering modes, as indicated by the skewed emission factor distribution: mean values were much greater than median values, and 90^{th} percentile NO_x emission rates were comparable to those measured when SCR was intentionally disabled. Periods of elevated NO_x emissions that caused this skewness likely occurred during intermittent high engine load operation to push the vessel steady against the dock, leading to high engine-out NO_x that was not scrubbed in the SCR because engine exhaust temperatures fell below the temperature required for urea injection.

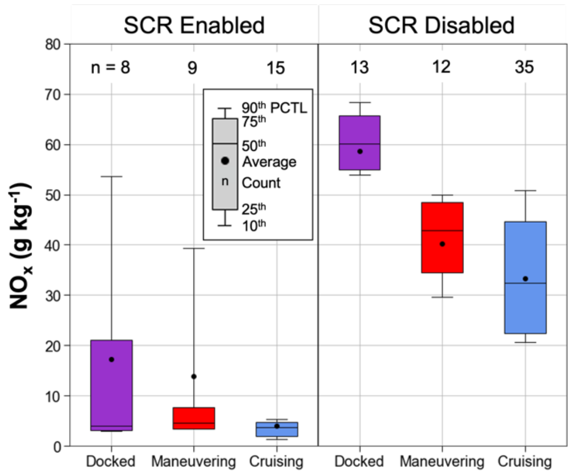


Figure 4. Distributions of operating-mode-specific tailpipe exhaust NO_x emission factors measured on a ferry with a Tier 3 engine, where the retrofit SCR system was enabled (left panel, engine test 23) and intentionally disabled (right panel, engine test 22). The number of emission factors included is noted above each distribution. The cruising distribution includes both slow and fast cruising emission factors.

Figure 5 shows the SCR data from engine test 17 and the corresponding NO_x emission factors. As shown in Figure 5a, urea injection was intermittent for a majority of this route, but there were no reported SCR system errors. NO_x emission rates decreased to <10 g kg^{-1} following urea injection and increased to ~40–70 g kg^{-1} minutes after urea injection stopped. As further illustrated in the map of this vessel's roundtrip route between Oakland and SF (Figure 5b), the lowest NO_x emission factors were measured when the ferry was cruising at high speeds across the SF Bay, while elevated NO_x emissions occurred when the ferry was docked, maneuvering, and slow cruising between docks in the Oakland Inner Harbor. An analogous pattern in NO_x emissions was observed for the newest ferry measured in this study that featured a Tier 4 engine originally equipped with an SCR system (Figure S5). Though data on the urea injection rate was not available for this ferry, the operator confirmed that there were no SCR system errors. It stands to reason that the elevated NO_x emissions occurred when the system stopped injecting urea into the catalyst because exhaust temperatures dipped below the minimum threshold during docked, maneuvering, and slow cruise operation, as was previously described from measurements on-board a New York-based ferry equipped with SCR.[21] These results highlight the importance of engine operation and vessel route on SCR effectiveness for NO_x reduction.

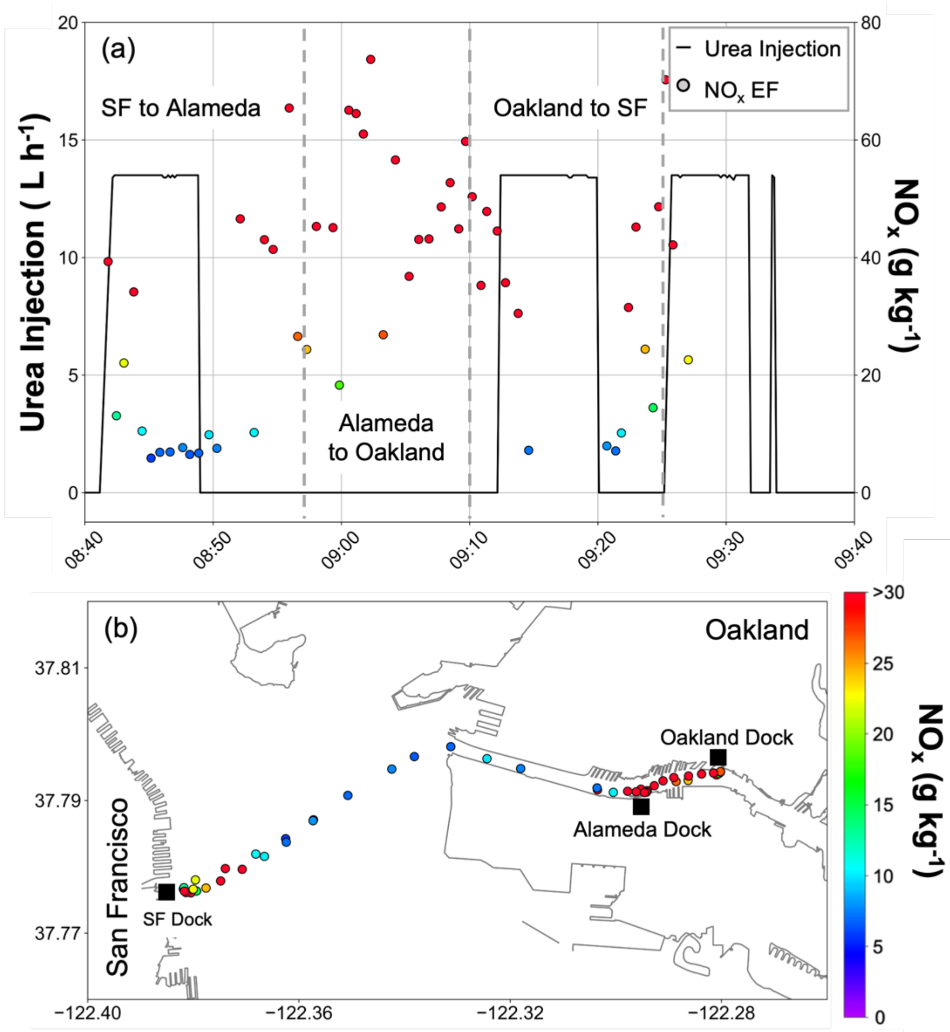


Figure 5. (a) Time series of simultaneously measured urea injection rate (black line) and tailpipe exhaust NO_x emission factors (circles) measured on a ferry with a Tier 3 engine with enabled SCR system (engine test 17). NO_x emission factors are reported on the secondary vertical axis and are also indicated by the color scale. Vertical lines and labels indicate the ferry's progress over the roundtrip between SF and Oakland. (b) Corresponding map of measured NO_x emission factors, which were greater during docked, maneuvering, and slow cruise operation compared to the fast cruising in the middle of the SF Bay. Docks are labeled and shown as black squares.

Comparison to EPA Emission Standards

The emission factors measured in this study are compared to EPA exhaust emission standards, which all engines are required to meet during laboratory certification testing. For this comparison, measured operating-mode-weighted average BC and NO_x emission factors for each engine test were converted from fuel- to power-based units using typical values for brake specific fuel consumption (BSFC), as described in the SI and reported in Table S7. Figure 6 shows the ratios of these converted average BC and NO_x emission factors and the corresponding EPA PM and NO_x emission standards. It should be noted that BC is a major but not sole component of diesel PM, such that real-world PM emission rates may be larger than the reported BC emission rates.

In this study, measured BC emission rates were less than the corresponding PM emission standards by 10–70% for all but one engine (Figure 6a). The in-use NO_x emission rates exceeded corresponding exhaust standards for most Tier 3 engines sampled, and Tier 4 engines were ~1.9 times the emission standard (Figure 6b). Note that the SCR system was intentionally disabled during engine tests 18 and 20–22, however, these engines are held to a Tier 3 standard that is independent of SCR retrofit. Though the in-use measurements presented here did not follow procedures to verify compliance with EPA standards, this work highlights that these standards should not be the default assumption in emission inventories.

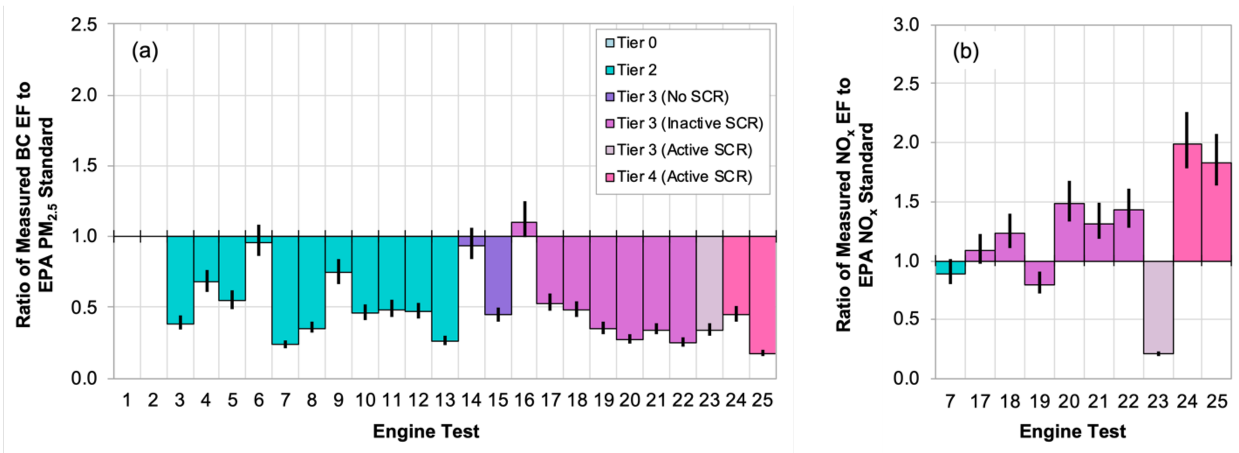


Figure 6. Ratios of mode-weighted average (a) BC and (b) NO_x emission factors measured for each engine test and their corresponding EPA PM and NO_x emission standards, respectively. The error bars represent uncertainty in actual BSFC due to engine operation variability, showing the range of ratios if the minimum and maximum values from Table S4 were used instead of the average. Tier 0 engines are not EPA certified, so the emission factors for engine tests 1–2 are not compared to a PM emission standard.

Commuter Emissions Footprint

To put these results into meaningful context, we consider the pollution and carbon footprints of commuting by ferry versus passenger vehicle. As an example, we compare the NO_x, BC, and CO_2-equivalent (CO_2-eq) emissions from modern light-duty, gasoline-fueled vehicles and diesel-fueled ferries with engines ranging Tier 0–4, including Tier 3 engines with inactive and active SCR retrofits. The following inputs and assumptions are used in this analysis.

BC and NO_x emission rates for commuting by passenger car were assumed to be 0.02 g BC kg^{-1} and 2.29 g NO_x kg^{-1}, based on light-duty vehicle fleet average values measured in the SF Bay Area.[26] BC and NO_x emission rates for each ferry engine type are reported in Tables S5 and S6, and emissions from both main engines on the ferries are assumed equal and summed. Ferry and light-duty car occupancies are assumed to be 200 and 1.18 passengers, respectively. The former represents 50% capacity for the observed ferries and the latter is the national average occupancy for a work commute.[28] The ferry fuel economy (0.2 km L^{-1}) was derived from engine data collected from the two long-haul ferries, as described above and detailed in Table S4. The 2020 national average fuel economy for passenger vehicles, 10.6 km L^{-1}, was used.[29] Conversion of BC and NO_x to CO_2-equivalents (CO_2-eq) is based on 20-year global warming potential (GWP) values of 3200 and –2.4, respectively.[30,31] Results for GWP values on a 100-year time horizon are reported in the SI.

Following these assumptions, emission rates of NO_x, BC, and CO_2-eq on a per passenger-km basis were calculated for each commute option, as summarized in Table S8 and shown in Figure 7 as emission ratios for each ferry engine type relative to light-duty vehicles. Across all engine tiers, ferries emit 1.6–9.4 and 2.0–27.1 times more NO_x and BC per passenger-km, respectively, than light-duty vehicles. Conversely, the net CO_2-eq (20-year) emissions per passenger-km is 1.0–1.3 times higher for the typical passenger vehicle than ferries. For both the passenger vehicle and ferries, the carbon footprint of each commute mode is overwhelmingly dominated by CO_2 emissions. The data reported in this study can be adapted to consider other scenarios, for example, with different route distances or vehicle and ferry occupancy.

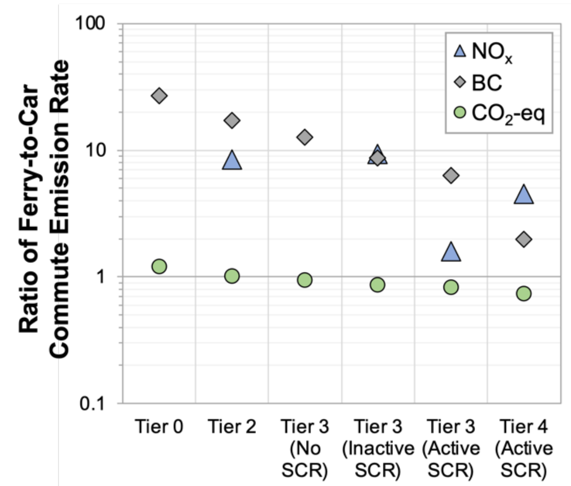


Figure 7. Ratio of ferry to light-duty vehicle NO_x, BC, and CO_2-eq (20-year GWP) emissions per passenger-km. Here, ratios greater than 1 indicate that commuting by ferry results in more pollution or carbon emissions than a commute by passenger car, and vice versa for ratios less than 1. A very small, negative contribution of NO_x emissions is not included in the reported CO_2-eq emissions value for Tier 0 and 3 vessels, as there were no on-board NO_x measurements for these engines.

As shown in this study, BC emission rates—a proxy for toxic, carcinogenic diesel PM—from ferries are lowest for Tier 4 engines. Thus, the disparity in BC emissions will decrease overtime as ferry fleets modernize. However, these results also indicate that NO_x emissions reductions from SCR systems may not be fully achieved due to frequent operation at low engine loads. This finding warrants further study to understand if it is generally true of a larger number of vessels. The results of the commuter analysis highlight the dependence on ridership levels: increasing ferry occupancy will help reduce the per-passenger air pollution and carbon footprints in comparison to light-duty vehicles. Whereas this analysis is illustrative, a health impacts assessment would further consider the proximity of emissions to population centers, as it is vital to consider where the pollution is occurring with respect to where people reside and breathe.

Supporting Information

Detailed description of materials and methods, BC and NO_x emission rates categorized by engine tier and engine test, and supporting figures and tables (Figures S1–S5 and Tables S1–S8)

Acknowledgements & Dedication

This paper is dedicated to our colleague and friend, Professor George Ban-Weiss, who left us too soon.

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