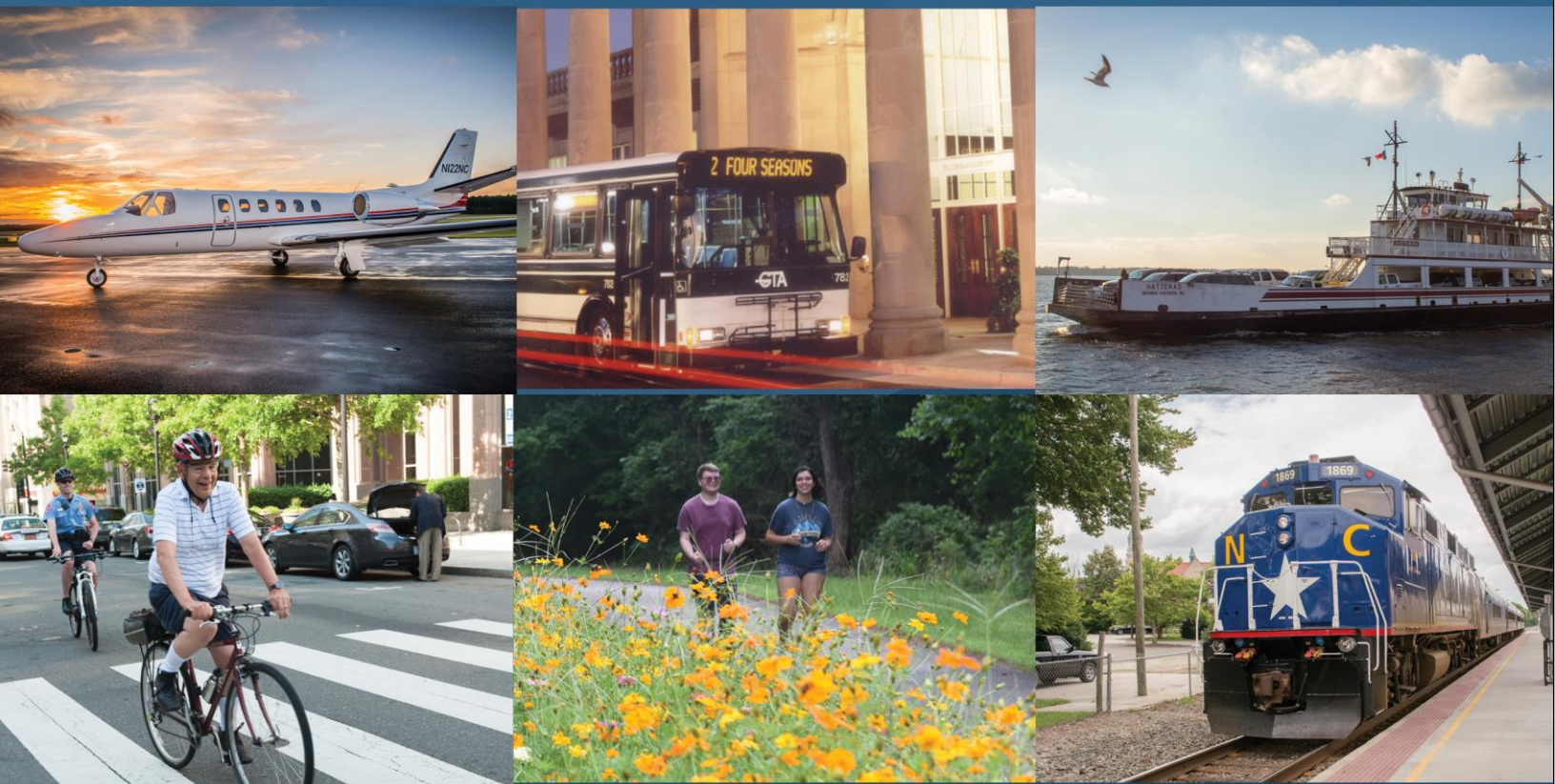


Quantification and Assessment of Ferry Vessel Emissions



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**RESEARCH &
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16. Abstract The objectives of this project are to (1) assess variability in real-world fuel use and emission rates (FUERs) across vessels, engines, and trips, and (2) quantify annual ferry fleet emissions, uncertainties, and reduction potentials. For the first objective, real-world measurements were conducted on two vessels, Motor Vessels (MVs) Frisco and Stanford White, operating on the Hatteras–Ocracoke route in North Carolina. Between 8 and 11 one-way trips per vessel were measured using Portable Emissions Measurement Systems to capture second-by-second exhaust concentrations of CO ₂ , NO _x , and particulate matter (PM) from port and starboard engines. Second-by-second vessel and engine activity data were also collected, with approximately 70,000 data points processed through synchronization and quality assurance. Results show that for an average trip and main engine, MV White has 16% lower fuel use and CO ₂ emission rates, but 80% and 18% higher NO _x and PM emission rates, respectively, than MV Frisco. For an average trip, variability in FUERs of a given vessel between main engines ranges from -33% to +48%, depending on the pollutant. For each vessel-engine combination, minimum trip-average FUERs are 7%–43% lower than maximum rates, depending on pollutant, highlighting the potential for fuel savings and emissions reductions due to modified ferry operations. Comparisons of FUERs across vessels, engines, and trips offer insights into the primary drivers of variability. The influence of sailing orientation and environmental conditions (e.g., sea current speed and direction) is also discussed. For the second objective, annual emissions were estimated for all 23 vessels in the North Carolina ferry fleet using an emission factor-based approach based on Environmental Protection Agency (EPA) certification databases, engine characteristics, operating hours, and trip-average loads. Uncertainty was estimated using non-parametric bootstrap simulations for NO _x + hydrocarbons (HC) and PM. CO ₂ emissions were estimated using a mass balance approach based on vessel fuel consumption data. Estimated annual emissions for 2024 varied from 2.1 tons (95% uncertainty range [UR]: 0.4–3.8 tons) to 35 tons (95% UR: 27–43 tons) for NO _x +HC, 0.06 tons (95% UR: 0.05–0.07 tons) to 0.62 tons (95% UR: 0.48–0.75 tons) for PM, and 218 to 2,234 tons for CO ₂ , depending on vessel. Three fleet-level mitigation scenarios were evaluated: vessel rearrangements reduced emissions by 6–7%, compliance engine upgrades achieved larger reductions for PM (32%) and NO _x +HC (26%), and maximum stringency upgrades achieved the largest reductions (up to 68% for both PM and NO _x +HC). This suggests vessel rearrangements may offer a cost-effective option for reducing fuel use and CO ₂ emissions, while engine upgrades may provide greater benefits for mitigating NO _x and PM emissions. Variation in estimated annual vessel emissions within the fleet was driven mainly by operating hours and main engine emission factors.			
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DISCLAIMER

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EXECUTIVE SUMMARY

Introduction

The NCDOT Ferry Division operates the nation's second-largest state fleet, with 23 vessels serving seven routes and transporting over 700,000 vehicles and 1.5 million passengers in 2024. These vessels range in age from approximately 10 to 50 years and typically operate with two diesel main engines and one auxiliary engine per vessel. Some of these engines pre-date the U.S. Environmental Protection Agency (EPA) emission standards. Although the Ferry Division has a long-term goal of transitioning toward greener, more sustainable technologies and operations, there is limited empirical data to assess in-use ferry fuel use and emission rates (FUERs). Furthermore, a baseline emission inventory is needed to determine which vessels and routes would benefit most from engine interventions. This project has two general objectives: (1) assess the variability in real-world FUERs across vessels, main engines, and trips; and (2) quantify annual ferry fleet emissions, associated uncertainties, and reduction potentials.

Methods

Real-world measurements were conducted on two vessels, Motor Vessels (MVs) Frisco and W. Stanford White, operating on the Hatteras-Ocracoke route in North Carolina. Eight to 11 one-way trips per vessel were measured. Portable Emissions Measurement Systems were used to measure second-by-second exhaust concentrations, including carbon dioxide (CO₂), nitrogen oxides (NO_x), and particulate matter (PM), from the port and starboard engines of each vessel. Second-by-second vessel and engine activity data were also collected. Approximately 70,000 second-by-second data points were processed through data synchronization and quality assurance. Operational and environmental indicators were derived to explore sources of variability, and analysis of variance (ANOVA) was applied to quantify the influence of vessel, engine, operational, and environmental factors on trip-average FUERs variability.

The analysis was extended to quantify emissions and reduction potentials for the ferry fleet, with diverse engine technologies and operational characteristics. Annual PM, and NO_x plus hydrocarbons (NO_x+HC) emissions were estimated from emission factors based on EPA engine certification datasets and activity factors based on engine rated power specifications, trip-based engine loads, and annual operating hours. CO₂ emissions were estimated using a carbon mass balance approach based on fuel consumption records. Uncertainties on annual emissions were estimated through non-parametric bootstrap simulations with 10,000 iterations per vessel, pollutant, and year (2019–2024). Correlation-based sensitivity analyses were used to assess the influence of engine and operational variables within and across years. Emission reduction potentials were evaluated under three scenarios: optimized vessel rearrangements, compliance upgrades to Tier 3 or Tier 4 standards, and full Tier 4 adoption. Finally, 2024 vessel-level emission intensities were compared on per-mile and per-passenger-mile bases to identify additional mitigation opportunities.

Results

Measurements revealed distinct operational and emission characteristics between MV Frisco and MV White, influenced by environmental conditions, vessel activity, engine load balance between main engines, and technological differences. MV Frisco operated at higher trip-aggregated speed and acceleration metrics than MV White, consistent with its higher power-to-weight ratio and twin-screw propulsion. MV Frisco maintained balanced engine loads, while MV White frequently exhibited starboard-dominant loading, especially during counter-current cruising, due to the unsteady thrust characteristics of Voith-Schneider propellers and lower thrust capacity. For

an average trip and main engine, MV White has 16% lower fuel use and CO₂ emission rates, but 80% and 18% higher NO_x and PM emission rates, respectively, than MV Frisco. For an average trip, variability in FUEs of a given vessel between main engines ranges from -33% to +48%, depending on pollutant. For each vessel-engine combination, minimum trip-average FUEs are 7%–43% lower than maximum rates, depending on pollutant, highlighting the potential for fuel savings and emissions reductions due to modified ferry operations. Comparisons of FUEs across vessels, engines, and trips offer insights into primary sources of variability. The influence of sailing orientation and environmental conditions (e.g., sea current speed and direction) is also discussed.

In 2024, vessel emissions and uncertainties varied widely, with the lowest emitters releasing 90–94% less than the highest, depending on pollutant. Vessel-level CO₂ emissions ranged from 218 to 2,234 t/year, NO_x+HC from 2 to 35 t/year, and PM from 0.06 to 0.62 t/year. Uncertainty bounds ranged from 35% to 94% between the lower and upper limits of the 95% uncertainty intervals for mean annual emissions, depending on pollutant and vessel. Emission reduction scenarios, such as optimized vessel rearrangements, compliance upgrades to Tier 3 or Tier 4 standards, and full Tier 4 adoption, demonstrate several feasible approaches. Fleet rearrangements yielded modest reductions of 6–7% across pollutants, while compliance upgrades achieved reductions of 8% for CO₂, 26% for NO_x+HC, and 32% for PM. The Tier 4 scenario provided the largest benefits, with fleetwide reductions of up to 68% for PM and 67% for NO_x+HC. Emissions were most sensitive to operating hours and main engine emission factors. MVs Ocracoke Express and Carteret had the highest per-passenger-mile emission intensities due to their relatively low occupancy and limited annual mileage. MV Ocracoke Express also exhibited the highest per-mile emission intensities for CO₂ and NO_x+HC, whereas MV Salvo had the largest for PM. Engine upgrades significantly cut PM and NO_x+HC but offered modest CO₂ reductions, indicating the need for electrification and low-carbon fuels for deep reductions in carbon emissions.

Conclusions

Vessel and engine differences primarily drove variability in fuel use, CO₂, and NO_x emissions, pointing to reduction opportunities through vessel modifications and engine upgrades. PM variability was mainly linked to intra-vessel differences in engines, including load imbalances during maneuvering and counter-current trips, especially for vessels with cycloidal propellers. A trade-off between NO_x versus fuel use and PM emissions highlighted the need for integrated engine–propulsion choices and strategic planning. Though smaller than vessel and engine effects, inter-trip variability remained meaningful, indicating an additional reduction potential through operational changes.

In 2024, MVs Silverlake, W. Stanford White, and Swan Quarter were the largest emitters. Fleet emissions were mainly driven by operating hours and main engine emission factors, pointing to activity management and targeted upgrades as key levers to reduce emissions. High per-passenger-mile emission intensities for MVs Ocracoke Express and Carteret, along with high per-mile intensities for MV Salvo, highlight the need to enhance vessel occupancy and operational frequency. Vessel rearrangement offered a cost-effective CO₂ reduction strategy, while Tier 3-4 engine upgrades provided substantial reductions for PM and NO_x+HC. Engine improvements alone yielded ≤ 10% annual CO₂ reductions, underscoring the need for additional measures such as electrification and low-carbon fuels to meet the International Maritime Organization’s (IMO) goal of achieving carbon neutrality by 2050.

CHAPTER 1: INTRODUCTION

1.1 Background

Diesel-powered vessels constitute 77% of the U.S. in-service ferry fleet and are a major source of particulate matter (PM), a pollutant associated with an estimated 60,000 global deaths annually from cardiopulmonary disease and lung cancer (Corbett et al., 2007). In addition to PM, diesel-powered maritime transport emits health-relevant pollutants such as nitrogen oxides (NO_x) and hydrocarbons (HC) (Gössling et al., 2021). The sector is also a significant contributor to carbon dioxide (CO₂) emissions, which are the focus of global decarbonization strategies (IMO, 2023a). The North Carolina Department of Transportation (NCDOT) Ferry Division operates the second-largest U.S. fleet among the 37 states with ferry systems. Its 23 vessels operate on seven routes and, in 2024, carried over 700,000 vehicles and 1.5 million passengers (NCDOT, 2024). The fleet has diverse vessel and engine characteristics, as well as varied compliance with EPA marine emission standards; over half of the main engines are uncertified, while the remainder meet Tier I–III standards. These vessels range from typically 10 to 50 years of age, with typically two large diesel main engines and one diesel auxiliary engine per vessel. Many engines, including those certified to emission standards based on the date of manufacture, have been in service for many years with accumulated wear and differing service or rebuild history; thus, their in-use emissions may differ from emissions certification values. A limited number of new vessels are entering the fleet to replace older vessels. The Ferry Division periodically seeks grants from federal or state agencies or programs to procure funding for vessel modifications or upgrades. Such applications typically require assessment of the energy and environmental impacts of the proposed project, including reduction of air pollutant emissions. An evaluation of ferry engine energy use and emissions can incorporate assessing real-world fuel use and emission rates (FUERs), where feasible, and should be complemented with the quantification of annual fleet emissions and associated uncertainties to support applications for federal and state grants to fund vessel modifications or upgrades.

1.2 Research Needs

Real-world measurements of FUERs reflect the operation and performance of in-use engines (Sugrue et al., 2022). However, real-world emissions from ferries have not been widely characterized in the literature, except for a few studies that have related emissions to engine operating conditions or assessment of post-combustion emission controls (Cooper, 2001, 2003; Durmaz et al., 2017; Frederickson et al., 2022; Sugrue et al., 2022). These studies have shown that ferries generally operate with at least two main propulsion engines and one auxiliary engine supplying electrical power and onboard services. However, most assessments to date have focused on monitoring exhaust emissions from only a single diesel main engine. In addition, assessing emissions variability has not been applied systematically across engines, vessels, and trips. Assessing variability is essential for linking sources to impacts in risk assessments, as it captures differences across engines and operational conditions (National Research Council, 2009), and helps ensure that decision-making is better supported (Frey & Bammi, 2002).

Thus, real-world measurements of ferry FUERs are needed to provide emission factors under actual operating conditions, thereby improving emission inventories (Sugrue et al., 2022). Leveraging such data supports the evaluation of interventions aimed at

mitigating emissions and modifying operational practices (Frey et al., 2012). Furthermore, assessing variability in ferry FUEs aligns with the U.S. Department of Transportation's Maritime Energy and Emissions Action Plan by directly targeting air pollutants and operational conditions (USDOT, 2024a).

Additionally, a comprehensive, fleetwide evaluation of FUEs of the NCDOT fleet should also incorporate uncertainty in all vessel emissions. This allows analysts to evaluate the probability of achieving emission reduction goals and evaluate the cost-effectiveness of mitigation strategies (Frey, 2007). Quantifying uncertainty in emissions, by means such as probabilistic analysis, can be particularly useful when in-use measurements are not feasible or are logistically challenging. Frey et al. (1999) have demonstrated the application of numerical simulation methods in quantifying uncertainty in emission factors, activity factors, and emission inventories from power plants and light-duty gasoline vehicles, highlighting their broader applicability for emissions modeling. However, probabilistic analysis has not yet been applied to assess ferry emissions. Moreover, there is growing interest in probabilistic, risk-based approaches to better inform mitigation planning (Morris et al., 2025). Consequently, probabilistic analysis could be extended to assess emission reduction potentials at the fleet level, as an alternative to traditionally assessed scenarios through deterministic analyses (Edenhofer, 2014; Lee & Romero, 2023; Rogelj et al., 2018).

Therefore, quantifying ferry emissions and their uncertainty should be extended to the fleet level, with explicit identification of key contributing factors to guide interventions and enable probabilistic interpretation of emission reduction potentials. This is required since, ultimately, assessing the benefits of reducing or avoiding mobile-source emissions is a critical step in evaluating operational strategies (Ashok et al., 2017; Gouge et al., 2013).

1.3 Objectives

This project has two general objectives: (1) assessing the variability in real-world FUEs across vessels, main engines, and trips; and (2) quantifying annual ferry fleet emissions, uncertainties, and reduction potentials.

1.4 Overview of the Report

The report consists of four chapters. The overview of each chapter is briefly described:

Chapter 1 (this chapter) is the introduction that includes research background, research needs, objectives, and an overview of the report.

Chapter 2 addresses research objective 1. This chapter is about assessing variability in main engine fuel use and emission rates based on real-world measurements of two passenger ferry vessels.

Chapter 3 addresses research objective 2. This chapter is about quantifying ferry fleet emissions and uncertainty with applications to reduction strategies.

Chapter 4 includes the key findings, conclusions, and recommendations from this research project.

Chapter 5 provides an implementation and technology transfer plan developed from the products of this research project.

Appendix A details the methodology and results for estimating annual ferry emissions and the associated uncertainties, using a case study vessel from the North Carolina ferry fleet, as an example. Appendix B provides estimated baseline annual emissions for each vessel in the ferry fleet for each year from 2019 to 2024.

CHAPTER 2: ASSESSING VARIABILITY IN MAIN ENGINE FUEL USE AND EMISSION RATES BASED ON REAL-WORLD MEASUREMENTS OF TWO PASSENGER FERRY VESSELS

2.1 Introduction

Marine vessels and port-related air pollution contribute substantially to the global health burden, establishing maritime transport as a critical source of air pollution and a significant health risk factor (Mueller et al., 2023). As a class of marine harbor craft, ferries often rely on diesel engines and substantially contribute to air pollution in both coastal areas and inland waterways (CARB, 2021). In 2022, a total of 618 vessels comprised the U.S. ferry fleet, with 89% reported as in-service. Diesel is the predominant fuel used by 77% of the U.S. ferry fleet (USDOT, 2024b), accounting for approximately 2 trillion British Thermal Units (BTU) of energy consumption annually (USDOT, 2024a).

Exposure to diesel particulate matter (PM) from vessel emissions is linked to respiratory illnesses (Pope & Dockery, 2006). Besides PM, pollutants of concern from diesel-powered maritime transport include nitrogen oxides (NO_x) and carbon dioxide (CO₂) (Gössling et al., 2021). Reducing NO_x emissions can help mitigate health burdens associated with the marine transportation industry (Sofiev et al., 2018). This is because vessel-related air pollution, including NO_x, was estimated to cause up to 266,00 premature deaths worldwide from lung cancer and cardiovascular disease in 2020 (Sofiev et al., 2018). Meanwhile, CO₂ emissions from the maritime transportation sector are being targeted to achieve carbon neutrality in 2050, as proposed by the International Maritime Organization (IMO, 2023a).

Although efforts to control emissions from marine vessels are underway, emission inventories should be updated with emission factors based on real-world measurements that reflect the operation and performance of in-use engines (Sugrue et al., 2022). Ultimately, leveraging data derived from real-world emissions will support the evaluation of interventions aimed at mitigating emissions and modifications in operational practices (Frey et al., 2012). Real-world emissions from ferries have not yet been widely characterized in the literature, except for a few studies that have related emissions to engine operating conditions or assessment of post-combustion emission controls (Cooper, 2001, 2003; Durmaz et al., 2017; Frederickson et al., 2022; Sugrue et al., 2022). These studies have shown that ferries typically operate with two main engines (port and starboard) for propulsion. However, these assessments have typically focused on measuring exhaust concentrations from a single main engine.

Assessing emissions variability is essential for linking sources to impacts in risk assessments, as it captures differences across engines and operational conditions (National Research Council, 2009). Evaluating variability in ferry fuel use and emission rates (FUERs) aligns with the U.S. Department of Transportation's Action Plan for Maritime Energy and Emissions by targeting air pollutants and operational conditions (USDOT, 2024a). Ultimately, evaluating variability in emission factors helps ensure that decision-making is better supported (Frey & Bammi, 2002).

Inter-engine variability in FUERs reflects differences in operation between the two main engines in a vessel, which are important to consider since they have not been

quantified by assessments of one single main engine in the existing studies. Inter-vessel variability in FUERs reflects differences between vessel characteristics, such as engine make, model, configuration, and emission standards. Acknowledging these differences is important to incorporate variations in FUERs from multiple vessels at the fleet level. For instance, in North Carolina, approximately half of the ferry fleet operates with main engines that are not certified under U.S. Environmental Protection Agency (EPA) marine emission standards. Inter-trip variability in FUERs for a vessel could be evidenced, even along the same route, from variations in piloting practices, engine operations, and external causes (e.g., wind and sea current conditions) that influence engine loads and emissions.

Therefore, the objectives of this study are to: (1) quantify real-world FUERs for passenger ferry vessels; and (2) assess the variability in FUERs across vessels, main engines, and trips.

2.2 Methods

The methods include: (1) study design; (2) instrumentation; (3) data collection; (4) data processing; (5) development of an engine-load-based FUERs model; (6) key sources of variability in FUERs; and (7) variability analysis.

2.2.1 Study Design

The North Carolina Department of Transportation (NCDOT) Ferry Division operates the second-largest fleet among the 37 states with ferry systems. The motor vessel (MV) Frisco and MV W. Stanford White (hereafter referred to as MV White) were selected to represent variations in vessel and engine characteristics, are presented in Table 2-1. Each vessel is powered by two main diesel engines manufactured by Caterpillar and running on ultra-low diesel fuel. The two main engines are of identical engine model and located at port and starboard positions within a vessel. MV Frisco is equipped with main engines certified to EPA Tier 3 marine emission standards, whereas MV White operates with main engines that are not certified to an emission standard.

Both vessels were operated on the Hatteras–Ocracoke route, which connects the Hatteras and Ocracoke-north ferry terminals in NC. The one-way trip between terminals is approximately 11 miles in length, with an average crossing time of 75 minutes and 15 minutes of dwelling at terminals. This route has the largest number of ferry operations in the NC ferry system.

Table 2-1. Characteristics of vessels and engines.

Description		Ferry Vessels	
		MV Stanford White	MV Frisco
Vessel Weight (t)*		395	241
Power-to-Weight Ratio (kW/t)		1.77	3.66
Length (ft)		180	150
Breadth (ft)		44	42
Depth (ft)		11	9
Carrying Capacity	No. of passengers	300	149
	No. of vehicles	40	30
Main Engine	Quantity	2	2
	Manufacturer	Caterpillar	Caterpillar
	Model	3412	C18
	Engine displacement (L)	27	18.1
	No. of cylinders	12	6
	Compression ratio	13	16.3
	Rated power (kW)	349	441
	Rated speed (RPM)	1200	1800
	Power density (kW/L)	12.9	24.4
	Emission Standard	Not certified	EPA Tier 3
Propeller Technology		Voith Schneider Propellers	Screw propellers 36x35 - 4 Blade Twin Disc MGX-5145SC, 2.5:1

*Vessel weights are reported from the U.S. Coast Guard Issued Stability Letters (USDOT, 1989, 2023).

2.2.2 Instrumentation

For each vessel, second-by-second (1 Hz) vented exhaust concentrations from the main engines were measured using a Portable Emissions Measurement System (PEMS). The PEMS used was the GlobalMRV Axion, which measures CO₂, carbon monoxide (CO), and hydrocarbons (HC) via nondispersive infrared analyzers, nitric oxide (NO) via electrochemical sensors, and PM via light laser scattering (GLOBALMRV, 2019). NO was used as a surrogate for NO_x, as it is the predominant component of NO_x emissions from diesel engines (Heywood, 1988). The PEMS underwent calibration in the laboratory before field measurements using a BAR 97 low calibration gas blend cylinder. PEMS has demonstrated good precision and accuracy in measuring exhaust emissions (Vu et al., 2020).

For each vessel, exhaust concentrations were sampled from a sampling port identified on the engine exhaust duct at approximately 20 inches from the source. Engine

exhaust was routed through a 20-foot stainless steel tube, connected to the sampling port using Swagelok fittings, to dissipate heat before transitioning to rubber sample hoses leading to the PEMS. The exhaust was continuously sampled and then vented from the PEMS to the atmosphere through exhaust-out tubes.

Engine activity data were recorded to allow quantification of 1 Hz FUEs. One Hz in-use engine activity data were recorded from each main engine's electronic control module (ECM) using a datalink scan tool, Caterpillar Electronic Technician (CAT-ET). Recorded engine variables included engine fuel flow rate, engine speed in revolutions per minute (RPM), and engine percent load, which is defined as the percentage of the engine rated power.

Global Positioning System (GPS) receivers were placed in the pilot room and used to record 1 Hz coordinates during trips and vessel speed-over-ground (relative to earth surface). Vessel speed data were inferred from coordinates retrieved by the GPS.

2.2.3 Data Collection

Real-world measurements were conducted over four consecutive days from October 11th to 14th in 2024. A trip was defined as a continuous period of engine operation during which the vessel traveled from one terminal to the other. One Hz vessel activity, engine activity, and emissions were classified as in-trip when the engine speed was above idle (typically greater than 600 RPM) and the vessel was underway (typically exceeding 0.35 mph). A total of 19 one-way trips were measured (8 for MV Frisco and 11 for MV White).

Exhaust concentrations were measured from one main engine per day, alternating by days of measurement. For instance, exhaust concentrations were typically measured on one main engine during all trips in a single day, then on the second main engine during the following day. Exhaust concentrations were measured on MV Frisco on the first two days, and on MV White on the last two days.

Engine activity data were recorded simultaneously from both engines, except on the third day of measurement on MV White, when one scan tool was unavailable. On that day, engine activity data were collected alternately from each main engine using one scan tool. Data completeness was assessed for each main engine and one-way trip, requiring that 1 Hz percent load data be valid for at least 80% of the travel time. Across all trips, simultaneous engine activity data from both main engines were recorded for 13 one-way trips (8 for MV Frisco and 5 for MV White). Vessel activity data (e.g., speed) were collected using GPS receivers for each trip measured.

Environmental conditions such as headwinds and currents influence vessel fuel consumption and emissions by increasing resistance (the net force opposing propulsion thrust) and reducing propulsion efficiency and vessel speed (Perera & Mo, 2018). To account for the influence of environmental conditions on the four-day measurement period, environmental data were retrieved to capture representative short-term conditions. Hourly sea current speed and direction were obtained through the Copernicus Marine Service for a location near the geometrical centroid (35.207° N, 75.757° W) of the Hatteras-Ocracoke route (Copernicus Marine Service, 2024). Hourly wind speed and direction were retrieved over the same period as reported by the Hatteras Station of the U.S. Coast Guard (NOAA, 2025).

2.2.4 Data Processing

One Hz data were time-aligned for exhaust concentrations measured from PEMS, engine activity data recorded from the ECM, and vessel activity data recorded from GPS receivers, following an established method presented by Sandhu and Frey (Sandhu & Frey, 2013). The time alignment involved PEMS-ECM synchronization and ECM-GPS synchronization. The PEMS-ECM synchronization was based on matching concurrent peaks of NO_x concentrations and engine RPM. The ECM-GPS synchronization was based on matching concurrent peaks in engine RPM and vessel speeds. Synchronized data from PEMS, ECM, and GPS were quality-assured following the methods described elsewhere (Sandhu & Frey, 2013).

The 1 Hz FUERs for each vessel, engine, and trip were estimated based on engine mass fuel flow rate, exhaust pollutant concentrations, and fuel composition. This required estimating the dry basis molar exhaust flow rate, assuming that all the carbon in the exhaust (e.g., CO₂, CO, and HC) is coming from the carbon content of the fuel. PM emission rates were estimated based on the ideal gas law. PM measured using the laser light-scattering detection method tends to be underestimated by a factor of 5 (Johnson et al., 2011). Thus, PM emission rates were adjusted by multiplying by 5 for bias correction. Details on estimating 1 Hz FUERs are given in Sandhu and Frey (Sandhu & Frey, 2013).

2.2.5 Engine-Load-Based Fuel Use and Emission Rates Model

To enable the comparison of FUERs across vessels, main engines, and trips on a consistent basis, a model was developed to estimate trip-average FUERs for each vessel and engine. The model was developed following the approach described by Liu and Frey (B. Liu & Frey, 2015). Trip-average FUERs estimated from the model were used to assess inter-engine, inter-vessel, and inter-trip variabilities.

The model was calibrated using empirical 1 Hz FUERs categorized by engine percent load, since it has been found to correlate strongly with emission rates (Zhai et al., 2008). For each vessel and engine, the model calibration involved: (1) categorizing 1 Hz FUERs into ten percent load bins for every 10% load interval; (2) quantifying trip-based time spent in each percent load bin; and (3) estimating trip-average FUERs based on:

$$TER_{V,E,T,P} = \frac{\sum_{B=1}^{10} (ER_{V,E,B,P} \times t_{V,E,T,B})}{d_T} \quad (2.1)$$

where,

$TER_{V,E,T,P}$	=	trip-average FUERs for vessel V , main engine E , trip T , and species P , including fuel use, CO ₂ , NO _x , and PM (g/mile);
$ER_{V,E,B,P}$	=	empirical emission rate for vessel V , main engine E , engine load bin B , and species P (g/s);
$t_{V,E,T,B}$	=	time spent for vessel V , main engine E , trip T , and engine load bin B (s); and
d_T	=	distance of trip T (mile).

The predictive performance of the FUERs model was evaluated via five-fold cross-validation.

2.2.6 Sources of Variability in Fuel Use and Emission Rates

Trip-based aggregated metrics of vessel activity data were determined to support characterizing trip-based variability in FUERs as later described. Such metrics are the average speed of the trip, the peak speed, the coefficient of variation of speed (CVS), and the relative positive acceleration (RPA). For each trip, the average speed was estimated as the quotient of trip length and trip crossing time. The peak speed is the maximum speed reached during the trip. The CVS was estimated as the standard deviation of 1 Hz speed divided by the trip-average speed and expressed as a percentage; higher CVS values denote larger deviations from the mean speed, whereas lower values indicate near-constant speed. The RPA was defined as the distance-weighted mean of all positive instantaneous accelerations, as described by Marotta and Tutuianu (Marotta & Tutuianu, 2012). Higher RPA values signify that a larger fraction of the trip distance was accumulated during acceleration bursts, while lower values reflect fewer or milder positive accelerations.

To account for representative environmental conditions at the trip level on FUERs, each one-way trip was assigned to one of two prevailing trajectory directions: southwest to northeast (Ocracoke to Hatteras) or northeast to southwest (Hatteras to Ocracoke). On each measurement day, trips whose trajectory aligned with the prevailing sea current and wind were classified as sailing co-current, and those whose trajectory opposed them as sailing counter-current. For each trip, average sea-current speed and wind speed were determined.

Variability in FUERs may be driven by operating conditions that reflect differences in percent load between the two main engines during a trip. This is because power outputs of main engines on harbor vessels have been shown to vary during daily operations, resulting in differences in fuel consumption and emissions (Chen et al., 2024). To quantify operational imbalances between the two main engines, the 1 Hz starboard-to-port load ratio was calculated for each trip and then categorized, using a $\pm 20\%$ disparity threshold, as port-dominant (ratio < 0.8), approximately balanced ($0.8 \leq \text{ratio} \leq 1.2$), or starboard-dominant (ratio > 1.2).

2.2.7 Variability Analysis

An analysis of variance (ANOVA) was applied to assess factors affecting variability in estimated trip-average FUERs, including vessels, engines, trip operational characteristics (e.g., average speed, peak speed, CVS, RPA), sailing orientation (e.g., co-current, counter-current), and environmental conditions (e.g., wind and current speeds). Results are presented in terms of the P-value (assessing statistical significance), F-ratio (comparing explained to residual variance), and Eta^2 (η^2 , quantifying the proportion of variance explained).

2.3 Results

Results include: (1) environmental conditions; (2) vessel activity; (3) engine activity; (4) FUERs and time spent by percent load bin; (5) variability in trip-average FUERs; and (6) comparison of sources of variability.

2.3.1 Environmental Conditions

Figure 2-1 summarizes hourly sea current and wind conditions during the four-day measurement period. Current and wind directions were generally consistent, shifting from southwest on October 11th to northeast on October 12th to 14th, which defined trip classifications as co- or counter-current. Minimum sea current speeds were 6–45% lower than daily maximums, and minimum wind speeds were 29–52% lower, depending on the day. Average sea current and wind speeds across all days were 0.55 mph (standard deviation [SD] = 0.11) and 12.17 mph (SD = 4.51), respectively.

2.3.2 Vessel Activity

Vessel activity data accounted for a total of 35,070 seconds for MV Frisco and 33,692 seconds for MV White. To assess the possible sources of variability of FUERS from vessel activity on a trip basis, Figure 2-2 shows the distributions of trip-aggregated vessel activity for the 13 one-way trips (8 for MV Frisco and 5 for MV White) used for the engine-load-based model, such as trip average speed, peak speed, RPA, and CVS.

Figure 2-2(a) shows that MV Frisco had a mean trip-average speed of 9.74 mph, approximately 7.9% higher than MV White's 9.03 mph. Minimum speeds were 11.2% and 17.8% lower than maximums for MV Frisco and MV White, respectively. This speed difference aligns with the propeller law derived from hydrodynamic principles (Psaraftis & Lagouvardou, 2023), which relates power to the cube of vessel speed at low Froude numbers (< 0.35). Given Froude numbers of 0.21 for MV Frisco and 0.17 for MV White, and their rated powers (882 kW vs. 698 kW), the predicted 8% speed difference closely matches the observed value.

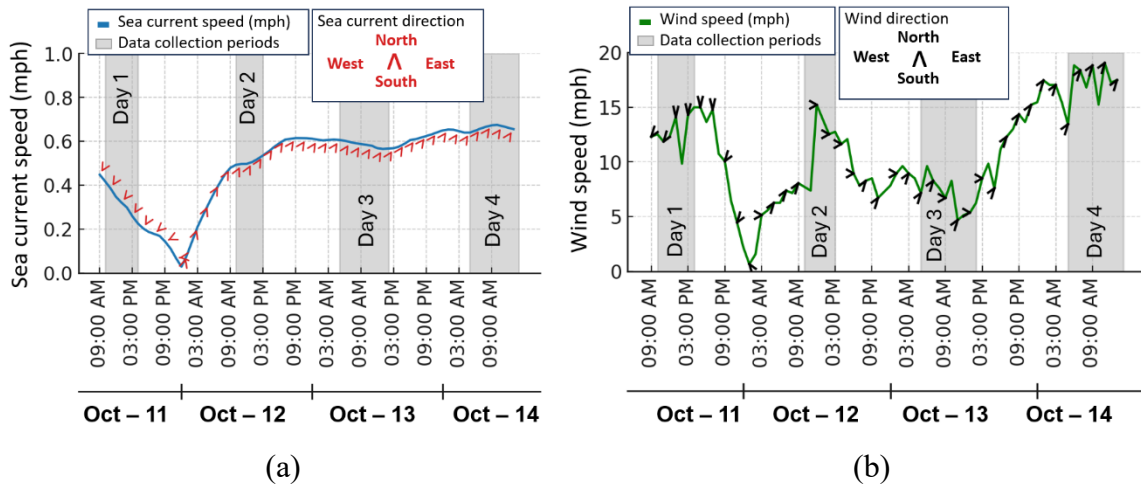


Figure 2-1. Local environmental conditions for the four days of measurement, including (a) sea current speed and direction, and (b) wind speed and direction.

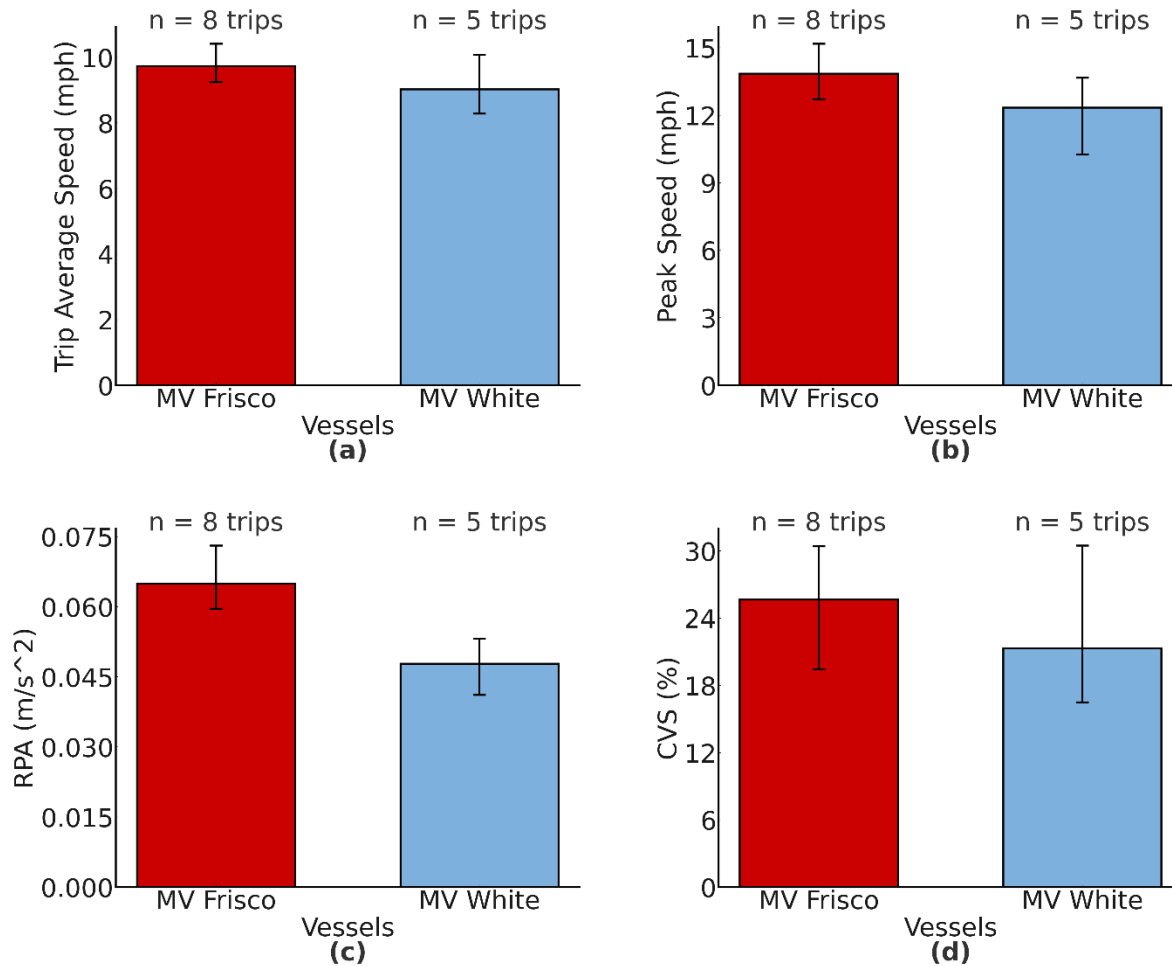


Figure 2-2. Distributions of trip-based vessel activity for 13 one-way trips (8 on MV Frisco and 5 on MV White): (a) Trip average speed, (b) Peak speed, (c) Relative positive acceleration (RPA), and (d) Coefficient of variation of speed (CVS). Error bars indicate the maximum and minimum values. Sample size n represents the number of trips.

Figure 2-2(b) shows that MV Frisco had a mean peak speed of 13.85 mph, with minimum values 16% lower than maximums, while MV White averaged 12.34 mph, with minimums 25% lower. MV White exhibited greater inter-trip speed variability, with a 9-percentage point larger range between its slowest and fastest trips, indicating more frequent fluctuations in peak speed.

Figure 2-2(c) indicates that MV Frisco had a mean trip RPA of 0.065 m/s², approximately 36% higher than MV White's 0.048 m/s². Minimum values were 18.5% and 17.8% lower than maximums for MVs Frisco and White, respectively. The higher RPA on MV Frisco suggests more frequent or intense acceleration bursts across its trips compared to MV White.

Figure 2-2(d) shows that MV Frisco had a mean CVS of 25.7%, approximately 20.5% higher than MV White's 21.3%. Minimum values were 36.1% and 45.9% lower than maximums for MVs Frisco and White, respectively. The higher CVS on MV Frisco

indicates greater fractional speed variability, suggesting more frequent or intense acceleration and deceleration events compared to MV White.

2.3.3 Engine Activity

Differences in RPA and CVS between vessels (Figure 2-2) are primarily explained by variations in engine-rated power and vessel weight. The power-to-weight (P/W) ratio, defined as total rated power divided by vessel weight, determines a vessel's acceleration capability (MAN Energy Solutions, 2018). The higher P/W ratio of MV Frisco indicates greater available propulsion power per unit mass, resulting in faster acceleration (MAN Energy Solutions, 2018). This explains the higher RPA and CVS by MV Frisco, both of which reflect more frequent and intense speed fluctuations relative to MV White.

Figure 2-3 presents the cumulative distribution of 1 Hz starboard-to-port engine load ratios to assess engine load balance. MV Frisco exhibited near-symmetric engine operation, with a mean ratio of 1.002 and an interquartile range (IQR) of 0.041; 93% of values were approximately balanced ($0.8 \leq \text{ratio} \leq 1.2$), and only 7% showed dominance by either engine. In contrast, MV White had a mean ratio of 1.191 and a much wider IQR of 0.357, indicating frequent starboard dominance and greater dispersion (an IQR nearly eight times larger). Only 55% of MV White's ratios were balanced, while 41% were starboard-dominant. These results suggest MV Frisco maintains balanced engine operation, whereas MV White frequently exhibits substantial load imbalances. Potential contributing factors include trip phases, environmental conditions, propeller performance, and vessel and engine characteristics such as power-to-weight ratio.

Results indicate that port- and starboard-dominant engine load ratios vary by trip phase. Each ferry trip exhibited five phases: departure-maneuvering, acceleration period, cruising, deceleration period, and docking-maneuvering. Based on 1 Hz vessel-speed data, maneuvering occurs below the 5th percentile of trip speed (2–5 mph), while acceleration and deceleration fall between the 5th and 20th percentiles (2–8 mph), identified by sustained speed changes of ± 0.25 mph/s for at least 3 seconds. Cruise speed spans the 20th-80th percentiles (8–11 mph), with high-speed bursts exceeding the 80th percentile (> 11 mph).

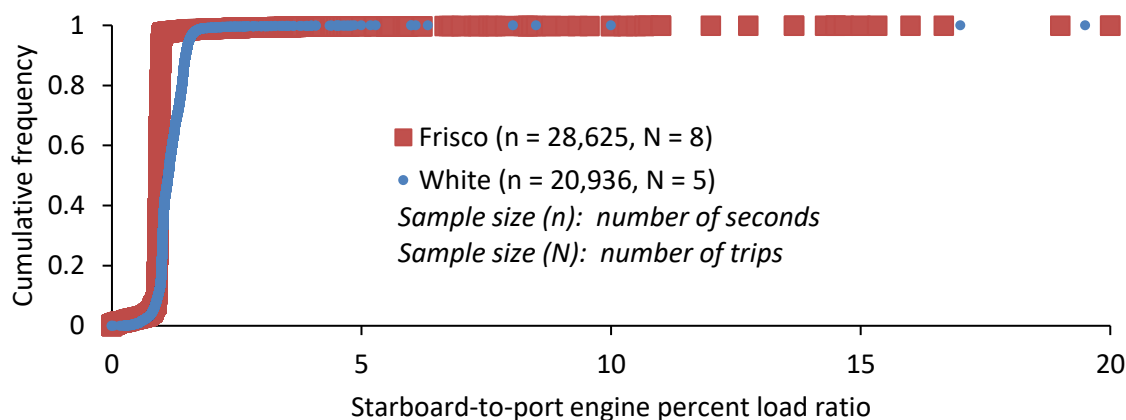


Figure 2-3. Cumulative frequency distribution of 1 Hz ratios of percent loads for starboard over port engines by vessel.

Figure 2-4 presents spatial patterns of 1 Hz starboard-to-port engine load ratios under co- and counter-current conditions to assess locations of unbalanced load. These were observed near ports during maneuvering phases, with both vessels exhibiting port- and starboard-dominant ratios. These imbalances coincide with frequent acceleration, deceleration, and sharp course changes. Such behavior reflects fluctuations in shaft power demand during tight maneuvers, and it is influenced by screw propeller dynamics (Viviani et al., 2007). In twin-screw vessels, these conditions can induce power and torque imbalances (Coraddu et al., 2013) due to limited steering effectiveness at low speeds and near-port operations (W. Liu et al., 2024).

Figure 2-4(c–d) shows that MV White exhibits substantially longer durations of unbalanced engine loading during counter-current cruising compared to MV Frisco. Under counter-current conditions, MV White operated with unbalanced loading for 59 to 72% of trip time, while MV Frisco did so for only 0.2–2.5%. During co-current cruising, both vessels maintained balanced loading for most of the trip, with MV White between 85–98% and MV Frisco between 98–100% of the trip time. These differences are likely attributed to variations in propeller technology and P/W ratios.

Differences in propeller technology support explaining the observed engine load imbalances. MV Frisco uses twin-screw propellers, while MV White is equipped with Voith-Schneider (VSP) cycloidal propellers: rotating disks with vertical blades capable of generating thrust in any horizontal direction (W. Liu et al., 2024). The VSP offers enhanced maneuverability by allowing continuous adjustments to both thrust magnitude and direction, although VSP thrust is inherently unsteady due to constant blade angle modulation (W. Liu et al., 2024). This unsteadiness is exacerbated by wind-induced resistance and requires continuous compensation, resulting in fluctuating blade thrust and engine load imbalances (Prabhu et al., 2019). These dynamic adjustments enable the VSP to maintain superior control in response to wind, waves, and currents (VOITH, 2024).

MV Frisco's P/W ratio is 107% higher than that of MV White, indicating greater thrust per unit hull mass from its twin-screw propellers. This higher thrust capacity explains MV Frisco's higher average speeds [Figure 2-4(a)] and its ability to maintain balanced engine loading while overcoming resistance during counter-current cruising. In contrast, MV White's lower P/W ratio contributes to the unbalanced loading observed under similar conditions [Figure 2-4(b)].

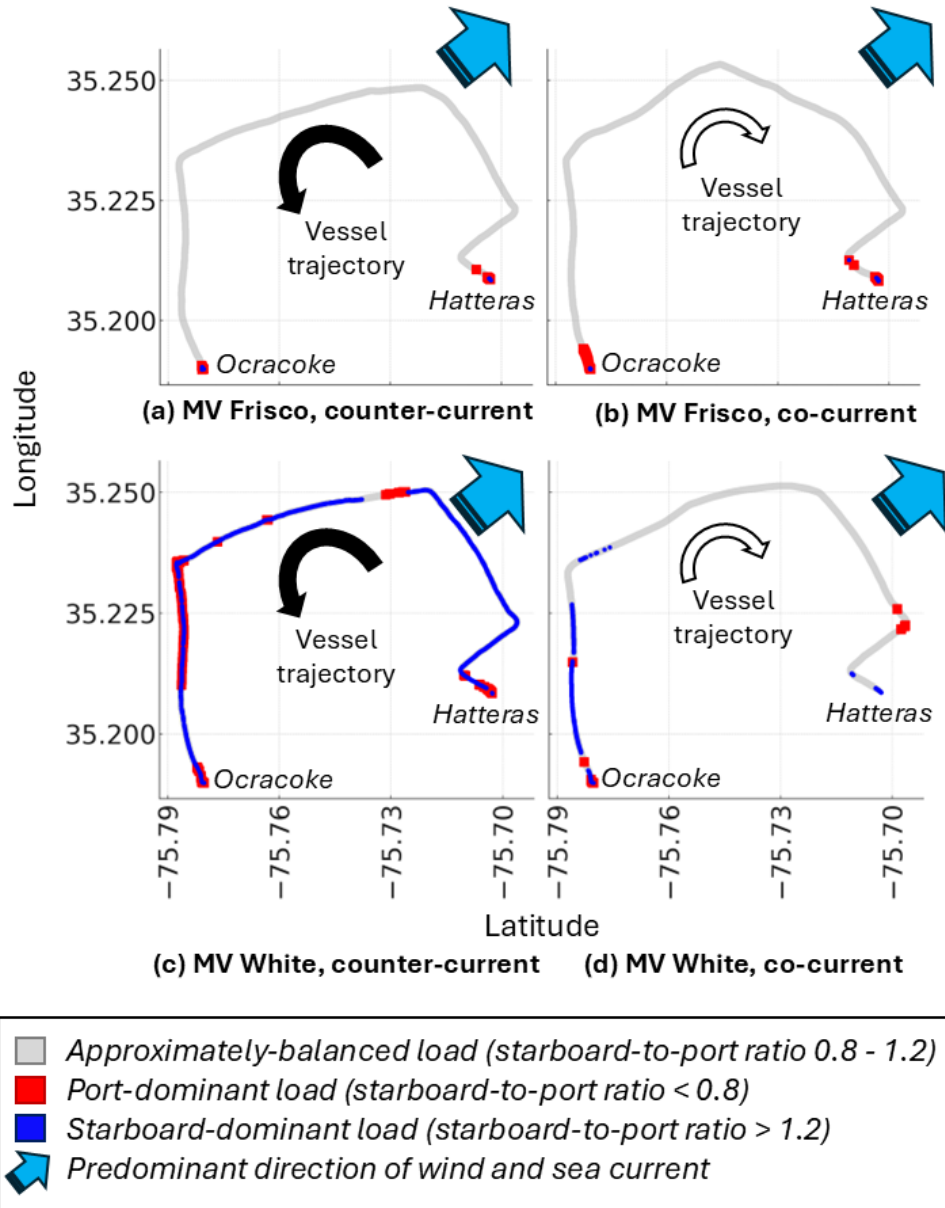


Figure 2-4. Examples of the spatial distribution of 1 Hz starboard-to-port percent load ratios for vessels operated on the Ocracoke-Hatteras route: (a) MV Frisco sailing counter-current, (b) MV Frisco sailing co-current, (c) MV White sailing counter-current, and (d) MV White sailing co-current.

Figure 2-5 presents cumulative distributions of 1 Hz engine percent loads to assess inter-trip variability. For MV Frisco, the starboard engine operated at mean loads of 66–80% (IQR: 4–22%), while the port engine ranged from 70–86% (IQR: 4–19%), depending on the trip. On average, the port engine operated at 7.2% higher loads than the starboard across trips. Despite this difference, both engines exhibited similar load distributions by central tendency and dispersion, indicating an overall balanced workload across trips and sailing orientations.

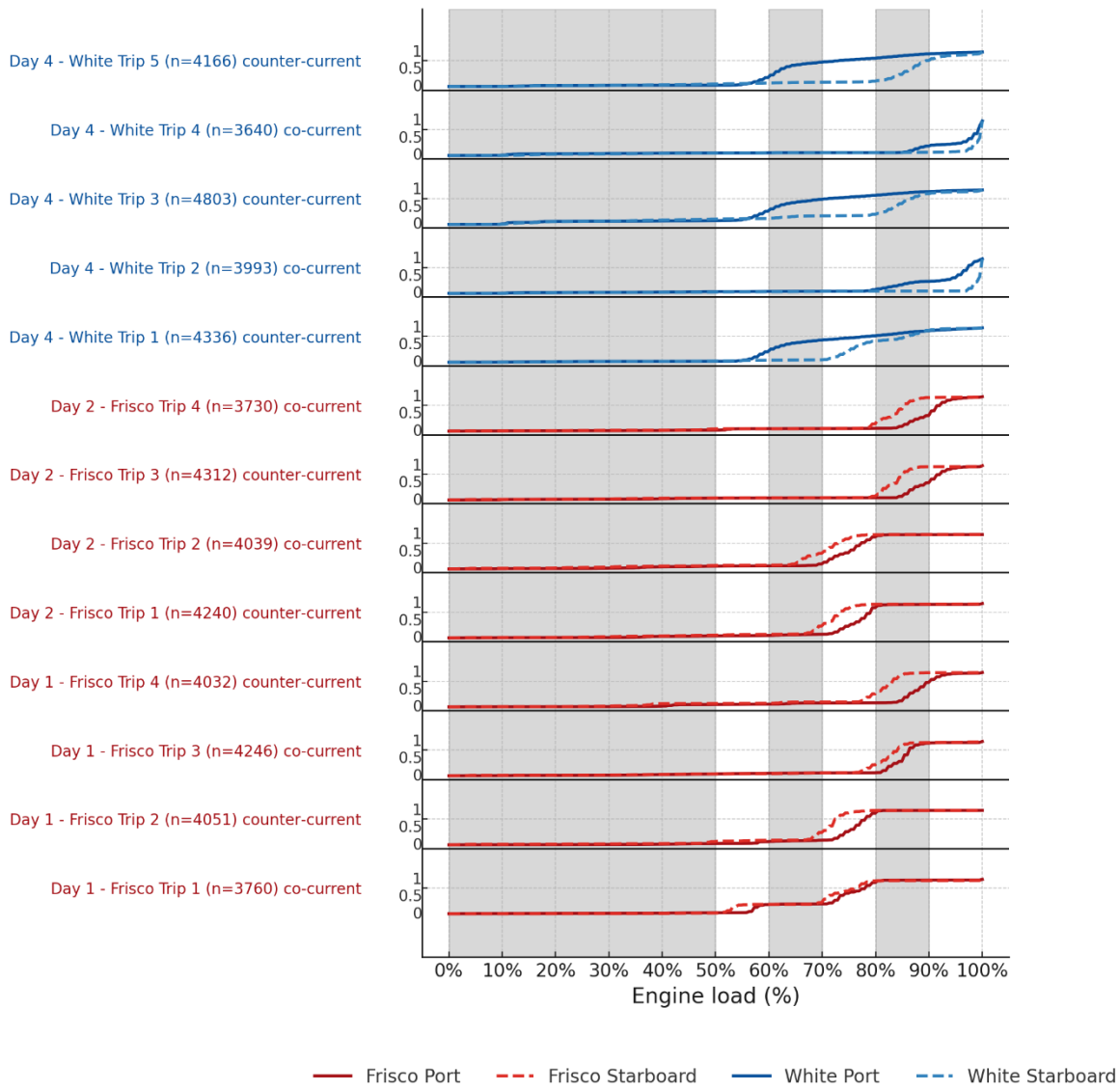


Figure 2-5. Cumulative frequency distribution of 1 Hz engine percent loads for the 13 one-way trips with simultaneous port and starboard data (8 trips for MV Frisco and 5 trips for MV White). Trips are categorized as sailing co-current or counter-current with sea and wind, and n indicates the number of seconds per trip.

Unlike MV Frisco, MV White exhibited notable load imbalances influenced by sailing orientation. During co-current trips, the starboard engine operated at consistently high mean loads (94–96%) with minimal variability (IQR: 2%), while the port engine averaged 89–90% with greater variability (IQR: 10–12%). These results indicate that MV White operated both engines near full capacity during co-current trips, with the starboard engine maintaining less variable load levels than the port.

During counter-current trips, MV White’s starboard engine operated at mean loads of 74–82% (IQR: 7–12%), while the port engine ranged from 62–68% with broader IQRs

of 13–19%. These lower port engine loads indicate a substantial imbalance, consistent with the thrust adjustments required by VSP propellers to counter opposing wind and sea currents. This pattern aligns with the starboard-dominant load ratios observed during counterclockwise trajectories from Hatteras to Ocracoke, where the starboard engine plays a dominant role in the vessel turning and displacing towards the southwest [Figure 2-5(c)].

2.3.4 Fuel Use, Emission Rates, and Time Spent by Percent Load Bin

One Hz empirical FUERs and the time spent by engine percent load bins are shown in Figure 2-6 and Figure 2-7, respectively. Over 85% of the empirical data were valid after quality assurance. Percent load bins between 0–50% were combined due to limited sample sizes and low variability in FUERs. Across all six bins, average modal rates of fuel use, CO₂, NO_x, and PM generally increased monotonically with engine percent load for each vessel-engine combination.

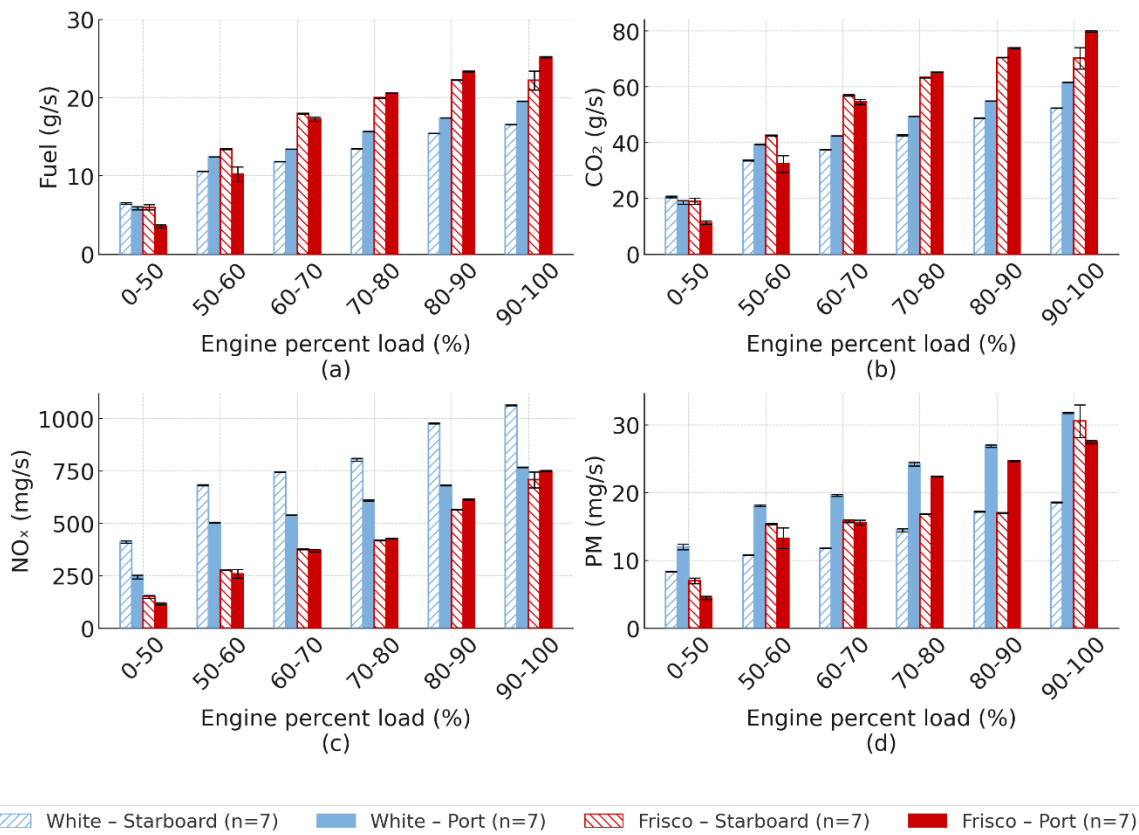


Figure 2-6. One Hz average in-use fuel use and emission rates by percent load bins for main engines and vessels: (a) fuel use, (b) CO₂, (c) NO_x, and (d) PM. Error bars indicate 95% uncertainty intervals, and n is the number of trips.

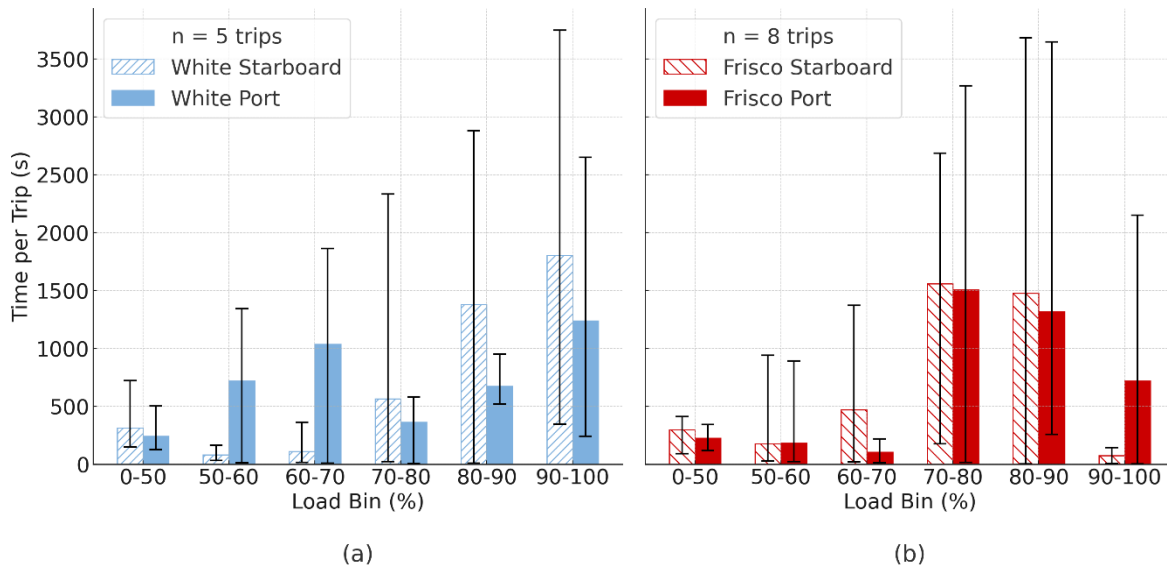


Figure 2-7. Variations in average time spent per trip by engine percent load bin for main engines and vessels: (a) MV White, and (b) MV Frisco. Error bars represent the minimum and maximum time per trip across all trips in each load bin, and n is the number of trips.

On average, MV White’s fuel use is 21% lower than MV Frisco’s [Figure 2-6(a)], consistent with NCDOT Ferry Division records indicating approximately 47% lower fuel use per mile when accounting for all fuel consumption sources, including auxiliary engines. This difference is primarily attributed to MV White’s lower total main engine rated power, which as predicted by the propeller law, estimates a 20% reduction in fuel consumption that closely resembles the observations. Additionally, cycloidal propellers offer more optimal operation across varying load conditions by optimizing torque, pitch ratio, and engine RPM (Henry, 1959), that can contribute to fuel savings of up to 30% compared to conventional screw propellers (PW Consulting Automotive & Machinery Research Center, 2024).

On average, across all six load bins and engines, MV Frisco’s NO_x emissions are approximately 37% lower and PM emissions about 2% lower than those of MV White [Figure 2-6(c–d)]. These differences are primarily attributed to engine technologies, particularly targeted for NO_x reduction. MV Frisco’s EPA Tier 3-certified engines use advanced features such as electronic fuel control (CAT ACERT), high-pressure injection, optimized combustion chamber design, and exhaust gas recirculation to reduce NO_x and soot formation (Caterpillar, 2012). In contrast, MV White’s uncertified engines rely on mechanically timed injections (Diesel Pro, 2025), not designed for emissions control. These findings underscore the potential emission reduction benefits of upgrading to EPA-certified engines.

It is noteworthy that there is a well-recognized trade-off for NO_x emissions versus fuel consumption and PM emissions, particularly for non-certified Tier engines such as those on MV White (DieselNet, 2020; IMO, 1999). At the engine level, the overall higher fuel use on the port engine compared with the starboard engine is likely associated with lower in-cylinder temperatures or delayed combustion, which suppress NO_x formation but

generate higher PM emissions. On MV Frisco, the implementation of Tier 3 standards is associated with higher fuel injection pressure, improved turbocharging and aftercooling, optimized combustion chamber design, and other upgrades that counteract this trade-off (DieselNet, 2020). At the vessel level, differences in FUEs are explained by engine design, which enables the MV Frisco engines to comply with EPA emission standards, while NO_x and PM emissions from the non-certified engines on MV White were higher.

Figure 2-7 shows that MV White operated predominantly at the highest engine loads (80–100%), whereas MV Frisco operated at moderately high loads (70–90%). MV White exhibited greater inter-engine variability, with the starboard engine spending 14 percentage points more time at high loads than the port engine. In contrast, MV Frisco maintained a more balanced operation, with only a 6 percentage point difference between engines.

2.3.5 Variability in Trip-Average Fuel Use and Emission Rates

Figure 2-8 shows the comparison of estimated trip-average FUEs across main engines and vessels. Based on five-fold cross-validation, the mean percentage errors of model estimates vary from 1.43% to 9.24% depending on pollutant species. This validation verified the model's accuracy in estimating trip-average FUEs.

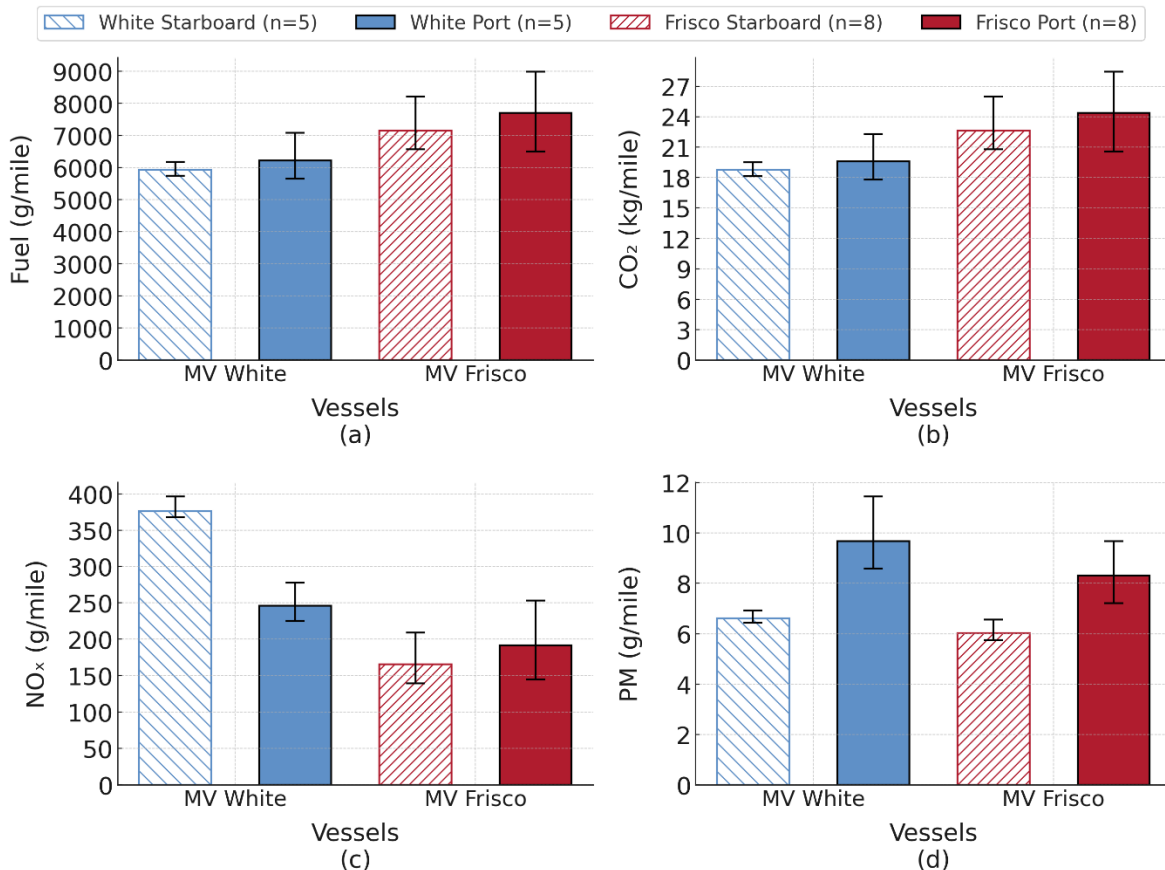


Figure 2-8. Estimated trip-average fuel use and emission rates between main engine and vessels: (a) Fuel use, (b) CO₂, (c) NO_x, and (d) PM. Error bars represent the minimum and maximum values among the trips, and n is the number of trips.

2.3.5.1 Inter-engine variability

For MV White, the starboard engine's trip-average fuel use and CO₂ emission rates are approximately 4% lower than those of the port engine. For MV Frisco, the starboard engine's trip-average fuel use and CO₂ emission rates are about 7% lower than those of the port engine.

Trip-average NO_x and PM emission rates vary by engine and vessel. For MV White, the port engine emits approximately 35% less NO_x than the starboard, while the starboard emits about 32% less PM than the port. For MV Frisco, the starboard engine emits roughly 14% less NO_x and 28% less PM than the port engine.

2.3.5.2 Inter-vessel variability

On a trip-average basis, MV White exhibits 18 % less fuel use and CO₂ emission rates per mile than MV Frisco. As mentioned, this is explained by differences in the P/W ratio. On a trip-average basis, MV Frisco emits approximately 43 % less NO_x and 12 % less PM emissions per mile compared to MV White. As mentioned, these differences are attributed to engine technologies.

2.3.5.3 Inter-trip variability

Inter-trip variability in FUERs was greater on MV Frisco than on MV White. On MV Frisco, trip-average rates varied by 20–28% for fuel use and CO₂, 33–43% for NO_x, and 12–25% for PM. In contrast, MV White exhibited smaller ranges: 7–20% for fuel use and CO₂, 7–19% for NO_x, and 7–25% for PM. This higher variability on MV Frisco is linked to more frequent acceleration/deceleration bursts and larger CVS and RPA. Overall, the minimum trip-average FUERs are approximately 7 % to 43 % lower than the corresponding maximum rates, depending on the pollutant.

Inter-trip variability in FUERs is also influenced by sailing orientation. For instance, for MV Frisco, the mean trip-average FUERs during co-current sailings are 1.7–4.8% lower than during counter-current sailing. This indicates a modest penalty in trip-based fuel use and emissions associated with environmental conditions such as sea current speed and direction.

2.3.6 Comparison of Sources of Variability

Results from the ANOVA for the relative importance of vessel, engine, trip operational characteristics, sailing orientation, and environmental factors are given in Table 2-2. Differences in engines explained about 70% of the variability in PM emissions, but less than 6% of the variability in fuel use, CO₂, and NO_x across trips. This suggests that the effects of load imbalances between both main engines could contribute to substantially influence the PM emissions across trips.

Differences in vessel characteristics accounted for about 53% of the variability in fuel use and CO₂ emissions, about 62% of the variability in NO_x emissions, but only 10% of the variability in PM emissions between trips. These differences include engine and vessel characteristics, such as differences in P/W ratio and propeller technologies that influence fuel consumption and CO₂ emission rates. Differences in vessel operation, such as in peak speed and CVS, explained less than 2% of the variability in FUERs across trips.

Table 2-2. Sources of variability in trip-average fuel use and emission rates based on analysis of variance. F-ratios, P-values, and classical η^2 (%) are shown. CVS = Coefficient of variation of speed; RPA = Relative positive acceleration. Significant sources are shown in bold (P-value <0.05).

(a) Fuel Use and CO₂				(b) NO_x				(c) PM			
Factor	F-ratio	P-value	η^2 (%)	Factor	F-ratio	P-value	η^2 (%)	Factor	F-ratio	P-value	η^2 (%)
Vessel	204.9	<0.01	52.9	Vessel	279.7	<0.01	62.2	Vessel	76.3	<0.01	9.5
Engine	22.6	<0.01	5.8	Engine	19.1	<0.01	4.2	Engine	566.0	<0.01	70.4
Peak speed	6.0	0.02	1.5	Peak speed	3.3	0.07	0.7	CVS	9.5	<0.01	1.2
Trip average speed	3.0	0.09	0.8	CVS	0.8	0.37	0.2	Avg. wind speed	2.7	0.11	0.3
RPA	1.7	0.20	0.4	RPA	0.8	0.37	0.2	RPA	1.2	0.27	0.2
CVS	1.6	0.21	0.4	Sailing orientation	0.1	0.73	0.0	Sailing orientation	0.8	0.37	0.1
Sailing orientation	1.5	0.22	0.4	Avg. wind speed	0.0	0.87	0.0	Avg. current speed	0.7	0.42	0.1
Avg. wind speed	0.2	0.66	0.1	Avg. current speed	0.0	0.94	0.0	Trip average speed	0.7	0.42	0.1
Avg. current speed	0.0	0.92	0.0	Trip average speed	0.0	0.97	0.0	Peak speed	0.0	0.98	0.0

2.4 Conclusions

Real-world FUERs were quantified for two passenger ferry vessels, and variability was assessed across vessels, main engines, and trips. Variability in trip-average fuel use, CO₂, and NO_x emission rates was predominantly explained by differences in vessel characteristics and engine technologies. These findings suggest opportunities for fuel savings and CO₂ and NO_x emissions reductions through vessel modifications and engine upgrades.

Variability in trip-average PM emission rates is mainly explained by differences between engines in each vessel. Load imbalances during maneuvering phases were common for both vessels, and more frequent during cruising on counter-current trips for vessels like MV White equipped with cycloidal propellers. These findings suggest that PM emissions could be reduced by addressing conditions that contribute to differences between main engines such as load imbalances, the influence of trip phases, environmental conditions, and propeller technologies on them.

The assessment of variability in FUERs evidenced a trade-off for NO_x emissions versus fuel consumption and PM emissions between main engines on MV White. This trade-off was likely counteracted by updated engine technologies on MV Frisco. This underscores the importance of engine upgrades and evaluating the integrated selection of engine and propulsion systems. Other considerations of importance involve trip planning based on environmental conditions, since their interaction with the engine and propeller systems could ultimately influence FUERs.

Although inter-trip variability in trip-average FUERs is relatively smaller than inter-vessel and inter-engine variabilities, it remains considerable (e.g., 7%–43%), highlighting the potential for fuel savings and emissions reductions through modified ferry operations. The inter-trip variability is also slightly influenced by sailing orientation, highlighting the impact of environmental conditions (e.g., sea current speed and directions) on trip FUERs.

CHAPTER 3: QUANTIFYING FERRY FLEET EMISSIONS AND UNCERTAINTY WITH APPLICATIONS TO REDUCTION STRATEGIES

3.1 Introduction

In 2022, diesel-powered vessels comprised 77% of the U.S. in-service ferry fleet (USDOT, 2024b), producing particulate matter (PM) emissions, a pollutant associated with an estimated 60,000 global deaths each year from cardiopulmonary and lung cancer (Corbett et al., 2007). Vessel emissions have also been identified as a contributing factor to cardiovascular and respiratory illnesses (Tichavska & Tovar, 2015). Ferries, in particular, represent a substantial source of air pollution in coastal areas and along inland waterways (Frederickson et al., 2022).

In addition to PM, diesel-powered maritime transportation is a notable source of health-relevant pollutants, including nitrogen oxides (NO_x) and hydrocarbons (HC) (Gössling et al., 2021). Reducing vessel emissions can mitigate health impacts from the marine transportation sector, as they contributed to up to 266,000 premature deaths worldwide from lung cancer and cardiovascular disease in 2020 (Sofiev et al., 2018). Maritime transportation is also a major source of carbon dioxide (CO₂) emissions, which are the target of decarbonization strategies under the International Maritime Organization's goal of achieving carbon neutrality by 2050 (IMO, 2023a).

With the growth of the maritime transportation sector in the United States, diesel engines of ferry vessels represent a readily addressable target for improving air quality (Corbett & Farrell, 2002). As a result, urban air quality and transportation planners aiming to meet National Ambient Air Quality Standards under the Clean Air Act may prioritize reducing local marine emissions over broader national or international initiatives (Corbett & Farrell, 2002). Therefore, accurately quantifying ferry emissions, along with the associated uncertainties, is essential for evaluating environmental impacts and supporting air quality improvements.

Uncertainty describes the limited knowledge about the true magnitude of emissions at a specific location and time. Accounting for uncertainty in emission rates allows analysts to evaluate the probability of achieving emission reduction goals and evaluate the cost-effectiveness of mitigation strategies (Frey, 2007). The robustness and effectiveness of these strategies are enhanced by incorporating uncertainty into decision-making processes (Frey & Zheng, 2002). Quantifying uncertainty also provides insight into the reliability of emission factors and forms the foundation for estimating uncertainty in emission inventories (Frey & Bammi, 2002). In addition, quantifying uncertainty in emissions, by means such as probabilistic analysis, can be particularly useful when in-use measurements are not feasible or are logistically challenging.

Probabilistic analysis, such as numerical simulation methods, has been employed to quantify the uncertainty in emission estimates. For instance, Frey et al. (1999) demonstrated the use of these methods for quantifying uncertainty in emission factors, activity factors, and emission inventories for power plants and light-duty gasoline vehicles, underscoring their broad applicability to emissions modeling. Larrahondo et al. (2025) applied numerical simulation approaches using non-parametric bootstraps to estimate emissions from one ferry vessel and associated uncertainty. This approach avoided assuming normality in reference emission or activity factors, was applicable to a small sample size, and produced results statistically comparable to other established methods (Larrahondo et al., 2025).

Besides estimating uncertainty in vessel emissions, evaluating their key contributing factors via sensitivity analyses supports developing improved estimates of emissions (Frey, 2007). Key contributing factors to vessel emissions include emission factors of main and auxiliary engines, engine load, rated power, and vessel operating hours (Larrahondo et al., 2025). Although the sensitivity of annual ferry emissions to these contributing factors has been evaluated at the vessel level, they have not yet been systematically assessed across multiple vessels and over multiple years at the fleet level. These assessments of key contributing factors should ultimately support decision makers and stakeholders by guiding the prioritization of scarce resources toward additional research and data collection, informing choices among alternatives under uncertainty, and enabling the evaluation of trends over time (Frey, 2007).

Evaluating emission reduction scenarios against current emissions will benefit fleet management and support subsequent efforts to quantify the benefits associated with these reductions. This is because quantifying the benefits resulting from reductions or avoidance of mobile source emissions has been an essential step in evaluating operational strategies (Ashok et al., 2017; Gouge et al., 2013), and in guiding technology adoption (Tessum et al., 2014) that can ultimately improve air quality. In the literature, potential emission reduction strategies are most often evaluated using deterministic scenario analyses (based on point estimates and comparative metrics) rather than formal probabilistic approaches (Edenhofer, 2014; Lee & Romero, 2023; Rogelj et al., 2018). These methods are common in the marine sector, where a baseline and one or more mitigation scenarios are typically defined using models or inventories, and their outcomes are compared or tested via sensitivity analyses (EPA, 2009; IMO, 2021). As noted by Morris et al. (2025) while these approaches provide useful insights, relying solely on a limited set of predefined emission scenarios constrains the range of uncertainty explored and prevents a quantitative probabilistic interpretation. Consequently, there is growing interest in probabilistic, risk-based approaches to better inform mitigation planning (Morris et al., 2025).

The objectives of this work are to: (1) quantify annual ferry fleet emissions and uncertainties, (2) evaluate key contributing factors affecting the emission estimates, and (3) assess potential emission reduction scenarios for the fleet.

3.2 Methods

The methods include: (1) study design, (2) estimation of ferry emissions, (3) quantifying uncertainty in emission estimates, (4) scenarios of emission reduction potentials, (5) sensitivity analysis, and (6) comparison of vessel emission intensities.

3.2.1 Study Design

The North Carolina Department of Transportation (NCDOT) Ferry Division operates the second-largest fleet among the 37 states with ferry systems. Its 23 vessels run on seven routes and in 2024 carried over 700,000 vehicles and 1.5 million passengers (NCDOT, 2024). Each vessel typically operates two identical diesel main engines and one auxiliary engine. This fleet has variable vessel characteristics in terms of compliance of EPA marine emission standards for main engines (over half are uncertified, while the remainder comply with Tier I–III), per-vessel passenger capacity (133–300 passengers), vehicle capacity (20–50 vehicles), main engine rated power (313–846 kW), and engine displacement (3.3–18.1 L).

3.2.2 Estimation of Ferry Emissions

Emission factor–based models are commonly applied in developing emission inventories, where pollutant releases from a source (e.g., an engine) are estimated as the product of emission factors and activity factors (EPA, 2024c). For a ferry vessel, annual emissions of a given pollutant (e.g., tons per year) were estimated by summing the products of emission factors and activity factors across all engines on the vessel according to Equation 3.1.

$$E_{y,p} = C \times \sum_{i=1}^n EF_{i,p} \times AF_{i,y} \quad (3.1)$$

where,

- $E_{y,p}$ = annual ferry emissions for year y and pollutant p (t/year);
- C = conversion factor ($t/1 \times 10^6$ g);
- n = number of engines in the vessel;
- EF_i = emission factor for engine i and pollutant p (g/kWh);
- $AF_{i,y}$ = activity factor for engine i and year y (kWh/year).

3.2.2.1 Emission Factors

Emission factors reflect average pollutant emission rates for specific source categories (EPA, 1995; Frey et al., 1999). For ferry engines, they are reported in grams of pollutant per kilowatt-hour of engine output (g/kWh) (ISO, 2020). Reference PM and NO_x+HC emission factors for main and auxiliary engines were identified from the U.S. EPA engine certification databases. These factors are derived from standardized testing protocols specified in 40 CFR Part 1065, which include duty cycles designed to replicate typical operating conditions, including speed and load variations (EPA, 2005). Primary data were obtained from the Marine Compression-Ignition Engine Certification Database (EPA, 2018b, 2024a), supplemented with secondary data from the Nonroad Compression-Ignition Engines Certification Database (EPA, 2018c, 2024b). Following a procedure similar to that proposed by Khan and Frey (2018), engine emission factors were matched to certification records based on characteristics such as engine manufacturer, model, EPA certification tier, model year group, displacement, rated power, and rated speed.

3.2.2.2 Activity Factors

Activity factors describe the level of emissions-related activity (EPA, 2024c), such as the annual energy output of a ferry engine (kWh/year). For each engine, the activity factor was calculated as the product of the engine load (expressed as a percentage of its rated power), the rated power, and the vessel's total annual operating hours according to Equation 3.2.

$$AF_{i,y} = L_i \times RP_i \times OH_y \quad (3.2)$$

where,

- L_i = trip-average percent load for engine i (%);
- RP_i = engine rated power for engine i (kW);
- OH_y = annual vessel operating hour for year y (h/year).

Trip-average engine loads were applied since the certification database emission factors are based on duty-cycle testing. Main engine percent loads were derived from measurements on two electronically governed CAT C18 engines over 18 one-way trips on the Hatteras–Ocracoke route. Two CAT Electronic Technician (CAT-ET) datalink tools recorded 1 Hz percent load data for each engine in each vessel. Data completeness and an evaluation that indicates that the two

main engines of a vessel operate equally on a per-trip basis were performed, and details are presented elsewhere (Larrahondo et al., 2025).

Annual CO₂ emissions were estimated using a mass balance approach based on annual fuel consumption for each ferry as reported by NCDOT records, and the ultimate analysis of ultra-low sulfur diesel fuel (Frey & Graver, 2012), the equivalent molecular formula for this fuel, and the assumption that 99% of the carbon in diesel fuel is converted to CO₂ (EPA, 2018a).

3.2.3 Quantifying Uncertainty in Emission Estimates

Uncertainty in emission estimates propagates from uncertainty in each input variable, namely, emission factors and activity factors (Kuenen & Dore, 2023). For emission factors, uncertainty was propagated from the distribution of reference PM and NO_x+HC emission factors for the two main engines and the auxiliary engine. For activity factors, uncertainty was propagated from the distribution of trip-average percent loads for each engine.

Uncertainty in annual ferry emissions was quantified using numerical simulation methods, specifically non-parametric bootstrap simulations (Frey & Bammi, 2002). For each vessel, pollutant, and calendar year between 2019 and 2024, 10,000 bootstrap iterations were performed by randomly resampling with replacement from the non-parametric distributions of emission factors and trip-average percent loads.

3.2.4 Sensitivity Analysis

Sensitivity analysis was applied to identify what factors predominantly influenced variability in emission estimates. This analysis quantified the correlations between annual emission estimates and key contributing factors, including engine emission factors, percent load, rated power, and annual operating hours. Correlation analyses were performed for six calendar years (2019–2024) to assess both interannual (between years) variability and intra-annual (within a year) variability in fleet emissions across all vessels. Monotonic relationships were assessed using Spearman’s rank correlation coefficients (ρ).

3.2.5 Estimation of Emission Reduction Potentials for the Ferry Fleet

The assessment of emission reduction potential includes three scenarios such as (1) vessel rearrangements; (2) a compliance engine upgrade scenario; and (3) a maximum stringency engine upgrade scenario.

3.2.5.1 Emission Reduction Potential by Vessel Rearrangements

An optimization model to minimize total annual fleet emissions in the year 2024 was proposed by minimizing the objective function according to Equation 3.3. For each vessel i and pollutant p , an emission rate $e_{i,p}$ (t pollutant/h) was assigned according to results obtained from non-parametric bootstrap simulations for the year 2024. Route–year “slots” s were defined as a service requirement to be met by a ferry with certain annual operating hours h_s and a certain vessel size class in 2024. Four vessel size classes were classified by maximum capacity of passengers, vehicles, and typical length overall in categories such as large vessel (300 passengers, 50 vehicles, 220 ft), medium vessel (300 passengers, 40 vehicles, 180 ft), small vessel (149 passengers, 30 vehicles, 150 ft), and passenger-only vessel (133 passengers, 92 ft). A one-to-one assignment of vessels to slots was constrained to satisfy size feasibility and to fill each slot exactly once, thereby preserving h_s . Rearrangements were computed, regardless of existing vessel routes, until minimizing the total annual fleet emissions of the pollutant p .

$$\min_{x \in \{0,1\}^{n \times m}} \sum_{i=1}^n \sum_{s=1}^m e_{i,p} h_s x_{is} \quad (3.3)$$

Subject to:

$$\sum_{i=1}^n x_{is} = 1; \quad \forall s = 1, \dots, m$$

$$\sum_{s=1}^m x_{is} = 1; \quad \forall i = 1, \dots, n$$

where,

- i = vessel index; n is the total number of vessels;
- s = slot index; m is the total number of route-year slots in 2024 (size-hours demand);
- x_{is} = decision variable: entries of a binary assignment matrix $X = [x_{is}]$ with rows = vessels (n) and columns = slots (m). Entry $x_{is} = 1$ if vessel i is assigned to slot s ; 0 otherwise;
- $e_{i,p}$ = expected emission rate of vessel i for pollutant p (t/h) from the non-parametric bootstrap;
- h_s = annual operating hours associated with slots.

A total of five vessels were excluded from this scenario due to operative limitations that constraint their relocation, being the MVs Governor Daniel Russell, Governor James B. Hunt, Ocracoke Express, Avon, and Salvo. The MV Governor Daniel Russell is a double-ended ferry equipped with a screw propeller and rudder at each end. It is the only River Class (medium-sized) ferry in the fleet that operates with this configuration, and compared to other vessels of the same size, it exhibits reduced maneuverability around the shoals near the barrier islands. Other vessels of this size employ propulsion technologies that provide superior maneuverability, such as Schottel Combi Drive propellers and Voith Schneider propellers.

The MV Governor James B. Hunt is certified by the U.S. Coast Guard to operate only in freshwater, specifically on the Currituck–Knotts Island route, which is the only freshwater route in the system. As a result, its credit dry dock cycle and maintenance requirements differ from those of vessels operating in saltwater. Consequently, the MV Hunt is not permitted to operate on any other routes.

The MV Ocracoke Express is a passenger-only vessel with a unique loading and offloading design. It is designated to operate on the Hatteras–Ocracoke route, supporting increased commuter demand between May and September.

MVs Avon and Salvo are double-ended ferries that operate on the Cherry Branch–Minnesott Beach route and are equipped with unique propulsion systems (Schottel Combi Drive propellers), which are not well suited for maneuvering around the shoals near the barrier islands. These vessels also have electrical systems that differ substantially from those of the rest of the fleet. At present, only the vessel crews and maintenance personnel based at Cherry Branch are qualified to operate and service them.

3.2.5.2 Compliance Engine Upgrade Scenario

The emission reduction potential from upgrading technologies on all feasible main and auxiliary engines was estimated by updating engine emission factors to the latest EPA standards (Tier 3 or

Tier 4), based on their current displacement and rated power. Only engines with rated power of 600 kW or higher are subject to be upgraded to Tier 4 according to the defined emission standards in the regulation. Emission factors for PM and NO_x+HC were selected in accordance with EPA regulations for marine compression-ignition engines (EPA, 2020). For each vessel and pollutant in 2024, these standards replaced the original emission factors across 10,000 bootstrap iterations (Section 3.2.3), generating distributions of reduced annual emissions and associated uncertainties. Percentage reductions were then calculated relative to the baseline for each iteration, producing distributions of 10,000 reduction values per vessel and pollutant, from which mean reductions and uncertainty ranges were derived.

Annual fuel use and CO₂ emissions for a given vessel were assumed to consist of 85% from the main engines and 15% from the auxiliary engines (IMO, 2023b). A 12% reduction in average annual CO₂ emissions was applied to all engines assumed to be upgraded from non-certified to EPA Tier 3 standards. This reduction is proportional to the reduction in fuel consumption documented for this intervention by the EPA on the MV Delaware ferry in the state of Delaware (EPA, 2015). This same percent reduction was applied to engines to be upgraded from Tier 1 to Tier 3 standards since the same harbor craft emission factors for CO₂ have been applied consistently between uncertified, Tier 1 and Tier 2 engines (ICF International, 2009). For incremental upgrades between Tier 2 and Tier 3, a 4% reduction in CO₂ emissions was estimated by comparing in-use emission measurements for two ferry vessels operating on these technologies (Frederickson et al., 2022). For incremental upgrades between Tier 3 and Tier 4 for the MVs Sea Level and Swan Quarter, an average 4% reduction in CO₂ emissions was applied based on a range of 2% to 6% reduction observed for commercial harbor crafts (Moorhead et al., 2019).

3.2.5.3 Maximum Stringency Engine Upgrade Scenario.

A maximum stringency scenario for emission reductions was evaluated by upgrading all main and auxiliary engines to meet Tier 4 standards. For this scenario, engines rated below 600 kW would require repowering to achieve Tier 4 emission factors, consistent with regulatory requirements. A 12% reduction in average fuel use and annual CO₂ emissions was applied to engines upgraded from non-certified or Tier 1 to Tier 4 standards (EPA, 2015). This is because a reduction of at least 12% could be expected from non-certified to Tier 3 standards (EPA, 2015). Moreover, non-certified engines were assumed to follow the least stringent emission factors (Tier 1) in the baseline. For upgrades from Tier 2 or Tier 3 to Tier 4, an average 7% reduction in average fuel use and annual CO₂ emissions was assumed based on a range of 5% to 9% expected for these interventions on marine engines (Finning CAT, 2025).

3.2.6 Comparison of Emission Intensities Between Ferries

Additional interventions that consider the ferry passenger occupancy and miles traveled can be identified by comparing emission intensities for the year 2024 expressed as annual emissions per unit of transport work (e.g., tons of pollutant/passenger-mile). Annual ferry emissions by pollutant (t/year) were determined as described in the Estimation of Ferry Emissions section. Annual passenger count for the fleet in 2024 was retrieved from NCDOT communications (NCDOT, 2024) and distributed by route according to observed annual proportions of vehicles and average vehicle occupancy (Bert et al., 2020). Within each route, passenger counts were further allocated to individual vessels using the product of vessel maximum capacity and annual number of trips as weighting factors. Annual mileage of the fleet in 2024 was estimated from annual ferry operating hours, the average duration of each trip in addition to an average 15 minutes of dwelling time, and

the average trip distance, as reported by Bert et al. (2020). Emission intensities were also compared on a per-mile basis.

3.3 Results

Results include: (1) annual ferry emissions and uncertainty estimates; (2) emissions reduction potential for the ferry fleet; (3) key factors contributing to ferry emissions estimates; and (4) comparison of ferry emission intensities.

3.3.1 Annual Emissions and Uncertainty Estimates

Estimation of annual ferry emissions and 95% uncertainty intervals for the year 2024 are shown in Figure 3-1 for CO₂, NO_x+HC and PM. Appendix A details the methodology and results for estimating annual ferry emissions and the associated uncertainties, using MV Rodanthe, as a case study vessel. Annual emissions and uncertainty estimates for each vessel in the fleet for years 2019–2023 are given in Appendix B.

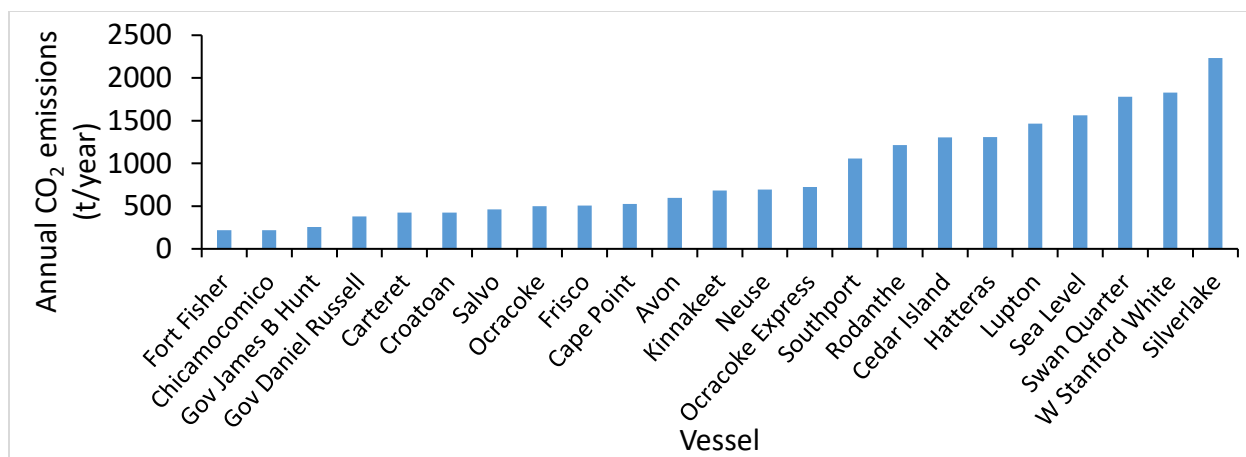
In 2024, annual CO₂ emissions varied substantially by vessel, ranging from 218 to 2,234 t/year. The lowest-emitting vessel was 90% lower than the maximum. Annual NO_x+HC emissions ranged from 2 to 35 t/year across vessels. The lowest-emitting vessel was 94% lower than the highest. The lower bounds of the 95% uncertainty intervals on the mean annual emissions were 85% to 94% lower than the upper bounds, depending on the vessel.

Annual PM emissions ranged from 0.06 to 0.62 t/year across vessels, with the lowest-emitting vessel 91% lower than the maximum. The lower bounds of the 95% uncertainty intervals on the mean annual emissions were 35 to 90% lower than the upper bounds, depending on the vessel.

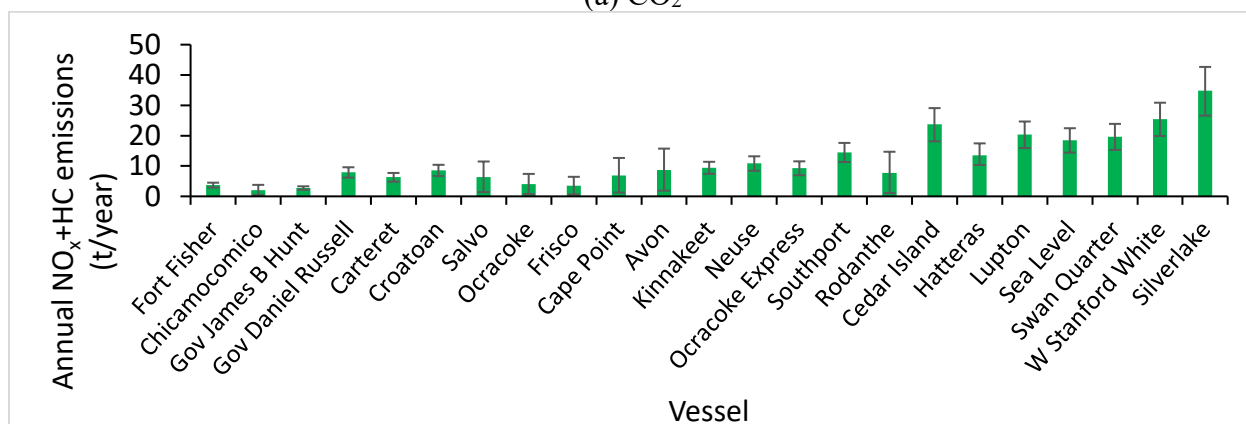
3.3.2 Key Factors Contributing to Ferry Emissions Estimates

Table 3-1 shows the results from correlation analyses for the contributing factors to intra-annual variability in PM and NO_x+HC emissions. Annual emission estimates for both PM and NO_x+HC are highly sensitive to operating hours ($\rho = 0.67 \pm 0.14$ to 0.88 ± 0.04 depending on the pollutant) and to main engine emission factors ($\rho = 0.30 \pm 0.10$ to 0.63 ± 0.07 depending on the pollutant).

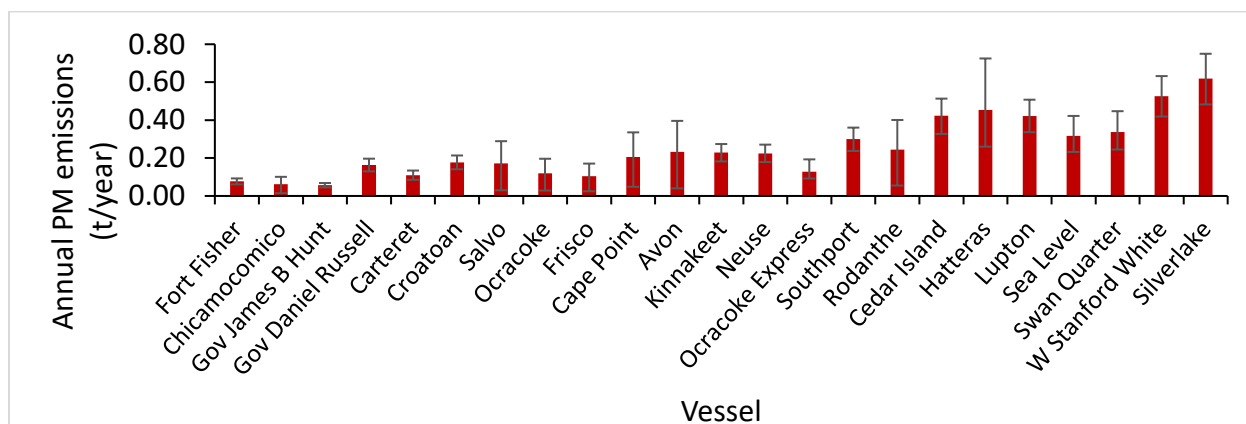
Table 3-2 shows the results from correlation analyses for the contributing factors to inter-annual variability in PM and NO_x+HC emissions. Annual emission estimates for both PM and NO_x+HC are highly sensitive to operating hours ($\rho = 0.70$ to 0.89 depending on pollutant) and to main engine emission factors ($\rho = 0.28$ to 0.60 depending on pollutant).



(a) CO₂



(b) NO_x+HC



(c) PM

Figure 3-1. Mean annual emissions for the year 2024 for (a) CO₂, (b) NO_x+HC, and (c) PM for the year 2024. Error bars represent the 95% uncertainty intervals. CO₂ emissions do not present uncertainty intervals because they were estimated based on fuel consumption and mass balance.

Table 3-1. Intra-year (within a year) correlation analysis of annual emission estimates for all vessels in the fleet from 2019 to 2024. Ranges show Spearman coefficients displayed as average $\pm$ standard deviation across the years. Sample size = 180,000 – 230,000 depending on year.

Contributing factor	Spearman Rank Correlation Coefficients	
	PM	NO _x +HC
Annual operating hours (h)	0.88 $\pm$ 0.04	0.67 $\pm$ 0.14
Emission factors of main engine (g/kWh)	0.30 $\pm$ 0.10	0.63 $\pm$ 0.07
Rated power of auxiliary engine (kW)	0.28 $\pm$ 0.20	0.38 $\pm$ 0.20
Rated power of main engine (kW)	0.18 $\pm$ 0.13	0.38 $\pm$ 0.07
Engine load of main engine (%)	0.16 $\pm$ 0.02	0.12 $\pm$ 0.02
Engine load of auxiliary engine (%)	0.023 $\pm$ 0.004	0.01 $\pm$ 0.002
Emission factors of auxiliary engine (g/kWh)	-0.08 $\pm$ 0.24	0.08 $\pm$ 0.04

Table 3-2. Inter-year (across years) correlation analysis of annual emission estimates for all vessels in the fleet from 2019 to 2024. Sample size = 1,240,000 for all contributing factors.

Contributing factor	Spearman Rank Correlation Coefficients	
	PM	NO _x +HC
Annual operating hours (h)	0.89	0.70
Emission factors of main engine (g/kWh)	0.28	0.60
Rated power of auxiliary engine (kW)	0.27	0.38
Rated power of main engine (kW)	0.17	0.38
Engine load of main engine (%)	0.13	0.10
Engine load of auxiliary engine (%)	0.02	0.01
Emission factors of auxiliary engine (g/kWh)	-0.08	0.07

Key contributing factors to both intra-annual and inter-annual variability were found to be annual operating hours and emission factors of main engines. This implies that reductions can be achieved by prioritizing managing vessel operating hours, followed by engine upgrades.

3.3.3 Emission Reduction Potential for the Ferry Fleet

Results for the reduction potential on the year 2024 emissions are shown for the three proposed reduction scenarios: (1) vessel rearrangements, (2) a compliance engine upgrade scenario, and (3) a maximum stringency engine upgrade scenario.

3.3.3.1 Rearrangement of the Fleet

Figure 3-2 illustrates the existing arrangement of the fleet in 2024, and proposed rearrangements to minimize the fleet annual emissions for CO₂, NO_x+HC, and PM, respectively. The rearrangements resulted in annual reductions of 7% for CO₂, 6% for NO_x+HC, and 7% for PM relative to the 2024 baseline emissions. All rearrangements involved redistributing vessels across routes, except for the Cedar Island–Ocracoke route, which exclusively operates large-size vessels. However, vessel rearrangements within this route were also optimized.

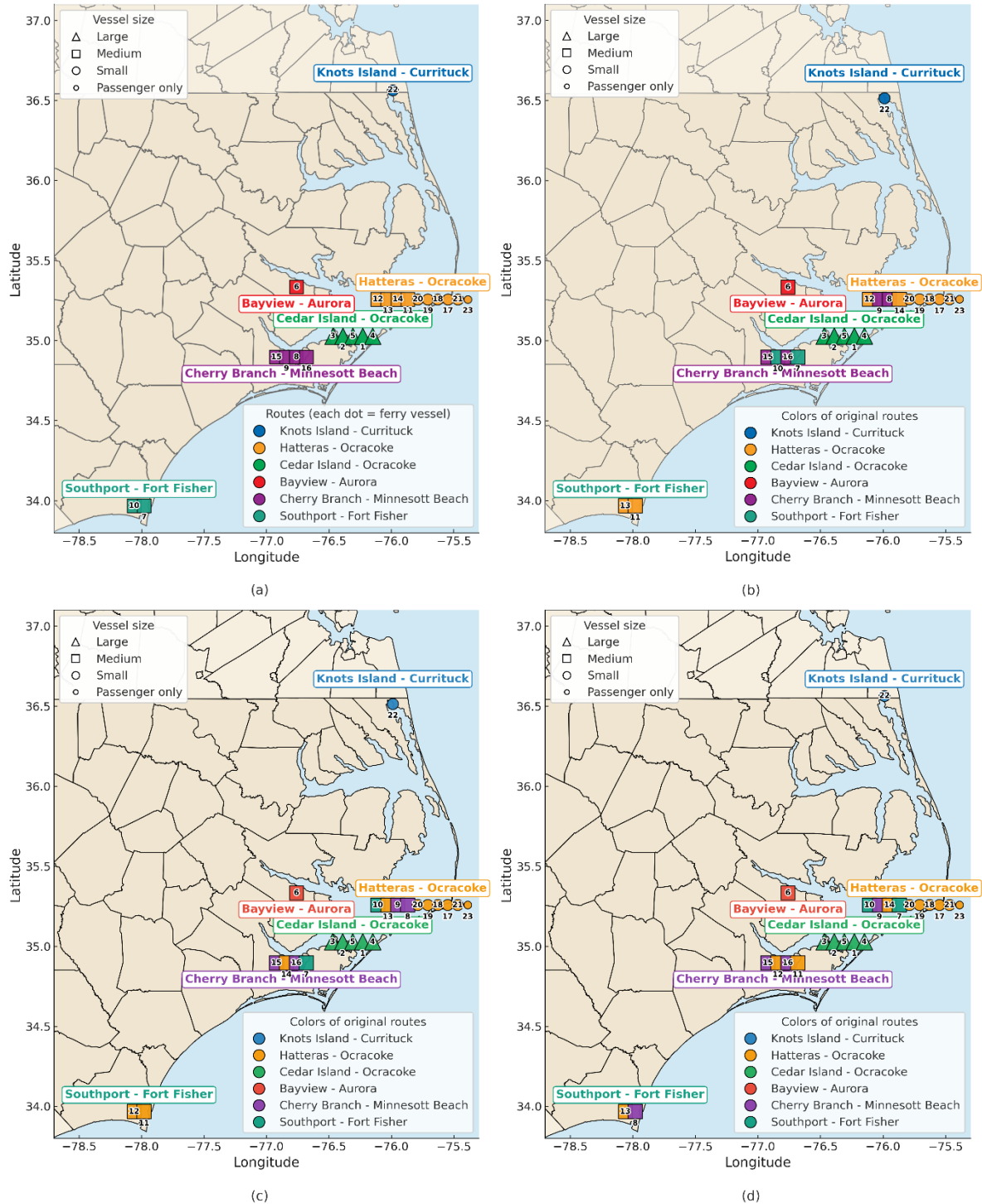


Figure 3-2. Location of vessels of the ferry fleet according to (a) existing arrangement, (b) rearrangement to minimize CO₂ emissions, (c) rearrangement to minimize NO_x+HC emissions, and (d) rearrangement to minimize PM emissions. Vessel IDs: (1) Silverlake, (2) Cedar Island, (3) Carteret, (4) Swan Quarter, (5) Sea Level, (6) Gov Daniel Russell, (7) Southport, (8) Neuse, (9) Lupton, (10) Fort Fisher, (11) W Stanford White, (12) Croatoan, (13) Hatteras, (14) Rodanthe, (15) Avon, (16) Salvo, (17) Kinnakeet, (18) Frisco, (19) Chicamocomico, (20) Cape Point, (21) Ocracoke, (22) Gov James B Hunt, (23) Ocracoke Express.

3.3.3.2 Compliance Engine Upgrade Scenario

A total of 19 vessels were identified for upgrades to main engines, in-use auxiliary engines, or both, as they are not certified to Tier 3 or Tier 4 standards for PM and NO_x+HC. Of these, 13 vessels are subject to upgrades on a total of 26 main engines, while 19 vessels on their 19 in-use auxiliary engines. Only the MVs Sea Level and Swan Quarter, which currently operate Tier 3 main engines rated above 600 kW, were subject to upgrades to Tier 4 standards.

Table 3-3 lists the 13 vessels identified for upgrades, along with their existing and updated engine emission factors, and percent reductions in emission factors by pollutant. Reductions in main engine emission factors ranged from 23% to 57% for PM, and up to 60% for NO_x+HC, depending on the vessel. Reductions in auxiliary engine emission factors ranged from 29% to 60% for PM and up to 32% for NO_x+HC, depending on the vessel.

Table 3-4 presents annual vessel emissions for 2024, by pollutant, alongside expected emissions after engine upgrades under the compliance scenario for all engines subject to upgrades. The compliance engine upgrade scenario resulted in reductions in annual vessel emissions ranging from 10% to 57% for PM, 42% to 76% for NO_x+HC, and 2% to 12% for CO₂ and fuel consumption, depending on the vessel. The vessels with the largest emission reductions were Hatteras for PM, Cedar Island for NO_x+HC, and Gov Daniel Russell for CO₂ and fuel consumption.

3.3.3.3 Maximum Stringency Engine Upgrade Scenario

All 73 engines of the 23 vessels of the fleet are subject to be repowered or retrofitted to Tier 4 emission standards. Table 3-5 lists all vessels, along with their existing and updated engine emission factors, and percent reductions in emission factors by pollutant. Reductions in main engine emissions ranged from 45% to 83% for PM and from 36% to 76% for NO_x+HC, depending on the vessel. Reductions in auxiliary engine emissions ranged from 14% to 84% for PM and from 31% to 76% for NO_x+HC, depending on the vessel.

Table 3-6 presents annual vessel emissions for 2024, by pollutants, alongside expected emissions after engine upgrades under the maximum stringency scenario for all engines. The maximum stringency upgrade scenario resulted in reductions in annual vessel emissions ranging from 46% to 83% for PM, 35% to 76% for NO_x+HC, and 7% to 12% for CO₂ and fuel consumption, depending on the vessel. The vessels with the largest emission reductions were Hatteras for PM, Cedar Island for NO_x+HC, and Gov Daniel Russell for CO₂ and fuel consumption.

Table 3-3. Existing mean emission factors and new emission factors for all main and auxiliary engines subject to technological upgrades for compliance with Tier 3 or Tier 4 emission standards for (a) PM and (b) NO_x+HC.

(a) PM

Vessel ID	Ferry	Main Engine			Auxiliary Engine		
		Existing Mean Emission Factor (g/kWh)	Upgraded Emission Factor (g/kWh)	Percent Reduction (%) ¹	Existing Mean Emission Factor (g/kWh)	Upgraded Emission Factor (g/kWh)	Percent Reduction (%) ¹
1	Silverlake	0.14	0.1	29	0.25	0.1	60
2	Cedar Island	0.14	0.1	29	0.25	0.1	60
3	Carteret	0.14	0.1	29	0.20	0.1	50
4	Swan Quarter	0.08	0.04	53	0.14	0.1	29
5	Sea Level	0.08	0.04	53	0.14	0.1	29
6	Gov Daniel Russell	0.15	0.1	33	0.25	0.1	60
7	Southport	0.15	0.1	33	0.25	0.1	60
8	Neuse	0.15	0.1	33	0.25	0.1	60
9	Lupton	0.15	0.1	33	0.25	0.1	60
10	Fort Fisher	0.15	0.1	33	0.25	0.1	60
11	W Stanford White	0.15	0.1	33	0.25	0.1	60
12	Croatoan	0.15	0.1	33	0.25	0.1	60
13	Hatteras	0.23	0.1	57	0.25	0.1	60
17	Kinnakeet	0.13	0.1	23	0.25	0.1	60
18	Frisco	0.09	NA ²	NA ²	0.25	0.1	60
19	Chicamocomico	0.09	NA ²	NA ²	0.25	0.1	60
20	Cape Point	0.09	NA ²	NA ²	0.25	0.1	60
21	Ocracoke	0.09	NA ²	NA ²	0.25	0.1	60
22	Gov James B Hunt	0.15	0.1	33	0.25	0.1	60

Note: 1. The reported percent reductions reflect changes at the individual engine level due to upgrades.
2. Upgrades for these vessels are not applicable because their main engines are already in compliance with Tier 3 standards.

Continued on next page.

Table 3-3. Continued.

(b) NO_x+HC

Vessel ID	Ferry	Main Engine			Auxiliary Engine		
		Existing Mean Emission Factor (g/kWh)	Upgraded Emission Factor (g/kWh)	Percent Reduction (%) ¹	Existing Mean Emission Factor (g/kWh)	Upgraded Emission Factor (g/kWh)	Percent Reduction (%) ¹
1	Silverlake	8.21	5.80	29	8.25	5.60	32
2	Cedar Island	8.21	5.80	29	8.25	5.60	32
3	Carteret	8.21	5.80	29	8.15	5.60	31
4	Swan Quarter	5.04	1.99	60	6.71	5.60	17
5	Sea Level	5.04	1.99	60	6.71	5.60	17
6	Gov Daniel Russell	7.64	5.60	27	8.25	5.60	32
7	Southport	7.64	5.60	27	8.25	5.60	32
8	Neuse	7.64	5.60	27	8.25	5.60	32
9	Lupton	7.64	5.60	27	8.25	5.60	32
10	Fort Fisher	7.64	5.60	27	8.25	5.60	32
11	W Stanford White	7.64	5.60	27	8.25	5.60	32
12	Croatoan	7.64	5.60	27	8.25	5.60	32
13	Hatteras	7.29	5.60	23	3.40	— ³	— ³
17	Kinnakeet	5.60	5.60	0	8.25	5.60	32
18	Frisco	3.10	NA ²	NA ²	8.25	5.60	32
19	Chicamocomico	3.10	NA ²	NA ²	8.25	5.60	32
20	Cape Point	3.10	NA ²	NA ²	8.25	5.60	32
21	Ocracoke	3.10	NA ²	NA ²	8.25	5.60	32
22	Gov James B Hunt	7.64	5.60	27	8.25	5.60	32

Note: 1. The reported percent reductions reflect changes at the individual engine level due to upgrades.
2. Upgrades for these vessels are not applicable because their main engines are already in compliance with Tier 3 standards.
3. The existing NO_x+HC emission factor for MV Hatteras is already below than the Tier 3 emission standard, so no additional reduction potential is required.

Table 3-4. Comparison of 2024 annual emissions on vessels subject to upgrades on engines before and after upgrades for compliance with Tier 3 or Tier 4 emission standards.

Vessel ID	Ferry	Annual Emissions (t/year)					
		Existing Engines			Upgraded Engines		
		PM	NO _x +HC	CO ₂	PM	NO _x +HC	CO ₂
1	Silverlake	0.62	34.80	2234	0.42	24.53	1966
2	Cedar Island	0.42	23.74	1306	0.29	16.73	1149
3	Carteret	0.11	6.31	425	0.08	4.45	374
4	Swan Quarter	0.34	19.64	1779	0.17	8.61	1708
5	Sea Level	0.32	18.50	1565	0.16	8.11	1502
6	Gov Daniel Russell	0.16	7.89	380	0.10	5.74	334
7	Southport	0.30	14.51	1058	0.19	10.56	931
8	Neuse	0.22	10.88	696	0.14	7.92	612
9	Lupton	0.42	20.37	1467	0.26	14.82	1291
10	Fort Fisher	0.08	3.73	218	0.05	2.71	192
11	W Stanford White	0.53	25.46	1827	0.33	18.53	1608
12	Croatoan	0.18	8.58	425	0.11	6.25	374
13	Hatteras	0.45	13.53	1310	0.19	10.88	1165
17	Kinnakeet	0.23	9.46	684	0.16	9.06	602
18	Frisco	0.10	3.48	507	0.09	3.33	498
19	Chicamocomico	0.06	2.06	220	0.06	1.96	216
20	Cape Point	0.21	6.84	527	0.18	6.51	518
21	Ocracoke	0.12	3.99	500	0.11	3.78	491
22	Gov James B Hunt	0.06	2.73	255	0.04	1.99	225

Table 3-5. Existing mean emission factors and new Tier 4 emission factors for all main and auxiliary engines for (a) PM and (b) NO_x+HC.

(a) PM

Vessel ID	Ferry	Main Engine			Auxiliary Engine		
		Existing Mean Emission Factor (g/kWh)	Upgraded Emission Factor (g/kWh)	Percent Reduction (%) *	Existing Mean Emission Factor (g/kWh)	Upgraded Emission Factor (g/kWh)	Percent Reduction (%) *
1	Silverlake	0.14	0.04	71	0.25	0.04	84
2	Cedar Island	0.14	0.04	71	0.25	0.04	84
3	Carteret	0.14	0.04	71	0.20	0.04	80
4	Swan Quarter	0.08	0.04	53	0.14	0.04	72
5	Sea Level	0.08	0.04	53	0.14	0.04	72
6	Gov Daniel Russell	0.15	0.04	73	0.25	0.04	84
7	Southport	0.15	0.04	73	0.25	0.04	84
8	Neuse	0.15	0.04	73	0.25	0.04	84
9	Lupton	0.15	0.04	73	0.25	0.04	84
10	Fort Fisher	0.15	0.04	73	0.25	0.04	84
11	W Stanford White	0.15	0.04	73	0.25	0.04	84
12	Croatoan	0.15	0.04	73	0.25	0.04	84
13	Hatteras	0.23	0.04	83	0.25	0.04	84
14	Rodanthe	0.09	0.04	57	0.16	0.04	75
15	Avon	0.09	0.04	57	0.05	0.04	14
16	Salvo	0.09	0.04	57	0.05	0.04	14
17	Kinnakeet	0.13	0.04	69	0.25	0.04	84
18	Frisco	0.09	0.04	57	0.25	0.04	84
19	Chicamocomico	0.09	0.04	57	0.25	0.04	84
20	Cape Point	0.09	0.04	57	0.25	0.04	84
21	Ocracoke	0.09	0.04	57	0.25	0.04	84
22	Gov James B Hunt	0.15	0.04	73	0.25	0.04	84
23	Ocracoke Express	0.07	0.04	45	0.14	0.04	71

Note: *The reported percent reductions reflect changes at the individual engine level due to upgrades.

Continued on next page.

Table 3-5. Continued.

(b) NO_x+HC

Vessel ID	Ferry	Main Engine			Auxiliary Engine		
		Existing Mean Emission Factor (g/kWh)	Upgraded Emission Factor (g/kWh)	Percent Reduction (%) *	Existing Mean Emission Factor (g/kWh)	Upgraded Emission Factor (g/kWh)	Percent Reduction (%) *
1	Silverlake	8.21	1.99	76	8.25	1.99	76
2	Cedar Island	8.21	1.99	76	8.25	1.99	76
3	Carteret	8.21	1.99	76	8.15	1.99	76
4	Swan Quarter	5.04	1.99	60	6.71	1.99	70
5	Sea Level	5.04	1.99	60	6.71	1.99	70
6	Gov Daniel Russell	7.64	1.99	74	8.25	1.99	76
7	Southport	7.64	1.99	74	8.25	1.99	76
8	Neuse	7.64	1.99	74	8.25	1.99	76
9	Lupton	7.64	1.99	74	8.25	1.99	76
10	Fort Fisher	7.64	1.99	74	8.25	1.99	76
11	W Stanford White	7.64	1.99	74	8.25	1.99	76
12	Croatoan	7.64	1.99	74	8.25	1.99	76
13	Hatteras	7.29	1.99	73	3.40	1.99	41
14	Rodanthe	3.10	1.99	36	3.6	1.99	45
15	Avon	3.10	1.99	36	2.88	1.99	31
16	Salvo	3.10	1.99	36	2.88	1.99	31
17	Kinnakeet	5.60	1.99	64	8.25	1.99	76
18	Frisco	3.10	1.99	36	8.25	1.99	76
19	Chicamocomico	3.10	1.99	36	8.25	1.99	76
20	Cape Point	3.10	1.99	36	8.25	1.99	76
21	Ocracoke	3.10	1.99	36	8.25	1.99	76
22	Gov James B Hunt	7.64	1.99	74	8.25	1.99	76
23	Ocracoke Express	5.40	1.99	63	4.00	1.99	50

Note: *The reported percent reductions reflect changes at the individual engine level due to upgrades.

Table 3-6. Comparison of 2024 annual emissions on all vessels before and after upgrades for compliance with Tier 4 emission standards.

Vessel ID	Ferry	Annual Emissions (t/year)					
		Existing Engines			Upgraded Engines		
		PM	NO _x +HC	CO ₂	PM	NO _x +HC	CO ₂
1	Silverlake	0.62	34.80	2234	0.17	8.43	1966
2	Cedar Island	0.42	23.74	1306	0.12	5.75	1149
3	Carteret	0.11	6.31	425	0.03	1.53	374
4	Swan Quarter	0.34	19.64	1779	0.15	7.57	1654
5	Sea Level	0.32	18.50	1565	0.14	7.13	1455
6	Gov Daniel Russell	0.16	7.89	380	0.04	2.04	334
7	Southport	0.30	14.51	1058	0.08	3.75	931
8	Neuse	0.22	10.88	696	0.06	2.81	612
9	Lupton	0.42	20.37	1467	0.11	5.27	1291
10	Fort Fisher	0.08	3.73	218	0.02	0.96	192
11	W Stanford White	0.53	25.46	1827	0.13	6.58	1608
12	Croatoan	0.18	8.58	425	0.04	2.22	374
13	Hatteras	0.45	13.53	1310	0.08	3.88	1162
14	Rodanthe	0.24	7.71	1215	0.10	4.86	1130
15	Avon	0.23	8.67	595	0.11	5.64	553
16	Salvo	0.17	6.38	463	0.08	4.14	430
17	Kinnakeet	0.23	9.46	684	0.06	3.22	602
18	Frisco	0.10	3.48	507	0.04	2.00	468
19	Chicamocomico	0.06	2.06	220	0.02	1.18	203
20	Cape Point	0.21	6.84	527	0.08	3.92	486
21	Ocracoke	0.12	3.99	500	0.05	2.29	461
22	Gov James B Hunt	0.06	2.73	255	0.01	0.71	225
23	Ocracoke Express	0.13	9.29	725	0.07	3.43	674

The range of NO_x+HC reductions under the maximum stringency scenario is similar to that observed for the compliance scenario. This is because the upper end of the range is driven by engines originally certified to Tier 0 (non-certified engines) or Tier 1, for which most NO_x+HC reductions are achieved when upgrading to Tier 3 under the compliance scenario. Upgrading those same engines from Tier 3 to Tier 4 yields only small additional percentage reductions. The lower end is set by engines already at Tier 3, which represent 48% of main engines and 17% of auxiliary engines in the fleet, for which upgrading to Tier 4 provides only modest additional reductions.

3.3.3.4 Comparison of emission reduction scenarios

A comparison of fleet emission reduction potentials is shown at the fleet level in Table 3-7 among the three reduction scenarios. Results indicate that upgrading all feasible engines to

comply with current standards based on rated power specifications can achieve substantial reductions in PM and NO_x+HC, with fleetwide reductions of 26–32% depending on the pollutant. Upgrading all fleet engines to Tier 4 emission standards could yield the largest reductions across all scenarios, with potential reductions of up to 68%. However, vessel rearrangements may be sufficient to achieve targeted reductions in annual CO₂ emissions and fuel consumption of approximately 7%.

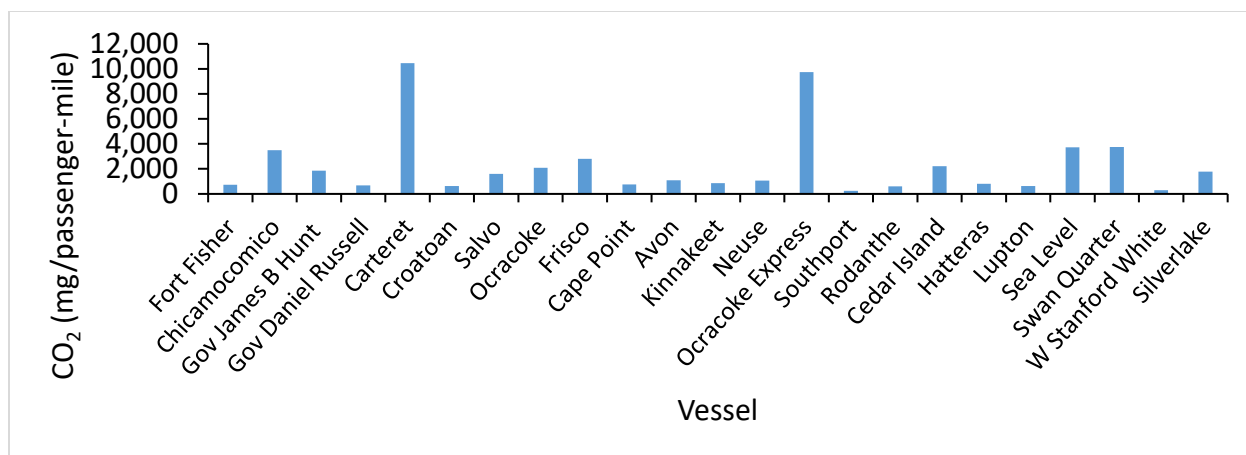
3.3.4 Comparison of Ferry Emission Intensities

Emission intensities by vessel and pollutant are compared as shown in Figure 3-3. The top two most intense polluting vessels were consistently found to be the MVs Ocracoke Express and Carteret for all pollutants. Although the MV Ocracoke Express emits substantially less in absolute terms (about 79% of the fleet maximum for PM, 53% for NO_x+HC, and 68% for CO₂), it ranks among the highest in emission intensities. This is because of its annual passenger occupancy being 97% and mileage 83% lower than the fleet's highest values. As a result, even modest annual emissions are distributed over a limited-service base. The limited-service base of the MV Ocracoke Express is attributed to its annual operating demand being limited to the summer season. This yields MV Ocracoke Express has the highest per passenger-mile emissions intensities for NO_x+HC and second-highest for CO₂ and PM in the fleet.

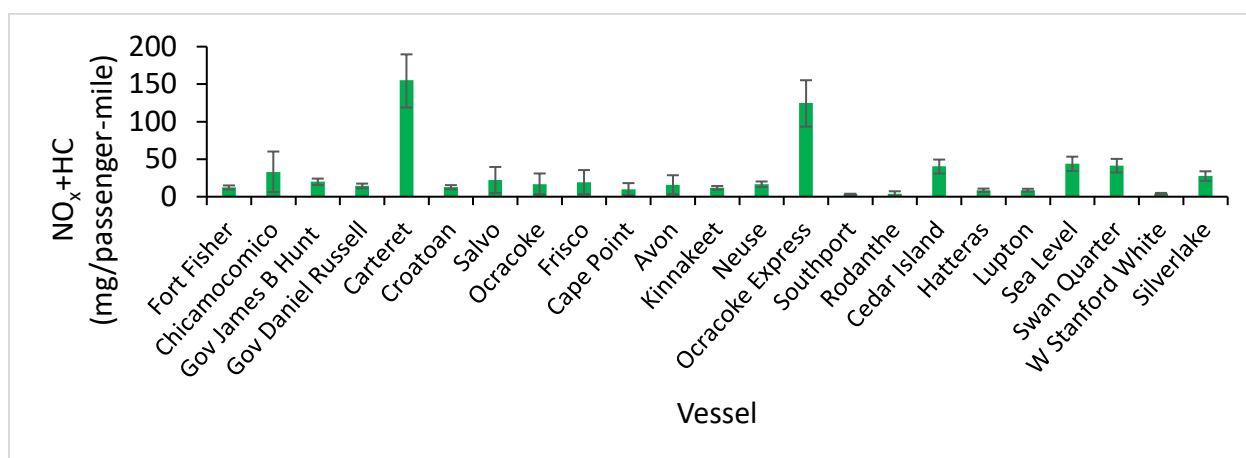
Although the MV Carteret emits far less in absolute terms (about 82% less than the fleet maximum for PM, 83% for NO_x+HC, and 81% for CO₂), it ranks as the most or second most intense emitter across pollutants. This is because of its annual passenger occupancy being 55% lower and mileage 45% lower than the fleet's highest values. As a result, even though its annual emissions are modest compared with the fleet maximum, they are distributed over a smaller transport-work base (passenger-mile) than the busiest ferry. This yields per-passenger-mile intensities that are among the highest in the fleet: highest for PM and CO₂, and second-highest for NO_x+HC. It is noteworthy that the main engines of the MV Carteret are not certified to EPA Tier standards, and therefore engine upgrades to the latest EPA standards could be justified to decrease annual emissions and therefore emission intensities.

Table 3-7. Comparison of fleet emission reduction potentials by pollutant for scenarios, including: (1) vessel rearrangements, (2) a compliance engine upgrade scenario, and (3) a maximum stringency engine upgrade scenario, with respect to the baseline 2024 annual emissions.

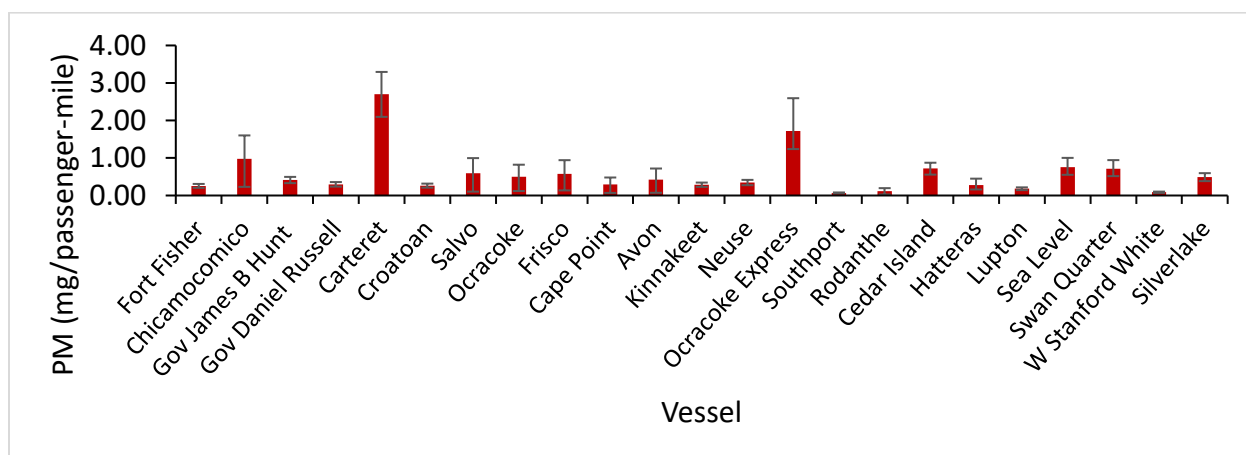
Scenario	Fleet Annual Emissions (t/year)			Emission Reduction Potential (%)		
	PM	NO _x +HC	CO ₂	PM	NO _x +HC	CO ₂
Baseline 2024 emissions	5.7	269	20,380	-	-	-
Vessel rearrangements	5.3	252	19,020	7	6	7
Compliance engine upgrades	3.9	199	18,756	32	26	8
Maximum stringency engine upgrades	1.8	89	18,336	68	67	10



(a) CO₂



(b) NO_x+HC



(c) PM

Figure 3-3. Per passenger-mile vessel emission intensities for (a) CO₂, (b) NO_x+HC, and (c) PM for the year 2024. Error bars represent the 95% uncertainty intervals. CO₂ emission intensities do not present uncertainty intervals because CO₂ emissions were estimated based on fuel consumption and mass balance.

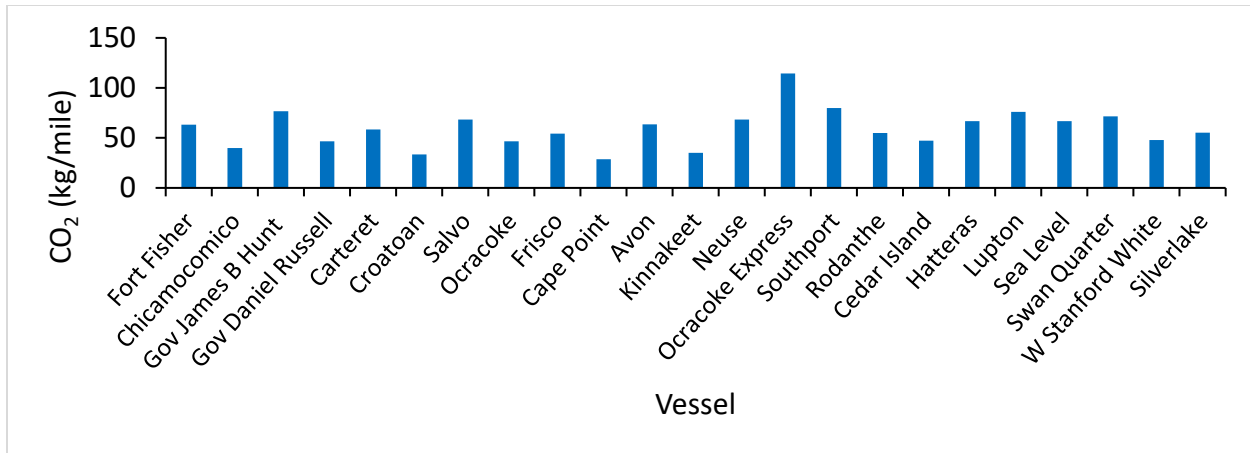
Fleet management should evaluate whether individual vessel's service is currently justified in terms of providing accessibility for commuters and tourists, and whether it is feasible to expand its service base by increasing passenger occupancy, improving operational frequency, or both. It is recommended that fleet managers interpret high emission intensities as a signal to re-evaluate deployment strategies and consider seasonal or limited service to adjust the passenger-mile service base, or to prioritize engine upgrades, emission controls, or electrification to reduce annual pollutant emissions.

Emission intensities by vessel and pollutant are presented on a per-mile basis in Figure 3-4Error! Reference source not found., with the MV Ocracoke Express identified as the most intense emitter for CO₂ and NO_x+HC for the reasons described above. The MV Salvo exhibits the highest per-mile PM emission intensity in the fleet although it is equipped with Tier 3 main and auxiliary engines. This is explained by the relatively lower mileage within the fleet in 2024 (40% lower than the fleet average).

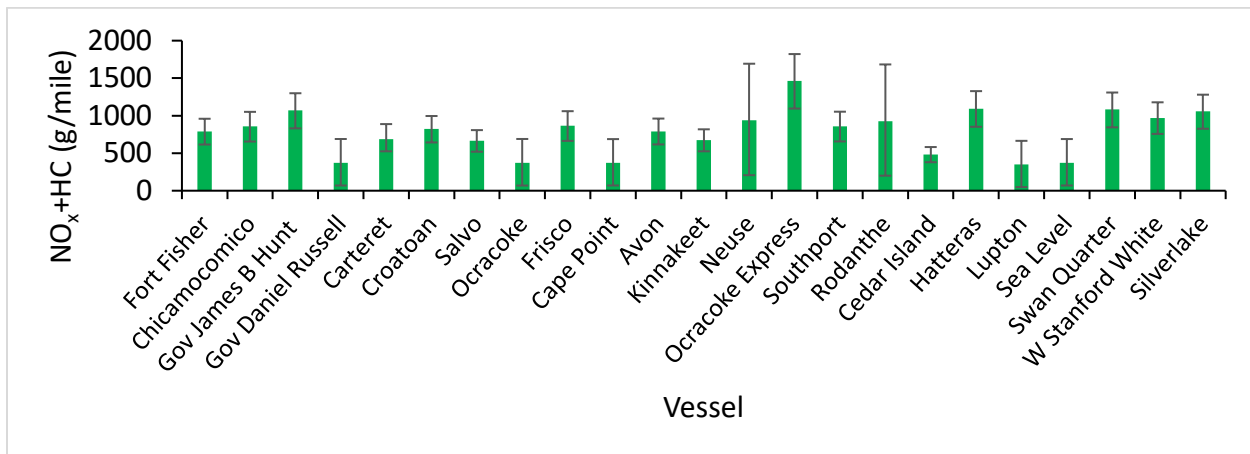
3.4 Discussion

Emission reduction scenarios, such as shown in Table 3-7, imply capital and operational costs as well as social costs or health benefits. Analyses to estimate them are typically assessed using benefit-per-ton (BPT) approaches that monetize avoided health and welfare damages from emission reductions (EPA, 2010). BPT values for primary PM_{2.5} (fine particulate matter with an aerodynamic diameter of 2.5 µm or less) can reach thousands of dollars per ton reduced, and regulatory analyses consistently show that these monetized benefits often outweigh capital and operational costs, including fuel savings (EPA, 2011; Fann et al., 2009, 2012). These analyses, however, would require robust cost information on retrofitting or repowering engines under different operational scenarios. At this stage, reliable data on retrofit and repower costs specific to the NCDOT ferry fleet are too limited to support such analyses. Future efforts could incorporate existing case studies and reports that evaluate the cost-effectiveness of repowering or retrofitting marine engines for emission reductions as reference estimates.

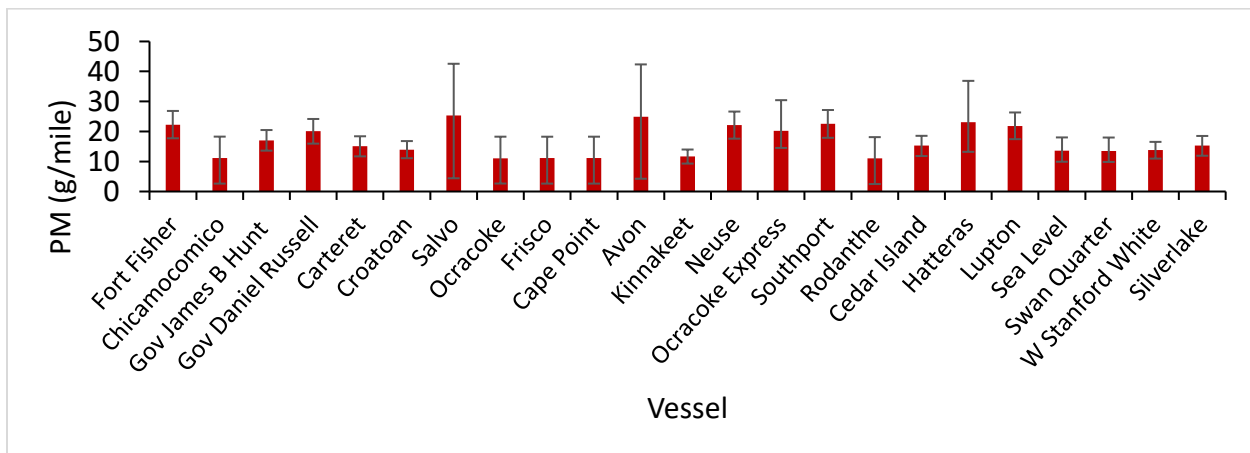
Ramboll (2019) estimated the cost-effectiveness (project cost per ton of pollutant reduced) of upgrading main engines on several towboats and harbor tugs based on their engine specifications, emission factors, and activity factors. For instance, a capital cost of \$650,000 was considered for upgrading a push boat operating with two uncertified main engines (total rated power of 746 kW and an average load of 60%) to EPA Tier 3 standards. The project, with a service life of 30 years and annual activity of 6,000 h/year, resulted in a reduction of 15.72 t/year of NO_x emissions and a cost-effectiveness of \$1,378 per ton.



(a) CO₂



(b) NO_x+HC



(c) PM

Figure 3-4. Per-mile vessel emission intensities for (a) CO₂, (b) NO_x+HC, and (c) PM for the year 2024. Error bars represent the 95% uncertainty intervals. CO₂ emission intensities do not present uncertainty intervals because CO₂ emissions were estimated based on fuel consumption and mass balance.

NO_x is a precursor to the formation of ground-level PM and ozone. According to EPA (2025), each ton of NO_x emissions reduced from internal combustion engines yields an estimated \$10,800 in PM_{2.5} related health benefits and \$60,200 in ozone-related health benefits, for a total social benefit of approximately \$71,000 (EPA, 2025). These estimates represent national average marginal benefits and may not fully capture local geographic, temporal, or source-specific factors relevant to marine operations. They also reflect economic assumptions and epidemiological relationships with inherent uncertainty. Therefore, the calculated benefits should be interpreted as indicative, rather than precise project-specific values.

Future studies would benefit from more complete information on engine retrofit and repower costs, as well as regionally specific estimates of health benefits per ton of pollutant reduced. Incorporating these dimensions would enable a more comprehensive cost-benefit framework to better support decision-making on long-term fleet modernization and emissions reduction strategies.

A prioritization framework for vessel interventions can be established based on the highest main engine emission factors by pollutants. For PM, the top three priority vessels for intervention are MVs Hatteras, W. Stanford White, and Lupton. For NO_x+HC, the top three priority vessels are MVs Silverlake, Cedar Island, and Carteret.

Findings indicate that, although operational and technological improvements to engines can contribute to reducing annual CO₂ emissions, their reduction potentials remain at or below 10% at the fleet level. Such reductions are very modest relative to the International Maritime Organization's (IMO's) decarbonization trajectory, which targets carbon neutrality for the maritime sector by 2050. Consequently, complementary or alternative strategies should be pursued, including the electrification of ferry vessels and the adoption of low-carbon fuels such as biodiesel or renewable diesel, to achieve deeper emission reductions and place the fleet on a pathway consistent with long-term climate goals.

3.5 Conclusions

In 2024, mean annual emissions and associated uncertainty varied substantially across vessels, with the lowest-emitting vessel emitting 90–94% less than the highest emitter, depending on pollutant. The MVs Silverlake, W. Stanford White and Swan Quarter were typically among the two largest emitters. Emission reductions for these vessels could be achieved by targeting engine technologies and managing operating activity.

Annual operating hours and main engine emission factors were identified as the dominant drivers of both intra-annual and inter-annual variability in emission estimates across all vessels. This finding suggests that meaningful reductions could be achieved by first managing vessel operating hours, followed by targeting engine upgrades.

A vessel rearrangement scenario resulted in up to 7% reduction in fleet annual emissions, depending on pollutant, and involved all routes except the Cedar Island–Ocracoke route and the MV Ocracoke Express. A reduction of 7% in CO₂ emissions (and consequently in annual fuel consumption) is non-negligible and could provide cost savings for the fleet. The fleet emission reduction potential of this scenario for CO₂ is comparable to that achieved by upgrading all feasible engines for compliance or all engines to Tier 4 emission standards. This suggests that vessel rearrangements may offer a cost-efficient alternative to engine upgrades for reducing CO₂ emissions and fuel consumption for the fleet.

An engine upgrade scenario in which all vessels with non-EPA-certified engines are upgraded to meet either Tier 3 or Tier 4 standards could reduce fleet overall PM emissions by 32% and NO_x+HC emissions by 26%. Compared to vessel rearrangements, this intervention achieves substantially greater reductions in health-relevant pollutants such as PM and NO_x+HC. However, upgrades of all engines in the fleet to Tier 4 emission standards provide the largest emission reduction benefits at fleet level (up to 68% depending on pollutant).

The top two most intense polluting vessels were the MVs Ocracoke Express and Carteret on a per passenger-mile basis, and MVs Ocracoke Express and Salvo on a per mile basis. Although these vessels contributed relatively modest annual emissions in the fleet, their low passenger occupancy or limited annual miles travel resulted in high emission intensities. These vessels are recommended for further evaluation of their commuting demand and potential strategies, such as improving passenger occupancy or operational frequency, to reduce their emission intensities.

A prioritization framework for vessel interventions can be established by targeting vessels with the highest main engine emission factors. For PM, MVs Hatteras, W. Stanford White, and Lupton are top priorities, while for NO_x+HC, MVs Silverlake, Cedar Island, and Carteret rank highest.

Although engine improvements can lower CO₂ emissions, their fleetwide impact is at or under 10%, falling short of IMO's 2050 decarbonization goals. Achieving deeper reductions will require complementary measures such as vessel electrification and low-carbon fuels.

CHAPTER 4: CONCLUSIONS

This chapter includes a summary of key findings and conclusions from this project.

4.1 Key Findings

Key findings are given as follows.

4.1.1 Assessing Variability in Real-World Ferry Fuel Use and Emission Rates

- F-1.1: A vessel such as MV Frisco, operating main engines with greater rated power than those of MV White, exhibited a higher mean trip-average speed (8% greater), consistent with the propeller law derived from hydrodynamic principles at low Froude numbers.
- F-1.2: MV Frisco exhibited larger RPA (21% greater) and CVS (36% greater) than MV White, indicating more frequent or intense acceleration bursts across its trips. These differences are attributable to the higher power-to-weight ratio of MV Frisco relative to MV White.
- F-1.3: MV Frisco generally maintained balanced operation between its main engines, whereas MV White frequently exhibited pronounced load imbalances. Contributing factors likely included trip phase, environmental conditions, propeller performance, and vessel- and engine-specific characteristics.
- F-1.4: MV White exhibited substantially longer periods of unbalanced engine loading during counter-current cruising compared to MV Frisco. These differences were likely driven by variations in propeller technologies (screw propellers on MV Frisco versus Voith-Schneider propellers on MV White) and by differences in vessel power-to-weight ratios.
- F-1.5: On average, MV White's fuel use was 21% lower than that of MV Frisco. This difference is primarily explained by MV White's lower total main engine rated power, as corroborated by NCDOT records of fuel consumption per mile. Differences in propeller technologies also contributed to this disparity.
- F-1.6: On average, across all six load bins and engines, emissions of MV Frisco were approximately 37% lower for NO_x and 2% lower for PM than those of MV White. These differences were primarily attributed to engine technologies, particularly targeted for NO_x reduction.
- F-1.7: A trade-off was observed for NO_x emissions versus fuel use and PM emissions between main engines on MV White in contrast to those on MV Frisco. This is explained by differences in engine design that lead MV Frisco's engines to comply with EPA emission standards. On non-certified main engines, lower in-cylinder combustion temperatures or delayed combustion suppress NO_x formation, that also invariably increases fuel consumption and PM emissions.
- F-1.8: Fuel use and CO₂ emissions were slightly lower for starboard engines (4% lower for MV White, 7% lower for MV Frisco) compared to port engines. However, NO_x and PM emissions varied: MV White's port engine produced 35% less NO_x while its starboard emitted 32% less PM, whereas MV Frisco's starboard emitted 14% less NO_x and 28% less PM than its port engine.
- F-1.9: On a trip-average basis, MV White exhibited 16% lower fuel use and CO₂ emission rates per mile compared with MV Frisco, whereas MV Frisco emitted 45% less NO_x and 15%

less PM per mile, attributable to differences in power-to-weight ratio and engine certification. Inter-vessel variability was further influenced by sailing orientation. MV White achieved 18–26% lower fuel use and CO₂ emissions than MV Frisco during counter-current trips and 10–16% lower during co-current trips, indicating that its relative fuel efficiency was 1.8–2 times greater under counter-current versus co-current conditions. Conversely, MV Frisco demonstrated consistently lower NO_x (16–57%) and lower PM emissions (4–26%) relative to MV White, depending on engine and sailing orientation.

- F-1.10: Inter-trip variability in FUERs was greater for MV Frisco than for MV White. On MV Frisco, trip-average emissions varied by 20–28% for fuel use and CO₂, 33–43% for NO_x, and 12–25% for PM, whereas MV White exhibited smaller ranges of 7–20% for fuel use and CO₂, 7–19% for NO_x, and 7–25% for PM. The higher variability observed on MV Frisco is attributed to more frequent acceleration–deceleration events and elevated trip CVS and RPA. Across both vessels, minimum trip-average FUERs were 7–43% lower than corresponding maximum rates, depending on pollutant.
- F-1.11: Differences in engines accounted for 70% of the variability in PM emissions but contributed less than 6% to the variability in fuel use, CO₂, and NO_x across trips. This indicates that factors such as load imbalances between main engines are a dominant driver of PM variability. In contrast, vessel differences explained 53% of the variability in fuel use and CO₂, and 62% of the variability in NO_x, but only 10% of the variability in PM. These results reflect differences in power-to-weight ratio and propulsion technologies, which strongly influence fuel consumption and emission rates. Differences in vessel operation, such as peak speed and CVS, explained less than 2% of FUER variability across trips, underscoring their limited contribution compared to vessel differences and engine operation.

4.1.2 Quantifying Ferry Fleet Emissions, Uncertainties, and Reduction Potentials

- F-2.1: In 2024, annual emissions varied widely across vessels. CO₂ ranged from 218 to 2,234 t/year, with the lowest-emitting vessel 90% lower than the highest. NO_x+HC emissions spanned 2 to 35 t/year, with a 94% difference between the lowest and highest emitters. PM ranged from 0.06 to 0.62 t/year, with the lowest-emitting vessel 91% lower than the maximum. Across pollutants, 95% uncertainty intervals were broad, with lower bounds 35–90% below upper bounds depending on the vessel.
- F-2.2: Intra-annual PM and NO_x+HC emissions were strongly correlated with operating hours ($\rho = 0.67 \pm 0.14$ and 0.88 ± 0.04 for PM and NO_x+HC, respectively) and moderately to strongly correlated with main engine emission factors ($\rho = 0.30 \pm 0.10$ and 0.63 ± 0.07 for PM and NO_x+HC, respectively). Inter-annual emissions showed similar patterns, with high sensitivity to operating hours ($\rho = 0.70$ – 0.89) and moderate sensitivity to main engine emission factors ($\rho = 0.28$ – 0.60).
- F-2.3: Vessel rearrangements reduced annual fleet emissions by 7% for CO₂, 6% for NO_x+HC, and 7% for PM relative to the 2024 baseline. These reductions were achieved by redistributing vessels across routes, with the exceptions of the Cedar Island–Ocracoke route, which operates only large vessels. A total of five vessels were excluded due to operative limitations that constrain their relocation such as the MVs Governor Daniel Russell, Governor James B. Hunt, Ocracoke Express, Avon, and Salvo.

- F-2.4: Nineteen of the 23 vessels operate either main or auxiliary engines not certified to EPA Tier 3 or Tier 4 standards, depending on their engine rated power, and are thus eligible for upgrades under a compliance scenario. Fleetwide emission reductions are expected to be approximately 8% for CO₂, 26% for NO_x+HC, and 32% for PM.
- F-2.5: The maximum stringency engine upgrades scenario achieved the greatest reduction of fleetwide PM (68%) and NO_x+HC (67%) than vessel rearrangements. However, both compliance and maximum stringency upgrade scenarios produced comparable reductions in the fleet CO₂ emissions of about 8 to 10%.
- F-2.6: The MVs Ocracoke Express and Carteret showed the highest emission intensities per passenger-mile despite relatively modest annual emissions. For MV Ocracoke Express, seasonal operation, low passenger occupancy, and limited annual mileage yielding the highest NO_x+HC emission intensities and near highest CO₂ and PM emission intensities in the fleet. The MV Carteret similarly ranked among the highest in normalized emissions due to reduced occupancy and mileage, with intensities at or near the fleet maximum across pollutants.
- F-2.7: The MV Ocracoke Express showed the highest emission intensity per mile for CO₂ and NO_x+HC for the reasons described previously. The MV Salvo exhibits the highest PM emission intensity in the fleet because of its comparatively lower miles traveled within the fleet despite its modest annual PM emissions.

4.2 Key conclusions

Key conclusions are given as follows.

4.2.1 Assessing Variability in Real-World Ferry Fuel Use and Emission Rates

- C-1.1: Variability in trip-average fuel use, CO₂, and NO_x emission rates was primarily driven by vessel characteristics and engine technologies. These results indicate that modifications to vessel design and upgrades to engine technologies present key opportunities for improving fuel efficiency and reducing CO₂ and NO_x emissions.
- C-1.2: Trip-average PM variability was largely driven by differences between engines, such as load imbalances, particularly during maneuvering and counter-current cruising on vessels with cycloidal propellers like MV White. Addressing load asymmetries related to trip phases, environmental conditions, and propulsion design offers a pathway to reduce PM emissions.
- C-1.3: FUEP variability revealed a trade-off between NO_x emissions versus fuel use and PM emissions, highlighting the need for integrated consideration of engine technology and propulsion system selection. Trip planning in relation to environmental conditions is also critical, as their interaction with engine and propeller performance can substantially influence emissions.
- C-1.4: Although smaller than inter-vessel and inter-engine variability, inter-trip FUEP variability remains important to consider, indicating potential for fuel savings and emission reductions through operational modifications. Sailing orientation also exerts a modest influence, underscoring the role of environmental conditions such as sea current speed and direction on trip-level emissions.

4.2.2 Quantifying Ferry Fleet Emissions, Uncertainties, and Reduction Potentials

- C-2.1: In 2024, vessel emissions varied widely. The MVs Silverlake, W. Stanford White, and Swan Quarter were typically the largest contributors to overall fleet emissions. Emission reductions for these vessels could be achieved by targeting engine technologies and managing operating activity.
- C-2.2: Annual operating hours and main engine emission factors were identified as the primary drivers of emission variability across vessels. Therefore, effective reductions could be achieved by first managing operating hours, followed by targeted engine upgrades.
- C-2.3: A vessel rearrangement scenario can potentially reduce fleet emissions up to 7% depending on the pollutant. The potential CO₂ reductions are comparable to those achieved by engine upgrades, suggesting that vessel rearrangements may be a cost-effective mitigation option for targeting this specific pollutant.
- C-2.4: Upgrading non-certified engines to meet Tier 3 or Tier 4 standards could reduce CO₂ emissions by 8%, NO_x+HC emissions by 26%, and PM emissions by 32%. However, upgrading all fleet engines to Tier 4 standards could reduce CO₂ emissions by 10%, and PM and NO_x+HC emissions up to 68%. Engine upgrades likely provide substantially greater health-related benefits than vessel rearrangements and deliver the largest overall reductions at both fleet and vessel levels.
- C-2.5: The deployment of the highest-intensity emitter vessels (e.g., MVs Ocracoke Express, Carteret, and Salvo) is recommended for further evaluation of their service demand and potential strategies, such as increasing passenger occupancy or operational frequency, to reduce their emission intensities.
- C-2.6: A vessel intervention framework can focus on upgrading engines with the highest main engine emission factors, prioritizing MVs Hatteras, W. Stanford White, and Lupton for PM, and MVs Silverlake, Cedar Island, and Carteret for NO_x+HC.
- C-2.7: Operational and technological improvements can lower CO₂ emissions, but fleetwide reductions remain at or under 10%. Complementary strategies like electrification and low-carbon fuels to meet IMO 2050 goals are recommended.

4.3 Recommendations

This project set a baseline for possible future work, such as to characterize the emissions benefits of alternative fuels or retrofitted emission control systems. In addition, with the developed ferry engine emission inventory, possible future work can quantify the benefits of reductions in on-road vehicle emissions avoided by ferry vessel service as part of grants for capital acquisition and for strategic planning purposes. Moreover, this work can be used to support public messaging regarding the commitment of the NCDOT Ferry Division to environmental awareness and sustainability, and to raise awareness of various stakeholders regarding the environmental benefits associated with ferry operations.

CHAPTER 5: Implementation and Technology Transfer Plan

This project produced the following key deliverables: (1) a methodological framework for measuring real-world ferry engine fuel use and emission rates; (2) a statistical approach for quantifying annual vessel emissions and uncertainties; (3) a database of baseline emission inventories by ferry vessels operated in the current fleet; (4) quantitative analyses of fuel saving and emissions reduction potential by comparing baseline versus various alternative emissions reduction scenarios; and (5) scholarly outputs, including a final technical report, research papers, and academic conference presentations.

The products of this project will influence the NCDOT Ferry Division in the following ways: (1) provide robust, engine-specific data on real-world fuel use and pollutant emissions under actual operating conditions; (2) enable data-driven comparisons across ferry vessels to prioritize operational and capital improvements for high-emitting engines; (3) support applications for federal grant programs by demonstrating fuel saving and emissions reduction benefits; (4) establish a baseline for future research, including evaluating emission control retrofits, engine upgrades, or alternative fuels; and (5) inform public outreach and strategic planning by demonstrating NCDOT's leadership in sustainability, energy efficiency, and environmental stewardship.

Implementation of this project's results will be led by the NCDOT Ferry Division. Anticipated uses include: (1) informing grant applications for vessel replacements and engine upgrades; (2) strategic planning based on existing fuel consumption and emissions profiles; and (3) outreach to the public and policymakers to demonstrate energy and environmental progress. The required NCDOT resources primarily include staff time for data interpretation, coordination with planning teams, and integration into existing workflows.

The benefits of the project are measured by its ability to: (1) support successful federal or state funding applications based on quantified fuel saving and emissions reductions; (2) guide operational improvements and capital investments; and (3) strengthen NCDOT's technical understanding of ferry operations. A post-project evaluation may include tracking total funding acquired and energy or emissions savings achieved due to project-informed decisions.

To maximize the long-term value of this work, continued support is recommended in the form of: (1) expanded data collection for additional vessels or under alternate route conditions; (2) evaluation of energy saving and emission reductions achieved through vessel rearrangements and engine upgrades proposed in this project; (3) assessment of retrofitted systems or alternative fuels for their energy and emissions performance; and (4) periodic tracking and updating of fuel use and emissions inventories. Such efforts will support energy saving and emissions reduction planning and strengthen NCDOT's leadership in sustainable marine transportation.

This project has already made contributions to scientific knowledge through multiple conference presentations and peer-reviewed venues, with additional journal publications planned. To date, the project team has presented findings at several national and state conferences, as cited below:

- Larrahondo, S., Wei, T., Grieshop, A. P., Frey, H. C., & Peele, C. (June 9–12, 2025). *Demonstration of approaches to quantifying ferry particulate matter emissions and uncertainty: A case study of a North Carolina vessel*, Extended abstract No. 1980495,

Proceedings of the 118th Annual Conference & Exhibition of the Air & Waste Management Association (A&WMA), Raleigh, NC. (Best Paper Award, Environmental Management Group).

- Larrahondo, S., Wei, T., Grieshop, A. P., & Frey, H. C. (April 13–16, 2025). *Real-world measurements of main engine fuel use and emissions from two passenger ferry vessels*, Poster presentation, Proceedings of the 35th Coordinating Research Council (CRC) Real World Emissions Workshop, Long Beach, CA.
- Larrahondo, S., Wei, T., Grieshop, A. P., & Frey, H. C. (October 1–2, 2024). *Quantification of ferry emissions in North Carolina using statistical simulations: A case study on two ferry vessels*, Poster presentation, Proceedings of the 9th NC Breathe Conference, Durham, NC.
- Larrahondo, S., Wei, T., Grieshop, A. P., & Frey, H. C. (March 10–13, 2024). *Demonstration of an approach for measuring real-world ferry engine fuel use and emissions*, Poster presentation, Proceedings of the 34th CRC Real World Emissions Workshop, San Diego, CA.

Furthermore, the team plans to submit journal manuscripts based on the core technical content of Chapters 2 and 3 of this final report. These publications and presentations enhance transparency, promote technology and knowledge transfer, and enable other agencies, researchers, and stakeholders to benefit from the data, methods, and insights developed through this project.

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APPENDICES

Appendix A. Demonstration of Approaches to Quantifying Ferry Particulate Matter Emissions and Uncertainty: A Case Study of a North Carolina Vessel

Appendix A details the methodology and results for estimating annual ferry emissions and the associated uncertainties, using the Motor Vessel (MV) Rodanthe, a case study vessel from the North Carolina ferry fleet, as an example.

A.1 Methodology

The methods include: (1) ferry characteristics and route; (2) estimation of ferry emissions; (3) approaches to quantifying uncertainty in emission estimates; and (4) correlation analysis.

A.1.1 Ferry Characteristics and Route

MV Rodanthe, a ferry operated on the Hatteras-Ocracoke route in North Carolina, was selected for the case study, representing a typical vessel size and operational frequency for this route. The route has a travel time of approximately 75 minutes and a distance of 10 miles.^{1,2} The vessel is operated with two main engines (port and starboard) for propulsion and one auxiliary engine for onboard services. The two main engines are Caterpillar (CAT) C18 models, and the auxiliary engine is a CAT C7.1 model (Table 1). These engines fall under Category C1 for commercial marine engines with a power density of 35 kW/L or less.³ These engines are all certified to Environmental Protection Agency's Tier 3 marine emission standards under the regulations of 40 CFR Part 1042.⁴

Table A.1. Vessel and engines characteristics for the Motor Vessel Rodanthe.

Gross Register Tonnage, GRT (100 ft³)^a	388	
Carrying capacity	300 passengers and 40 vehicles	
Engines	Main engine	Auxiliary engine
Number of engines	2	1
Manufacturer and model	Caterpillar (CAT) C18	Caterpillar (CAT) C7.1
Engine displacement (L) / category	18.1 / C1	7 / C1
Number of cylinders	6	6
Rated power (kW) / speed (RPM)	441 / 1800	150 / 1500
Power density (kW/L)	24.4	21.4
Marine engine emission standard	EPA Tier 3	EPA Tier 3

a. Total enclosed volume of a ship, including all usable and not usable spaces.

A.1.2. Estimation of Ferry Emissions

An emission factor-based model has been widely used in emission inventory development, where emissions from a unit (e.g., an engine) are estimated by multiplying emission factors with activity factors for the release of the pollutant.⁵ Annual PM emissions (e.g., t/year) for a ferry were estimated by summing the products of emission factors and activity factors for each engine on the vessel:

$$E_y = C \times \sum_{i=1}^n EF_i \times AF_{i,y} \quad (\text{A.1})$$

where,

- E_y = annual ferry PM emissions for year y (t/year);
- C = conversion factor ($\text{ton}/1 \times 10^6 \text{ g}$);
- EF_i = PM emission factor for engine i (g/kWh);
- $AF_{i,y}$ = activity factor for engine i and year y (kWh/year).

A.1.2.1 Emission Factors

Emission factors represent average emission rates for specific pollutant source categories.^{6,7} For ferry engines, emission factors are expressed in grams of pollutant per kilowatt-hour engine output (g/kWh).⁸ A procedure was developed to identify reference PM emission factors for main and auxiliary engines from EPA's engine certification databases. Emission factors in these databases are derived from standardized testing procedures for marine, non-road, and heavy duty compression-ignition engines on duty test cycles outlined in the regulation 40 CFR Part 1065.⁹ Predefined duty test cycles aim to simulate typical engine operating conditions, as well as speed and load variations.⁹ Emission factors were retrieved as primary data from the Marine Compression-Ignition Engine Certification Database,^{10,11} and as secondary (complementary) data from the Nonroad Compression-Ignition Engines Certification Database.^{12,13} Engine emission factors were identified using a protocol similar to Khan and Frey (2018),¹⁴ which matched key engine characteristics (e.g., engine manufacturer, model name, certification standard, model year group, displacement, rated power, and rated speed) with EPA's certification databases.

A.1.2.2 Activity Factors

Activity factors represent the emissions-generating activity, such as the annual engine output (kWh/year) for a ferry engine.⁵ The engine activity factor was quantified as the product of the engine percent load (e.g., percentage of engine rated power), rated power, and the annual vessel operating hour:

$$AF_{i,y} = L_i \times RP_i \times OH_y \quad (\text{A.2})$$

where,

- L_i = trip-average percent load for engine i (%);
- RP_i = engine rated power for engine i (kW);
- OH_y = annual vessel operating hour for year y (h/year).

Trip-average engine percent loads were used because the reference emission factors from the certification databases were determined based on duty test cycles. For main engines, engine percent loads were obtained from a prior data collection effort on two electronically governed CAT C18 engines (port and starboard) of a ferry over eight one-way trips on the same Hatteras-Ocracoke route. Two CAT Electronic Technician (CAT-ET) datalink scan tools were used, one for each

main engine, to simultaneously record second-by-second (1 Hz) percent load. Data completeness was assessed for each main engine and one-way trip, requiring that 1 Hz percent load data be valid for at least 80% of the trip travel time. The average percent load was calculated for each main engine and valid trip. To evaluate if the two main engines of a vessel operate equally on a per-trip basis, the Wilcoxon signed-rank test,¹⁵ a non-parametric hypothesis test, was performed on paired trip-average percent loads for both main engines over all valid trips.

For the auxiliary engine, a nearly constant load profile was observed for powering onboard systems like heating, air conditioning, lighting, and communications.¹⁶ Auxiliary engines typically operate between 40% and 60% of their rated power;¹⁷ thus, trip-average percent loads for the auxiliary engine were assumed to follow a uniform distribution within this range.

The engine rated power for main engines and the auxiliary engine were obtained from engine characteristics (Table A.1). Engine annual operating hours were assumed to be the same as the vessel's annual operating hours, as provided by the North Carolina Department of Transportation Ferry Division.

A.1.3 Approaches to Quantifying Uncertainty in Emission Estimates

Uncertainty in emission estimates is contributed by the uncertainty from each input variable (i.e., emission factor, activity factor).¹⁸ Uncertainties in emission factors were assessed based on the distribution of reference PM emission factors for the two main engines and one auxiliary engine. Uncertainties in activity factors were assessed based on the distribution of trip-average percent loads for each engine.

Estimation of uncertainty in annual ferry emissions was conducted applying both analytical and numerical simulation methods. For the analytical method, uncertainty (e.g., 95% uncertainty intervals) on the mean emission estimates was propagated using the Taylor series approximation.¹⁹ For the numerical simulation method, bootstrap simulations were implemented. For each engine, emission factors and trip-average percent loads were randomly resampled from their respective distributions.

The bootstrap simulations include parametric and non-parametric approaches. For each year, bootstrap resampling was performed iteratively 10,000 times for each non-parametric and parametric approach. The non-parametric bootstrap randomly generates resamples with replacement from a non-parametric distribution (e.g., an empirical distribution).^{20,21} In contrast, the parametric bootstrap generates resamples from a parametric distribution (e.g., a probabilistic distribution).⁶ To determine an appropriate parametric distribution for the engine emission factor data and trip-average percent load data, the goodness-of-fit was assessed across multiple candidate parametric distributions using the Anderson-Darling test.²² The best-fitting parametric distribution was then identified using the Akaike Information Criterion (AIC), selecting the distribution with the lowest AIC value.²³

A.1.4 Correlation Analysis

Correlation analyses were applied to assess the sensitivity of factors influencing annual emission estimates. The analyses quantified the relationship between annual emission estimates and multiple contributing factors, including engine emission factors, percent loads, rated power, and annual operating hours. The correlation analyses were conducted across four calendar years (2020–2023) to evaluate inter-year variability and within each calendar year to evaluate intra-year variability. Pearson’s correlation (r) and Spearman’s rank correlation (ρ) were used to assess the linear and monotonic relationships, respectively.

A.2. Results

Twelve PM emission factor values were retrieved from the certification databases for the CAT C18 main engine, with a mean of 0.09 g/kWh, varying from 0.01 g/kWh to 0.14 g/kWh. In the parametric bootstrap, the emission factor data for main engines were best described by a normal distribution (p -value = 0.36, AIC = -35). For the auxiliary engine, two identical emission factor values (0.16 g/kWh) were retrieved from the certification databases. Thus, the emission factor for the auxiliary engine was treated as a constant in the parametric bootstrap.

All eight one-way trips met the data completeness criteria and were deemed valid. Trip-average percent loads vary from 64% to 87% for the port engine, with a mean of 75%, and from 74% to 79% for the starboard engine, with a mean of 72%, depending on trip.

The Wilcoxon signed-rank test yielded a p -value of 0.078, suggesting that the trip-average percent loads for both main engines are not statistically significant different. Thus, the two main engines of the vessel were assumed to operate equally on a per-trip basis. In the parametric bootstrap, the trip-average percent loads for main engines were best described by a lognormal distribution (p -value = 0.71, AIC = -36).

Figure A.1 shows the estimated mean annual PM emissions and 95% uncertainty intervals for each estimation approach, including analytical, non-parametric bootstrap, and parametric bootstrap. Over the period 2020–2023, the three approaches yield nearly identical mean estimates, differing by within 0.002 t/year (1% of the mean). For each approach, annual emission estimates increased by 49% from 2020 to 2021, followed by a slower 7.2% rise from 2021 to 2022, and then surged by 92% from 2022 to 2023. This increasing trend corresponds to the annual increase in the vessel’s operating hours, which rose from 1,782 hours in 2020 to 5,439 hours in 2023, following the end of the pandemic. Furthermore, for each year, the main engines contributed 76% to 83% of the vessel’s annual emissions depending on the estimation approach. This is attributed to the main engine having 2.6 times larger displacement and 2.9 times higher rated power than the auxiliary engine (Table A.1).

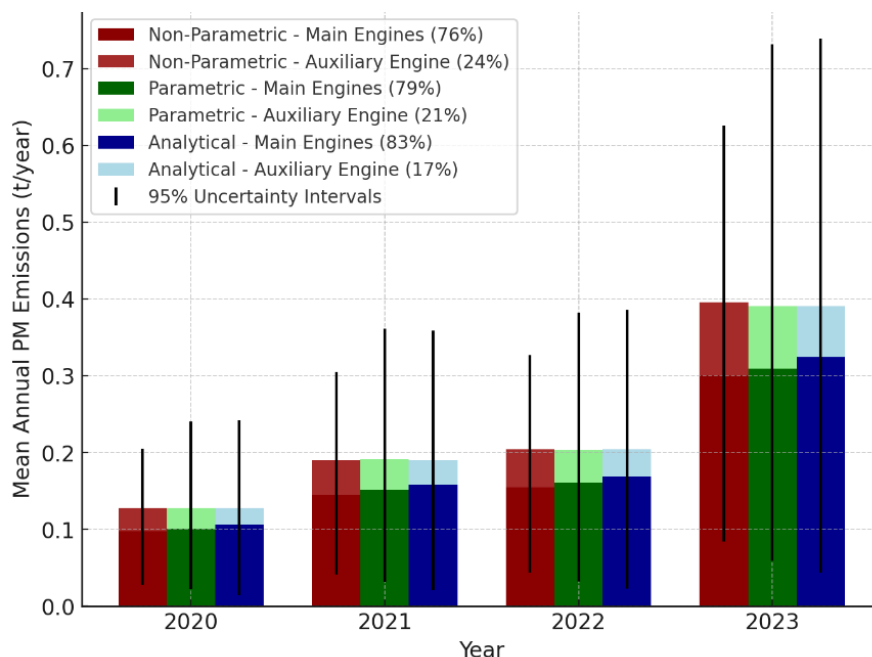


Figure A.1. Comparison of mean annual particulate matter (PM) emission estimates, along with 95% uncertainty intervals, for Motor Vessel Rodanthe among three estimation approaches: analytical, non-parametric bootstrap, and parametric bootstrap. Percent contributions to annual vessel emissions are indicated in parentheses in the legend.

The 95% uncertainty intervals show large overlap across approaches: 98% between parametric bootstrap and analytical, 88% between non-parametric bootstrap and analytical, and 89% between parametric and non-parametric bootstraps. The analytical and parametric bootstrap approaches have the largest overlap in uncertainty intervals, as both assume that main engine emission factors follow a normal distribution. Since emission estimates are highly sensitive to main engine emission factors (as explained later), this assumption contributes to the similarity in their uncertainty estimates.

Compared to the non-parametric bootstrap, the 95% uncertainty intervals from the parametric bootstrap were larger. This is because the parametric bootstrap allows resampling of values beyond the range of observed values in the reference sample (e.g., emission factors, percent loads), whereas the non-parametric bootstrap does not.⁶

Table A.2 shows results from correlation analyses of annual ferry PM emission estimates versus contributing factors. For the inter-year variability, annual emission estimates are highly sensitive to operating hours ($r = 0.67$, $\rho = 0.57$) and to main engine emission factors ($r = 0.66$, $\rho = 0.71$). For the intra-year variability, annual emission estimates are predominantly sensitive to main engine emission factors ($r = 0.98$, $\rho = 0.90$).

Table A.2. Correlation analysis of annual particulate matter (PM) emission estimates for Motor Vessel Rodanthe with multiple contributing factors, including inter-year correlation (across years) and intra-year correlation (within a year).

Contributing Factors ^a	Inter-Year Correlation ^b		Intra-Year Correlation ^c	
	Pearson correlation coefficient (r)	Spearman correlation coefficient (ρ)	Pearson correlation coefficient (r)	Spearman correlation coefficient (ρ)
Emission factors of main engines (g/kWh)	0.66	0.71	0.98	0.90
Trip average percent load for main engines (%)	0.13	0.16	0.18	0.33
Trip average percent load for auxiliary engine (%)	0.05	0.07	0.06	0.11
Annual operating hours (h/year)	0.67	0.57	NA ^d	NA ^d

- The auxiliary engine emission factor and the rated power for the main engines and auxiliary engine are not included, because their correlations are unavailable due to their constant values across all years.*
- Sample size for the inter-year correlation analysis is 40,000 (10,000 bootstrap resamples × 4 years).*
- Sample size for the intra-year correlation analysis is 10,000 for each year (10,000 bootstrap resamples for each year).*
- Intra-year correlations are not available (NA) for annual operating hours because they are constant within each year.*

A.3. Summary

Trip-average percent loads between the two main engines of a ferry vessel are not found to be significantly different based on actual operational data. Thus, for ferry emissions quantification, the two main engines can be assumed to operate equally on a per-trip basis. If both main engines share the same make, model, and certified emission standard, total emissions from the main engines can be estimated by doubling the emissions from one main engine.

Main engines predominantly contribute to the vessel's PM emissions (e.g., 75% to 85%) when main and auxiliary engines are certified to the same emission standard, as demonstrated in this case study. Annual PM emission estimates are highly sensitive to main engine emission factors both within and across years. Therefore, PM emission mitigation efforts should focus primarily on the main engines, such as upgrading them to newer engines certified to a more stringent Tier-level standard (e.g., Tier 4). Additionally, inter-year variability in annual PM emission estimates is influenced by operating hours, suggesting that effective management of vessel operating hours can largely contribute to emissions reduction.

This study establishes a methodological framework for high-level PM emissions estimation for a case ferry vessel. This framework is also applicable to other air pollutant species and ferry vessels. Additionally, the study demonstrates three approaches for quantifying uncertainties in

emission estimates: analytical, non-parametric bootstrap, and parametric bootstrap. These approaches exhibit nearly identical mean PM emission estimates with largely overlapping uncertainty intervals. Thus, no single approach can be considered significantly different in estimating ferry emissions and uncertainties.

This work is limited by the availability of ferry engine emission factor data. Although EPA's engine certification databases provide emission factor data, the amount available for each engine make and model remains limited. With more data, the emission estimation could better capture the representative distribution, resulting in more accurate uncertainty quantification. For example, in this case study, the reference sample for the auxiliary engine consists of only two identical emission factors, which prevents the assessment of variability and uncertainty in the auxiliary engine emissions. A larger sample with non-identical emission factors would provide more insightful results in identifying variability and uncertainty in emission estimates. Such a dataset could be obtained through conducting real-world emissions measurements. Additionally, emissions data from real-world measurements could be used to validate the estimation approaches presented here, which is recommended for future work.

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Appendix B. Estimated Baseline Annual Emissions for North Carolina Ferry Vessels

Table B.1. Estimated baseline annual emissions for the North Carolina ferry fleet for year 2024.

Vessel ID	Vessel Name	Annual Emissions for Pollutants (ton/year)				
		CO ₂ *	NO _x +HC		PM	
			Mean	95% Uncertainty Range	Mean	95% Uncertainty Range
1	Silverlake	2234	34.8	26.60 - 42.66	0.62	0.48 - 0.75
2	Cedar Island	1306	23.74	18.14 - 29.08	0.42	0.33 - 0.51
3	Carteret	425	6.31	4.83 - 7.71	0.11	0.09 - 0.13
4	Swan Quarter	1779	19.64	15.33 - 23.89	0.34	0.24 - 0.45
5	Sea Level	1565	18.5	14.42 - 22.46	0.32	0.23 - 0.42
6	Gov Daniel Russell	380	7.89	6.16 - 9.58	0.16	0.13 - 0.2
7	Southport	1058	14.51	11.31 - 17.61	0.30	0.24 - 0.36
8	Neuse	696	10.88	8.44 - 13.20	0.22	0.18 - 0.27
9	Lupton	1467	20.37	15.91 - 24.67	0.42	0.34 - 0.51
10	Fort Fisher	218	3.73	2.91 - 4.51	0.08	0.06 - 0.09
11	W Stanford White	1827	25.46	19.86 - 30.87	0.53	0.42 - 0.63
12	Croatoan	425	8.58	6.67 - 10.40	0.18	0.14 - 0.21
13	Hatteras	1310	13.53	10.32 - 17.46	0.45	0.26 - 0.73
14	Rodanthe	1215	7.71	1.07 - 14.70	0.24	0.05 - 0.4
15	Avon	595	8.67	1.87 - 15.73	0.23	0.04 - 0.4
16	Salvo	463	6.38	1.40 - 11.48	0.17	0.03 - 0.29
17	Kinnakeet	684	9.46	7.43 - 11.39	0.23	0.18 - 0.27
18	Frisco	507	3.48	0.65 - 6.44	0.10	0.02 - 0.17
19	Chicamocomico	220	2.06	0.38 - 3.79	0.06	0.01 - 0.1
20	Cape Point	527	6.84	1.27 - 12.66	0.21	0.05 - 0.34
21	Ocracoke	500	3.99	0.74 - 7.40	0.12	0.03 - 0.2
22	Gov James B Hunt	255	2.73	2.14 - 3.31	0.06	0.05 - 0.07
23	Ocracoke Express	725	9.29	6.94 - 11.54	0.13	0.09 - 0.19

Note: * Annual CO₂ emissions were estimated using a mass balance approach based on vessel's fuel consumption.

Table B.2. Estimated baseline annual emissions for the North Carolina ferry fleet for year 2023.

Vessel ID	Vessel Name	Annual Emissions for Pollutants (ton/year) **				
		CO ₂ *	NO _x +HC		PM	
			Mean	95% Uncertainty Range	Mean	95% Uncertainty Range
1	Silverlake	260	3.12	2.38 - 3.81	0.06	0.04 - 0.07
2	Cedar Island	1134	21.06	16.02 - 25.76	0.37	0.29 - 0.45
3	Carteret	2072	30.97	23.72 - 37.88	0.54	0.42 - 0.66
4	Swan Quarter	2099	24.67	19.32 - 29.94	0.42	0.31 - 0.56
5	Sea Level	1723	20.36	15.86 - 24.66	0.35	0.25 - 0.47
6	Gov Daniel Russell	457	7.01	5.48 - 8.52	0.14	0.12 - 0.17
7	Southport	583	8.47	6.59 - 10.28	0.17	0.14 - 0.21
8	Neuse	1148	20.21	15.69 - 24.51	0.42	0.33 - 0.5
9	Lupton	600	9.58	7.48 - 11.60	0.20	0.16 - 0.24
10	Fort Fisher	855	12.43	9.69 - 15.07	0.26	0.21 - 0.31
11	W Stanford White	1512	20.54	15.96 - 24.90	0.42	0.34 - 0.51
12	Croatoan	1604	22.21	17.30 - 26.96	0.46	0.37 - 0.55
13	Hatteras	1267	12.94	9.84 - 16.80	0.44	0.25 - 0.7
14	Rodanthe	2278	12.93	1.79 - 24.60	0.41	0.09 - 0.67
15	Avon	NA	NA	NA	NA	NA
16	Salvo	315	5.67	1.26 - 10.28	0.15	0.03 - 0.26
17	Kinnakeet	492	6.94	5.52 - 8.36	0.17	0.14 - 0.2
18	Frisco	162	1.58	0.29 - 2.91	0.05	0.01 - 0.08
19	Chicamocomico	578	4.4	0.82 - 8.12	0.13	0.03 - 0.21
20	Cape Point	24	0.25	0.05 - 0.46	0.01	0 - 0.01
21	Ocracoke	180	1.5	0.28 - 2.79	0.04	0.01 - 0.07
22	Gov James B Hunt	537	5.51	4.32 - 6.68	0.11	0.09 - 0.14
23	Ocracoke Express	607	8.31	6.22 - 10.35	0.11	0.08 - 0.17

Note: * Annual CO₂ emissions were estimated using a mass balance approach based on vessel's fuel consumption.

** NA: not applicable because the vessel was not in service in year 2023.

Table B.3. Estimated baseline annual emissions for the North Carolina ferry fleet for year 2022.

Vessel ID	Vessel Name	Annual Emissions for Pollutants (ton/year) **				
		CO ₂ *	NO _x +HC		PM	
			Mean	95% Uncertainty Range	Mean	95% Uncertainty Range
1	Silverlake	1362	20.28	15.50 - 24.88	0.36	0.28 - 0.44
2	Cedar Island	1875	30.65	23.39 - 37.51	0.54	0.42 - 0.66
3	Carteret	2087	43.74	33.53 - 53.45	0.76	0.59 - 0.93
4	Swan Quarter	638	7.36	5.73 - 8.94	0.13	0.09 - 0.17
5	Sea Level	608	7.18	5.61 - 8.73	0.12	0.09 - 0.16
6	Gov Daniel Russell	674	10.29	8.03 - 12.46	0.21	0.17 - 0.26
7	Southport	1479	22.81	17.79 - 27.68	0.47	0.37 - 0.57
8	Neuse	1086	21.05	16.38 - 25.53	0.43	0.35 - 0.52
9	Lupton	1601	21.66	16.88 - 26.27	0.45	0.35 - 0.54
10	Fort Fisher	602	16.16	12.61 - 19.60	0.33	0.27 - 0.4
11	W Stanford White	389	5.62	4.38 - 6.82	0.12	0.09 - 0.14
12	Croatoan	427	5.84	4.55 - 7.08	0.12	0.1 - 0.15
13	Hatteras	1091	12.29	9.38 - 15.82	0.41	0.24 - 0.66
14	Rodanthe	1075	6.7	0.94 - 12.81	0.21	0.05 - 0.35
15	Avon	NA	NA	NA	NA	NA
16	Salvo	NA	NA	NA	NA	NA
17	Kinnakeet	454	5.94	4.70 - 7.17	0.14	0.12 - 0.17
18	Frisco	1108	8.49	1.57 - 15.73	0.25	0.06 - 0.41
19	Chicamocomico	1004	7.83	1.48 - 14.57	0.24	0.06 - 0.38
20	Cape Point	1068	8.06	1.50 - 14.85	0.24	0.06 - 0.39
21	Ocracoke	NA	NA	NA	NA	NA
22	Gov James B Hunt	472	5.3	4.16 - 6.41	0.11	0.09 - 0.13
23	Ocracoke Express	853	11.74	8.77 - 14.59	0.16	0.12 - 0.24

Note: * Annual CO₂ emissions were estimated using a mass balance approach based on vessel's fuel consumption.

** NA: not applicable because the vessel was not in service in year 2022.

Table B.4. Estimated baseline annual emissions for the North Carolina ferry fleet for year 2021.

Vessel ID	Vessel Name	Annual Emissions for Pollutants (ton/year) **				
		CO ₂ *	NO _x +HC		PM	
			Mean	95% Uncertainty Range	Mean	95% Uncertainty Range
1	Silverlake	1967	30.86	23.50 - 37.80	0.55	0.43 - 0.67
2	Cedar Island	1813	29.37	22.36 - 36.02	0.52	0.41 - 0.63
3	Carteret	237	3.66	2.81 - 4.48	0.06	0.05 - 0.08
4	Swan Quarter	1911	22.37	17.41 - 27.13	0.38	0.28 - 0.51
5	Sea Level	1462	17.25	13.49 - 20.96	0.30	0.22 - 0.39
6	Gov Daniel Russell	578	9.27	7.22 - 11.22	0.19	0.15 - 0.23
7	Southport	233	3.39	2.64 - 4.11	0.07	0.06 - 0.08
8	Neuse	293	5.32	4.13 - 6.44	0.11	0.09 - 0.13
9	Lupton	172	2.57	2.00 - 3.11	0.05	0.04 - 0.06
10	Fort Fisher	276	3.60	2.80 - 4.36	0.07	0.06 - 0.09
11	W Stanford White	1522	19.79	15.39 - 23.98	0.41	0.33 - 0.49
12	Croatoan	1866	24.33	18.98 - 29.53	0.50	0.4 - 0.6
13	Hatteras	1329	13.94	10.61 - 17.95	0.47	0.27 - 0.75
14	Rodanthe	889	6.29	0.87 - 11.96	0.20	0.04 - 0.33
15	Avon	NA	NA	NA	NA	NA
16	Salvo	NA	NA	NA	NA	NA
17	Kinnakeet	202	2.93	2.33 - 3.54	0.07	0.06 - 0.08
18	Frisco	684	5.22	0.98 - 9.63	0.16	0.04 - 0.26
19	Chicamocomico	462	3.25	0.61 - 6.02	0.10	0.02 - 0.16
20	Cape Point	1192	8.74	1.63 - 16.22	0.26	0.06 - 0.43
21	Ocracoke	818	6.11	1.14 - 11.29	0.18	0.04 - 0.3
22	Gov James B Hunt	498	5.13	4.01 - 6.22	0.11	0.09 - 0.13
23	Ocracoke Express	12	1.02	0.76 - 1.26	0.01	0.01 - 0.02

Note: * Annual CO₂ emissions were estimated using a mass balance approach based on vessel's fuel consumption.

** NA: not applicable because the vessel was not in service in year 2021.

Table B.5. Estimated baseline annual emissions for the North Carolina ferry fleet for year 2020.

Vessel ID	Vessel Name	Annual Emissions for Pollutants (ton/year) **				
		CO ₂ *	NO _x +HC		PM	
			Mean	95% Uncertainty Range	Mean	95% Uncertainty Range
1	Silverlake	699	10.74	8.22 - 13.17	0.19	0.15 - 0.23
2	Cedar Island	1030	16.7	12.76 - 20.46	0.30	0.23 - 0.36
3	Carteret	1609	24.26	18.57 - 29.65	0.43	0.33 - 0.52
4	Swan Quarter	902	10.27	8.02 - 12.49	0.18	0.13 - 0.23
5	Sea Level	1451	17.04	13.28 - 20.69	0.29	0.21 - 0.39
6	Gov Daniel Russell	396	5.98	4.66 - 7.26	0.12	0.1 - 0.15
7	Southport	380	5.52	4.29 - 6.71	0.11	0.09 - 0.14
8	Neuse	1108	24.22	18.89 - 29.36	0.50	0.4 - 0.6
9	Lupton	229	4.64	3.62 - 5.62	0.10	0.08 - 0.12
10	Fort Fisher	528	7.7	5.99 - 9.32	0.16	0.13 - 0.19
11	W Stanford White	1615	22.79	17.82 - 27.60	0.47	0.38 - 0.57
12	Croatoan	1919	26.52	20.59 - 32.21	0.55	0.44 - 0.66
13	Hatteras	1411	15.16	11.54 - 19.53	0.51	0.29 - 0.81
14	Rodanthe	661	4.23	0.59 - 8.07	0.13	0.03 - 0.22
15	Avon	NA	NA	NA	NA	NA
16	Salvo	NA	NA	NA	NA	NA
17	Kinnakeet	141	1.77	1.41 - 2.14	0.04	0.03 - 0.05
18	Frisco	22	0.2	0.04 - 0.36	0.01	0 - 0.01
19	Chicamocomico	19	0.11	0.02 - 0.20	0.00	0 - 0.01
20	Cape Point	597	4.7	0.88 - 8.66	0.14	0.03 - 0.23
21	Ocracoke	551	4.29	0.80 - 8.00	0.13	0.03 - 0.21
22	Gov James B Hunt	275	2.94	2.30 - 3.55	0.06	0.05 - 0.07
23	Ocracoke Express	NA	NA	NA	NA	NA

Note: * Annual CO₂ emissions were estimated using a mass balance approach based on vessel's fuel consumption.

** NA: not applicable because the vessel was not in service in year 2020.

Table B.6. Estimated baseline annual emissions for the North Carolina ferry fleet for year 2019.

Vessel ID	Vessel Name	Annual Emissions for Pollutants (ton/year) **				
		CO ₂ *	NO _x +HC		PM	
			Mean	95% Uncertainty Range	Mean	95% Uncertainty Range
1	Silverlake	477	8.02	6.14 - 9.80	0.14	0.11 - 0.17
2	Cedar Island	864	14.13	10.80 - 17.35	0.25	0.2 - 0.31
3	Carteret	937	14.01	10.75 - 17.17	0.25	0.19 - 0.3
4	Swan Quarter	892	9.79	7.63 - 11.89	0.17	0.12 - 0.22
5	Sea Level	1430	15.58	12.15 - 18.91	0.27	0.19 - 0.36
6	Gov Daniel Russell	374	5.55	4.31 - 6.73	0.11	0.09 - 0.14
7	Southport	164	2.38	1.86 - 2.89	0.05	0.04 - 0.06
8	Neuse	504	8.57	6.67 - 10.38	0.18	0.14 - 0.21
9	Lupton	456	5.49	4.28 - 6.65	0.11	0.09 - 0.14
10	Fort Fisher	440	6.1	4.76 - 7.40	0.13	0.1 - 0.15
11	W Stanford White	636	7.99	6.22 - 9.68	0.17	0.13 - 0.2
12	Croatoan	1047	13	10.11 - 15.78	0.27	0.21 - 0.32
13	Hatteras	780	8.37	6.37 - 10.77	0.28	0.16 - 0.45
14	Rodanthe	NA	NA	NA	NA	NA
15	Avon	NA	NA	NA	NA	NA
16	Salvo	NA	NA	NA	NA	NA
17	Kinnakeet	268	3.18	2.53 - 3.84	0.08	0.06 - 0.09
18	Frisco	300	1.99	0.37 - 3.71	0.06	0.01 - 0.1
19	Chicamocomico	350	2.31	0.42 - 4.24	0.07	0.02 - 0.11
20	Cape Point	130	0.94	0.18 - 1.74	0.03	0.01 - 0.05
21	Ocracoke	NA	NA	NA	NA	NA
22	Gov James B Hunt	209	2.28	1.79 - 2.76	0.05	0.04 - 0.06
23	Ocracoke Express	NA	NA	NA	NA	NA

Note: * Annual CO₂ emissions were estimated using a mass balance approach based on vessel's fuel consumption.

** NA: not applicable because the vessel was not in service in year 2019.