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Remote Sensing of Emissions from In-Use Small Engine Marine Vessels

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ABSTRACT: This paper reports the first use of a remote sensing device to measure emissions from in-use marine vessels. Emissions from 307 small marine vessels were measured as they passed through the Hiram M. Chittenden locks near Seattle, WA. Of these vessels, 89 were matched to state registration information to allow for further analysis of emissions vs model year, fuel type, and engine type. Emission factors are reported for CO, HC, and NO_x in grams of pollutant per kilogram of fuel. The measured emission factors generally agreed with those derived from laboratory studies. HC emissions are disproportionately skewed across the fleet where 40% of the emissions come from just 10% of the fleet. These are most likely due to the remaining two-stroke engines in the fleet. CO and HC emissions show no improvement with newer vessels.

INTRODUCTION

On-road sources dominate the mobile source emissions inventories of carbon monoxide (CO), hydrocarbons (HC), and the oxides of nitrogen (NO_x).[1] However, these sources have seen stricter regulations over the last several decades leading to significantly reduced on-road emissions, thus allowing other mobile sources to gain an increasing proportion of the total inventory.[2,3] Nonroad spark ignition (gasoline) mobile sources now make up 23% and 26% of mobile source CO and HC emissions, respectively.[4] Nonroad compression ignition (diesel) engines contribute 27% of mobile source NO_x which now exceeds the total NO_x emissions from on-road gasoline engines.[5] Local and regional air quality is also affected by commercial vessels, such as tug boats and fishing vessels, as well as recreational vessels.[7] Washington state has 258 000 registered boats, and although this constitutes only 5% of all registered vehicles, boats are the next largest category after automobiles and light trucks.[8] In fact, boat registrations are nearly double that of truck tractors, buses, and motorcycles combined. On the basis of data from Maine's 2002 National Emissions Inventory and the MANE-VU (Mid-Atlantic/Northeast Visibility Union) 2002 Emissions Inventory, recreational vessels emit 7574 tons of HC which make up 5% of the total Maine inventory and 15% of the mobile source inventory.[9] Emissions of HC and NO_x are of concern due to their involvement in the production of ground level ozone. These nonroad, mobile sources such as construction equipment, aircraft, locomotives, and marine vessels are now under increased regulatory scrutiny.[6]

Determining the contribution of nonroad sources to the total emissions inventories, such as the Maine study above, involves significant uncertainty which is generally due to the lack of in-use data, fuel consumption, and activity level.[10] Instead, inventories rely on a number of assumptions including manufacturer test data rather than in-use testing and, at best, using regional activity and fuel consumption data applied to the local level.[10] Models with this uncertainty can then lead to disagreement. The nonroad emission contributions reported by the U.S. EPA and California's OFFROAD models are reportedly high if fuel consumption data are used rather than activity estimates.[11,12] In the marine sector, the least well studied components are commercial marine vessels and recreational vessels.[7,10] Previous studies of emissions from the engines of these vessels have been confined to a laboratory setting[13−15] with only one study of in-use emission factors published to date.[7] This previous in-use study provides emission factors for 116 plumes encountered from small marine vessels. Determination of fuel type was not confirmed but was assumed based on characteristic NO_x/CO ratios.

New U.S. EPA marine regulations began in 2010 and affect gasoline vessels including outboard engines, personal watercraft, and sterndrive/inboard engines. These standards require HC+NO_x and CO reductions of 70% and 50%, respectively, from new sterndrive/inboard engines. Outboard and personal watercraft engines are required to reduce HC+NO_x by 60%.[4] Previous regulations required, in essence, that two-stroke outboard engines be phased out and replaced with four-stroke engines over a 9 year period from 1998 to 2006.[16] This switch was designed to reduce HC emissions from gasoline outboard engines by 75%. Note, the use of "two-stroke" in this paper is

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meant to indicate a gasoline engine and not a supercharged, two-stroke diesel engine.

With government agencies efforts to model and regulate emissions from these crafts, having only a limited amount of data restrict the efforts to increase certainty of the models and determine the real-world effectiveness of the new regulations. The following study increases the number of in-use emission measurements of small marine craft 3-fold from the previously available data as well as provides vessel characteristics by matching to state licensing records

EXPERIMENTAL SECTION

Apparatus. Emissions from in-use marine vessels were measured noninvasively by a remote sensing device (RSD) that uses open-path optical spectroscopy to analyze CO, HC, nitric oxide (NO), and nitrogen dioxide (NO_2) emissions.[17] The RSD employed in this study was the Fuel Efficiency Automobile Test (FEAT) which has been discussed previously for on-road light-duty[18−21] and heavy-duty vehicles [22−24] as well as nonroad applications such as snowmobiles[25] and locomotives.[26] The system is briefly described below; however, a detailed review of the system exists.[17] FEAT consists of a light source that directs a collinear UV/IR beam of light across a roadway to a detector unit housing UV spectrophotometers for measuring NO and NO_2 and non-dispersive IR detectors to measure CO_2, CO, and HC. The FEAT measures the ratios of pollutants to CO_2, from which grams of pollutant per kilogram of fuel burned can be calculated based on a carbon mass balance.[17] Although the system is HC calibrated with propane, a correction factor determined by Singer et al. is used to adjust the measured HC ratio to reflect a measurement determined by a flame ionization detector (FID).[27] The instrument was calibrated daily with the use of two certified gas mixtures (Praxair; Tacoma, WA) (1) 6.01% CO_2, 6.06% CO, 6190 ppm propane, and 3016 ppm NO in N_2, (2) 520 ppm NO_2 and 14.87% CO_2 in air. Accuracy is achieved by comparison to the certified cylinders which have reported uncertainties of ±5% or better. Accuracy and precision of the instrument have been discussed elsewhere; however, the instrument has been compared during an in-use study to on-board gas analyzers and agreed within ±5% and ±15% for CO and HC, respectively.[17]

Field Measurements. During the summers of 2008 and 2009, 22 days of field measurements provided remote sensing measurements of in-use recreational and commercial marine vessels at the Hiram M. Chittenden locks in Seattle, WA. This site was chosen because marine traffic enters and exits in single file which allowed for plumes to be individually measured and assigned to passing vessels. Traffic through the locks consisted almost exclusively of small marine vessels such as commercial diesel and recreational vessels which were the focus of this study. These two subtypes have very different exhaust routes as most recreational vessels emit at or below the water level. Commercial diesel vessels emit through an elevated exhaust pipe. The advantage at the locks of measuring these two vessel types with very different elevations of exhaust is that the locks inherently have water levels that are different at the two ends of the channel. The concrete piers of the locks were raised approximately 1 m above the water level on the east side and up to 6 m above the water level on the west side depending on the tides. This allowed for the FEAT system to be set up on the pier to measure at different elevations above the water level, in-line with the exhaust plumes, depending on which end of the channel it was set.

The locks consist of two separate, side-by-side channels, connecting the fresh water body of Lake Union to the brackish water of the Puget Sound. The larger of the two channels was used for this study. This channel is 24.4 m wide by 251.5 m long.[28] The large channel typically supports commercial traffic while recreation vessels are sent through the small locks. However, during the summer of 2008 the small locks were closed for repairs and all traffic moved through the large locks. The large locks are also used for recreational vessels on high volume weekend events. Measurements were continued at the large locks during the summer 2009 campaign even though the small locks had reopened. Recreational traffic was heaviest on weekend days, and commercial traffic was not preferential to day of the week. The majority of the recreational measurements were made during the two busiest boating weekends of the summer, July fourth and Seattle's Seafair festival (8/2/08−8/3/08 and 8/1/09−8/2/09). Recreational vessel measurements were taken at the east gate to the locks at the mouth of Lake Union. Commercial vessel measurements were taken midweek at the west gate to the locks.

In previous on-road applications of the FEAT RSD, the distance between the light source and detector is approximately 10 m or the width of a single lane of traffic with shoulders. For this application the FEAT detector unit and the light source were spaced further apart and set up on the concrete piers on either side of the channel with a path length of 24.4 m. The FEAT system is typically controlled on-road with software that averages 50 sequential 10 ms discrete measurements. The measurement series is initiated by a beam block/unblock by a passing vehicle and last for 500 ms. The exhaust for these vehicles is predictable and comes from the tailpipe at the rear. For this marine application, 500 sequential 10 ms measurements were recorded for each passing vessel. This five-second program was initiated using a manual beam block to try to limit beam obstructions such as lines, flags, railings, and people while measuring. The manual initiation also allowed for measurements of some commercial vessels that passed entirely under the beam's path at the west side. The five second program allowed for collection of unpredictable trailing exhaust plumes to be captured from vessels with underwater exhaust. Previous studies suggest that there are not significant losses in marine engine CO, HC, or NO_x gaseous emissions with water contact.[16] Figure 1 shows the graphical result of the 5-s FEAT program. Nearly 2 s pass before the exhaust gases emerge from the water and pass through the detection beam for the high emitting gasoline vessel in Figure 1a. The commercial diesel vessel in Figure 1b does not show this delay because of the elevated, "dry" exhaust.

Previous in-use remote measurements of small marine craft have reported emissions using a carbon mass balance including just CO and CO_2. A more complete emission factor for most vessels is presented here that incorporates hydrocarbons into the mass balance. The reported NO_x is the sum of the NO and NO_2 measurements with the NO converted to NO_2 equivalents. The NO_x values reported here have not been adjusted for temperature and humidity.[29]

The use of the RSD and the single file nature of the site provide emission factors for individual vessels. Further vessel specifications were attempted for each boat by manually recording the boat's registration hull identification number or vessel name. The recorded registration numbers were matched to the WA Department of Licensing to obtain registered vessel characteristics.

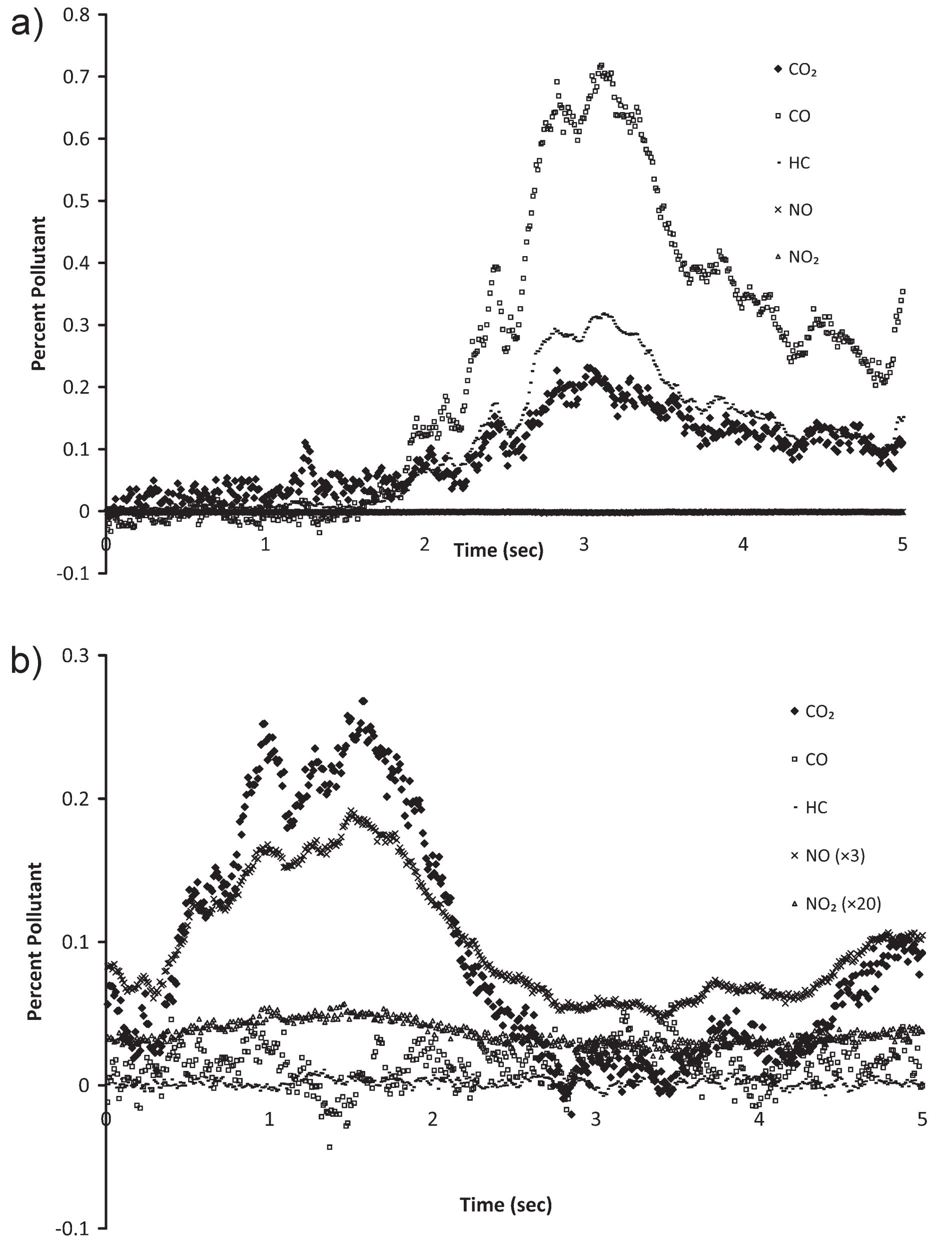

Figure 1. Five hundred 10 ms measurements from FEAT show % pollutant vs time for five species from (a) a high emitting gasoline recreational vessel and (b) a diesel commercial tugboat. The NO and NO_2 have been increased in plot b by 3 and 20, respectively, to help show their relation to CO_2.

Unfortunately, registrations of named vessels could not be matched, which were a substantial fraction of the fleet. Named vessels seemed to come through the locks in all sizes, but few large recreational vessels had hull identification numbers. Thus large recreational vessels, most likely powered by diesel engines, are poorly represented in the state-matched data. Vessels matched to state registry provided vessel fuel type, model year, hull length, propulsion type, and hull construction. In addition to the named vessels, many boats either did not have a hull number or they were unable to be matched to vessel registration records, which significantly reduced the number of vessels for which additional information could be determined. For example, a total of 307 valid CO emission measurements were made and 89 boats matched the state registry. Commercial diesel vessels were visually identified by name and matched to company Web sites to provide hull and engine data.

Table 1. Mean CO, HC, and NO_x Emissions for All Vessels[a]

total fleet	g CO/kg (n)	g HC/kg (n)	g NO_x/kg (n)
2008	336 ± 23 (179)	61 ± 9 (93)	57 ± 4 (104)
2009	326 ± 23 (128)	50 ± 4 (114)	58 ± 3 (126)
combined mean	332 ± 16 (307)	55 ± 5 (207)	57 ± 3 (230)
combined median	257	35	58

[a] Uncertainties are the standard error of the mean.

RESULTS AND DISCUSSION

Mean CO, HC, and NO_x emissions in grams per kilogram of fuel for 2008, 2009, and combined years are shown in Table 1. Results are presented with the standard error of the means (standard deviation divided by the square root of the number of observations) as is typical with the presentation of

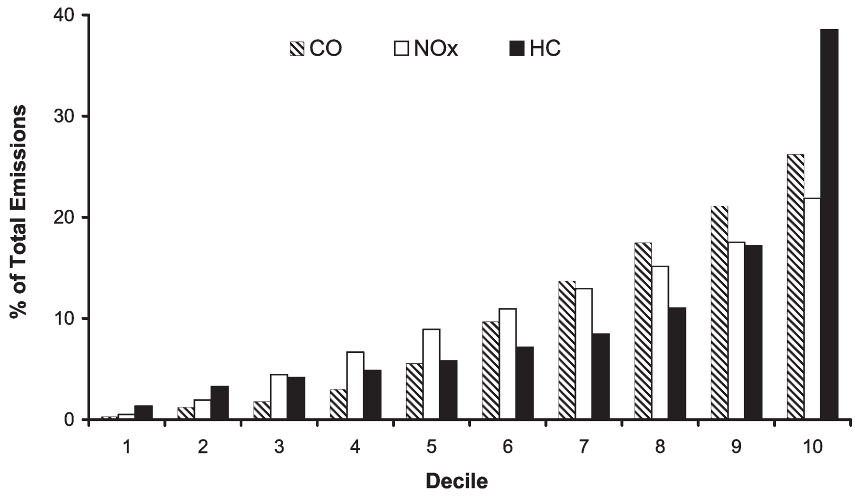

Figure 2. CO, NO_x, and HC emissions in grams per kilogram of fuel binned by cleanest to dirtiest mean deciles.

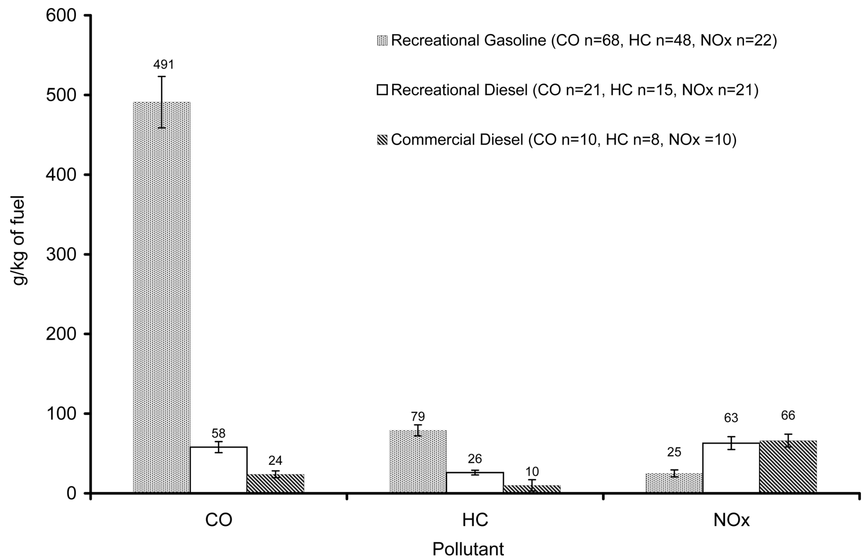

Figure 3. Mean CO, HC, and NO_x emissions in grams per kilogram of fuel from recreational gasoline, recreational diesel, and commercial diesel vessels. Uncertainties are the standard error of the mean.

fleet data. The comparison of emission factors from the 2008 and 2009 studies at the locks show no statistical differences in CO, HC, and NO_x emissions between the two years and are combined for all subsequent analyses. Table 1 shows that the number of valid emission measurements varied from year to year with 29% more valid CO measurements in 2008, and 18% and 17% more HC and NO_x measurements, respectively, in 2009. While the number of measurements differs between years, vessel operations were very similar from year to year. Vessels entering the locks were typically at low power while boats exiting the locks were typically accelerating to the posted speed limit of 7 knots. On the basis of these observations, the emission factors from this site are considered to be for low-speed transient vessel operations.

Emissions from on-road passenger vehicles show non-normal γ-distributions.[2] These distributions contain gross emitting vehicles that have malfunctioning or nonexistent emission control systems. On-road, the fleet emissions are dominated by a small number of gross emitting vehicles. The marine vessels in this study do not yet have emission control systems that could lead to γ-distributions. Figure 2 shows an emission by decile plot where individual vessel emissions are sorted and binned by deciles. This places the cleanest 10% of the fleet in decile 1 at the left end of the histogram and the dirtiest 10% on the right. Each successively higher emitting group makes up a higher percentage of the overall emissions. For CO and NO_x, these trends are fairly linear and not indicative of gross emitters. However, the HC profile is more exponential, suggesting that the gross emitters (probably two-stroke engines) exist for this species in the small marine craft fleet. Here the dirtiest 10% of the fleet is emitting nearly 40% of the total hydrocarbons. The distribution seen in Figure 2 and the difference between the means and medians in Table 1 come from measuring a fleet with very different combustion strategies. The fleet NO_x emissions are dominated by the smaller, diesel portion of the fleet. The lower NO_x mean compared to the median is pulled down by the larger proportion of fuel-rich gasoline combustion engines. The fleet HC emissions are primarily from two-stroke gasoline engines that are higher emitting than their four-stroke counterparts.

Grouping a fleet of dissimilar engines together has benefits when assessing average local air quality; however, additional

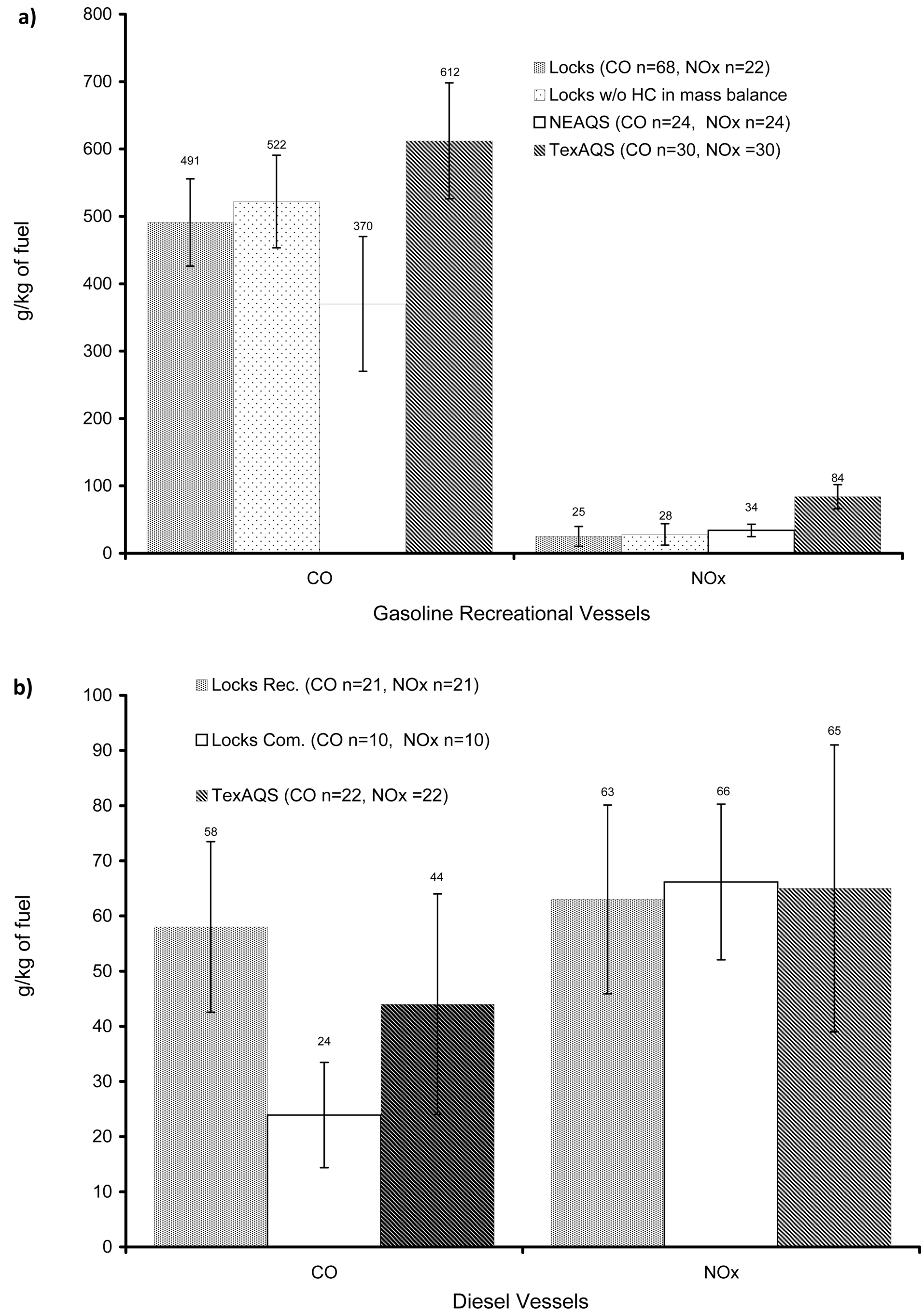

Figure 4. Comparison of mean CO and NO_x from this study to published in-use emission factors for (a) gasoline vessels and (b) diesel vessels.[7] Further comparison of the locks data is shown when emission factors are calculated without HC in the carbon mass balance as was done in the referenced fleets. Uncertainties of the mean are at 95% confidence for comparison.

interpretation of results requires individual measurements to be sorted by vessel specifics. Washington Department of Licensing matched 89 vessels which gives data on specific characteristics. Further analysis assumes the registration information to be current and accurate except for three boats removed from the diesel subcategory due to their impossibly high CO readings for lean burn diesel combustion.[30] The three removed vessels have an average CO emission factor of 600 g CO/kg fuel while all of the remaining diesels have an average of 58 ± 15 CO g/kg at the 95% confidence interval.

Figure 3 shows vessels binned by recreational boat fuel type, as determined from WA licensing records, and commercial diesel vessels. Large differences exist between gasoline and diesel boats with 8× more CO and 3× more HC emissions for recreational gasoline boats compared to recreational diesel boats. Even larger differences of 21× more CO and 8× more HC emissions exist for recreational gasoline boats compared to commercial diesel boats. Both recreational and commercial diesel boats showed ~2.5× more NO_x emissions than that of recreational gasoline boats. The high NO_x for the diesel fleets was the sum of measured NO and NO_2. The NO_2/NO_x ratio was 19% and 12% for the recreational and commercial fleets, respectively.

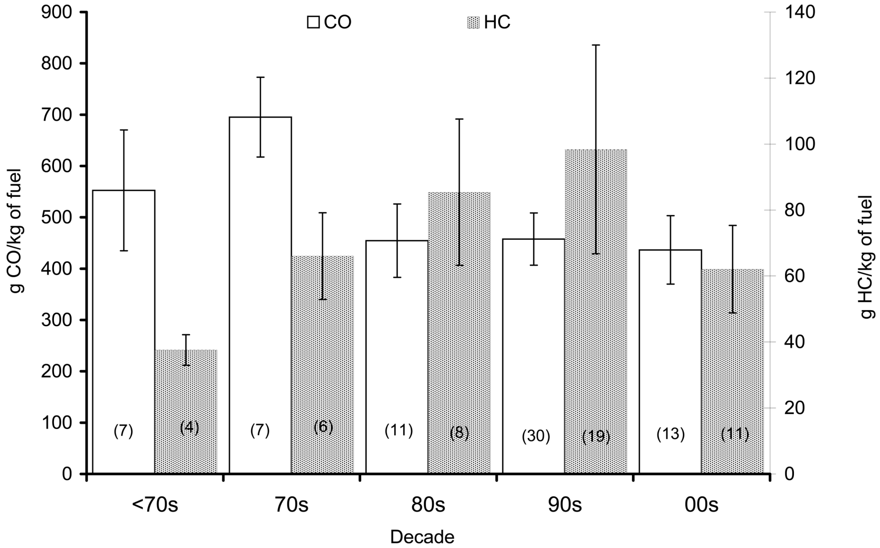

Figure 5. Mean CO and HC emissions for the gasoline fleet in grams per kilogram of fuel binned by model year decade (*n*). Uncertainties are the standard error of the mean.

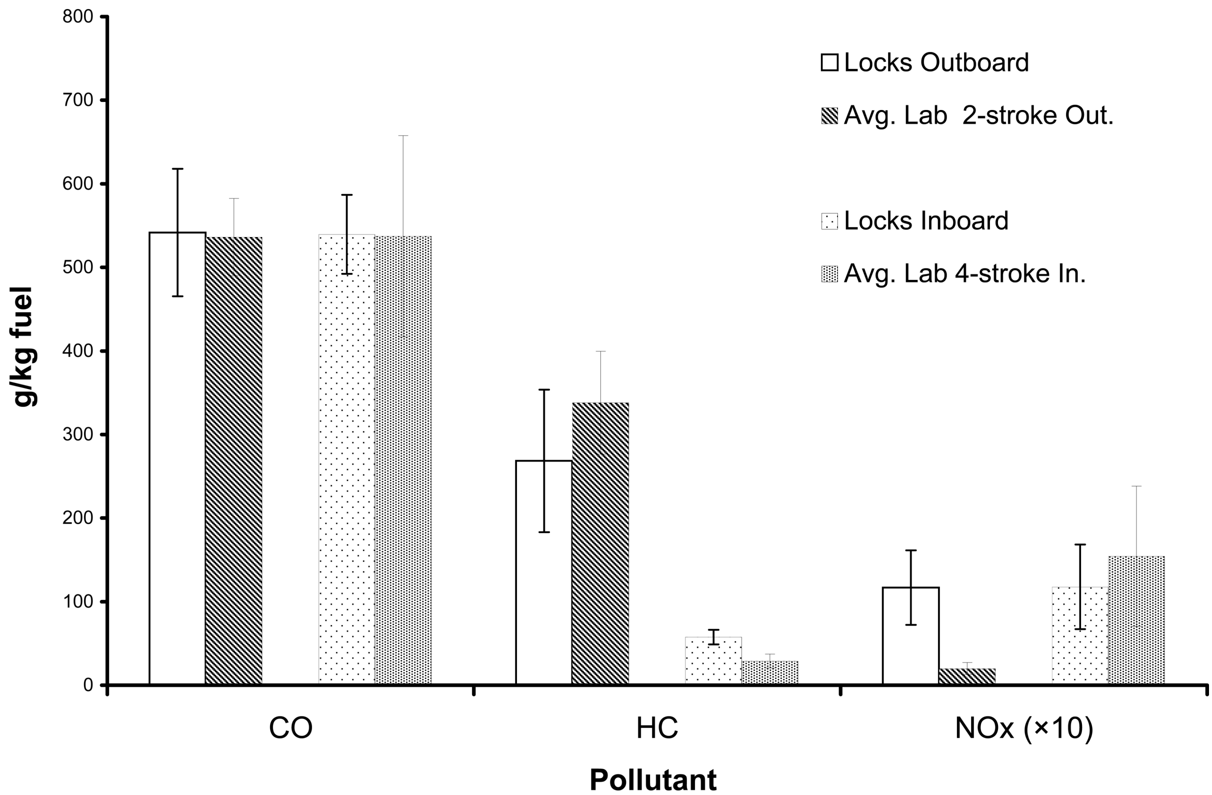

Figure 6. Mean in-use, fuel consumption-based gasoline fleet emissions grouped by engine type and compared to an average of laboratory testing emission factors.[3,13,14,31] Uncertainties are the standard error of the mean.

To date there is only one other published study of in-use recreational marine vessels.[7] The study consists of two campaigns, the Texas Air Quality Study (TexAQS) and the North Eastern Air Quality Study (NEAQS). NEAQS and TexAQS vessels were not individually identified but were binned by gasoline and diesel fuel type based on the NO_x/CO ratio from each plume. Figure 4a shows a comparison for gasoline vessels of CO and NO_x among the three studies. The NEAQS and TexAQS results fall within the uncertainty at the 95% confidence interval of the results at the locks. The consistently high CO and NO_x values for the TexAQS gasoline boats are reportedly due to 30 measurements taken during a race with high performance boats operating under high loads. Neither the TexAQS nor the NEAQS study report HC emission factors, and thus no comparisons are possible. Figure 4a also shows the locks data calculated when HC measurements are not included in the carbon mass balance denominator. This calculation is representative of how these literature emission factors were obtained since the NEAQS and TexAQS did not measure HC. As expected, when the emission factors do not include HC in the denominator, the other exhaust gases are not divided by as large of a carbon balance, and the CO and NO_x values are higher by 6% and 11%, respectively. The addition of HC to the carbon mass balance should make the emission factors from the locks a better representation of in-use emissions; however, with the small data sets and inherent variability of vessels, the changes fall within the uncertainties from the three field studies. Nine of the gasoline vessels were positively identified as outboard engines and show a larger effect from including HC in the calculations. Most of these are presumed to be two-stroke engines with high HC emissions, and the CO was 24% higher without HC in the mass balance.

Figure 4b shows CO and NO_x emissions from recreational and commercial diesel boat measurements at the locks compared to the TexAQS. No diesel vessels were reported for NEAQS and the TexAQS study did not differentiate between recreational and commercial vessels. This may account for the TexAQS emission factor falling between the emission factors at the locks. The recreational and commercial diesel emission factors from the locks were also calculated without HC included in the denominator. This caused the CO to increase by 2% and <1% and the NO_x to increase by 8% and 6% for the recreational and commercial fleets, respectively. The comparisons made in Figure 4 show good agreement between the two in-use studies using different measurement techniques and locations.

Trends in average emissions by model year have been useful in understanding and assessing deterioration and regulation effectiveness in the on-road fleet.[2] The registration-matched data from the locks provide the first glimpse of emissions versus model year for an in-use marine fleet. Figure 5 shows average CO and HC emissions binned by model year decade for gasoline vessels. Unlike their on-road counterparts, marine gasoline engines do not appear to be cleaner with newer model year. This lack of emissions reductions with newer model year is also true for NO_x emissions from both the gasoline and diesel fleets. Emissions reductions are noticeable in on-road vehicles post-1996 when On Board Diagnostics II (OBDII) systems were mandated.[2] The introduction of computer-controlled engines in the commercial on-road diesel fleet prompted significant NO_x emissions changes.[22] It is not surprising that the marine fleet shows no model year-dependent emissions trends since emission control systems, such as OBDII, have not yet been introduced and no universal regulations have been mandated with the gasoline marine fleet. New U.S. EPA regulations for inboard/sterndrive and outboard engines should make noticeable emission improvements with future model year gasoline engines.

U.S. EPA new 2010 emission requirements are the first for inboard/sterndrive engines and are more stringent than those for outboard engines.[4] It is assumed that inboard engine emissions can be better controlled since they have space for three-way catalysts and closed-loop fuel injection. These regulations are power-based units and not directly comparable to the mass fuel-based emissions measured at the locks. However, some laboratory studies report fuel consumption data[3,14,31] or brake-specific CO_2 emissions[13] which can then be used to calculate a carbon mass balance to allow for a comparison. Figure 6 shows average CO, HC, and NO_x emissions from outboard and inboard engines at the locks. These data are aligned next to an average of a survey of emission factors from laboratory studies. The laboratory value is an average value of different engines operating in different modes as is the fleet at the locks. Outboard locks data is compared to laboratory outboard two-stroke engines and inboard locks data is compared to laboratory inboard four-stroke engines. Figure 6 shows that both in-use and laboratory-based outboard gasoline engines have a significantly higher HC emission factor than inboard engines as expected; however, their CO emission factors show no difference. In comparison to emissions from laboratory tested engines, the in-use outboard fleet is shifted toward emitting less HC and more NO_x. This shift is likely due to the U.S. EPA regulation that phased in four-stroke outboard engines from 1998 to 2006 which are now comprising a larger part of the outboard fleet. Interestingly, the fleet of registered gasoline vessels at the locks had a median model year of 1991. This nearly 20 year lapse suggests that it will take many years before the effects of the new regulations will substantially affect the emissions inventory.

Lastly, license registration records provided data on vessel hull length. Recreational vessels from 7 to 90 feet passed through the locks during this study. Hull length was assumed to be proportional to engine power which could be used to provide trends in engine size versus emissions. However, neither gasoline nor diesel engines illustrated any emission trends for CO, HC, or NO_x versus hull length.

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