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Methane slip measurement and mitigation: a multi-vessel case study and lessons learned

Dual Fuel / Gas / Diesel

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ABSTRACT

Low pressure dual fuel natural gas engines have gained significant popularity in recent years, as they provide a cost-effective approach for sulfur, NOx, and PM emission mitigation. Furthermore, they hold the potential for CO2 reductions; however, for this to equate to tank-to-wake (TtW) greenhouse gas (GHG) reductions, emission of unburned CH4 must be minimized. This is particularly challenging for coastal vessels that tend to use 4-stroke medium speed engine configurations, and have duty cycles with considerable low load operation. Both of these factors have been seen to result in problematic CH4 emissions. This paper summarizes an ongoing research program to characterize and mitigate the CH4 emissions from coastal vessels using LPDF engines and provides best practice recommendations for measurement and TtW emission factor calculation.

Exhaust emission measurements were performed on four vessels with baseline and updated engine control software, during both seatrial and commercial operations. The measurement procedures were based on ISO 8178 and the NOx technical code; however, accommodations were made for the unique circumstances of each vessel. A comparative assessment of CH4 concentration measurement techniques including a flame ionization detector, fourier transform infrared spectrometer, and wavelength modulation spectroscopy system was carried out.

The measured exhaust concentrations, flow rates, and engine output were used to calculated representative Emission Factors (EF) based on realworld operation. For the considered vessels, the daily EF varied by factor of 3.6, depending on the vessel operation and engine configuration. A scenario analysis indicated a best-case average EF of 2.9 gCH4/kWh, and a worst-case EF of 10.4 gCH4/kWh. The significant variability in CH4 EFs due to engine specific emissions and vessel operation demonstrate the need to consider actual TtW emissions for current and future fuels, where the latter may introduce new GHG species.

1 INTRODUCTION

The use of liquefied natural gas (LNG) instead of marine gas oil (MGO) is motivated by its lower NOx, particulate matter (by mass and number), and SOx emissions, as well as the potential for greenhouse gas (GHG) reductions through lower CO_2 emissions. As of June 2024, 6.7% of vessels in operation and 36% of vessel on order (by gross tonnage) are capable of using LNG as a fuel [1], representing the largest fraction of alternative fuels. LNG is commonly combusted using the low pressure dual fuel (LPDF) combustion concept in which vapourized LNG is inducted with air into the engine. At the end of the compression stroke, the premixed natural gas and air mixture is ignited by injection a small amount of MGO.

Studies have evaluated the impact of LPDF combustion on air quality pollutants relative to MGO, and found significant reductions in NOx, SOx, and particulate matter, coupled with an increase in hydrocarbon and carbon monoxide emissions (e.g., [2], [3]). Subsequent works confirmed that the hydrocarbon emissions are primarily due to unburned methane and are particularly problematic at low engine loads [4], [5], where the high air-fuel ratio results in incomplete combustion. The CH_4 emissions must be addressed due to the significant global warming potential of CH_4 and its potential to offset any CO_2 reduction afforded by natural gas, relative to MGO. Indeed, current and pending international and national regulations require that the GHG contribution of CH_4 is considered in accounting for the tank to wake (TtW) emissions.

Modified vessel operation to avoid low load, as well as updated engine control software have been demonstrated to mitigate CH_4 emissions. Earlier works demonstrated this for coastal vessels, which have significant and unavoidable low load operation, but where the NOx, SOx, and PM improvements provided by LNG are desirable in light of the proximity of these vessels to urban centers [6]. Recently, the CH_4 (and other) emissions have been evaluated for modern vessels, which included additional software improvements and resulted in further CH_4 emission reductions [7], [8]. In most cases, the CH_4 emissions decrease with newer engine generations. A 2023 review summarizes the CH_4 emissions from numerous engines and vessels [9], from both on-vessel and engine test bed measurements. For four stroke LPDF engines, the specific CH_4 emissions varied by two orders of magnitude, with a particular sensitivity to engine load demonstrating the significant differences in CH_4 emissions between engines. For comparison, the CO_2 emissions from a similar engine vary by much less than one order of magnitude over all engine loads [6], and are similar from engine to engine.

Regulatory test cycles (e.g., NOx Technical Code, NTC, [10]) prescribe the engine operating conditions considered during emissions measurement. These typically do not consider the full engine operating region and can exclude the critical low load operation for the case of main engines (e.g., E2 test cycle). Several on-vessel studies have considered a more comprehensive range of steady-state engine loads (e.g., [4], [6], [7], [8], [11]), as well as limited investigations using continuous measurements during commercial operation ([6], [7], [11]). The emission factor – i.e., grams CH_4 emitted per unit energy produced [g/kWh] can be calculated based on a prescribed engine duty cycle weighting (e.g., from regulatory cycles [10]) or through consideration of the actual engine operation (e.g., [4], [6], [12]). Depending on the operation characteristics of the vessel, there may be reasonable agreement in the two methods, or the exclusion of low-load operation may result in the emissions being underestimated. Many of the works cited here have commented on the need to consider the actual vessel operation and do so through consideration of individual sailings or logged engine data for multiple sailings (days to months).

To quantify the CH_4 emissions from a specific vessel, the CH_4 concentration is typically measured using lab grade instruments, such as a flame ionization detector (FID), gas chromatograph, or Fourier Transform Infrared (FTIR) spectrometer. The NTC specifies use of a heated FID for hydrocarbon measurement, but does not explicitly specify how CH_4 should be measured. The ISO standard for engine test-bed exhaust measurements specifies that the CH_4 may be measured using an FID with non-methane catalytic cutter, or gas chromatograph [13]. It should be noted that the gas chromatograph is not suitable for time resolved measurements, and that all of these methods require a trained operator, capital investment, and process gases.

These previous works have considered individual vessels with a range of different engines and engine technologies, as well as with varying instrumentation. This study presents a summary of an ongoing, seven-year collaborative research program aimed at measuring and mitigating the CH_4 emissions from four LPDF roll-on, roll-off (RORO) and roll-on passenger (ROPax) ferries operating in the same geographic area. In particular, the objectives of this study are to:

1. Quantify CH_4 emissions from coastal LPDF vessels and provide estimates of the vessel-

specific emission factors, with particular consideration of the operating characteristics.
2. Characterize the efficacy of engine software updates to reduce the CH_4 emissions.
3. Provide recommendations for best practices for high quality, low impact, on-vessel CH_4 measurements that can be implemented during commercial operation.

A summary of the vessels, engines, measurement approach, and instrumentation will be presented, followed by a discussion of the emission factors, including estimates of the best and worst-case scenarios. Recommendations for best practices are discussed throughout this paper, where relevant.

2 ON-VESSEL MEASUREMENTS

The exhaust stream CH_4 emissions were measured from four different coastal vessels with LPDF engines, using a suite of portable emission measurement systems. The vessels, instrumentation, and measurement campaign structures are discussed below.

All vessels are natural gas fuelled ferries operating in the Salish Sea near British Columbia Canada, and all utilize LPDF engines for their propulsion needs. The specifications of the vessels are summarized in Table 1. Vessels 1 and 2, use an engine and generator configuration for propulsion and vessel power. They are not equipped with auxiliary engines, but do have batteries that can be used for peak shaving (Vessel 1) and/or fully-electric propulsion (Vessel 2). The batteries can be charged by the LPDF main engine during sailing or while docked, or via shore power (only Vessel 2). Vessels 3 and 4 are sister vessels and utilize LPDF main engines for propulsion and vessel power, but do not have any battery storage. All vessels are fuelled by locally produced LNG and are bunkered by truck. Vessel 2 is unique in this study, as its hybrid power train allows for significant flexibility in the engine operation. Generally, the hybrid system is used to mitigate low engine load operation during, e.g., maneuvering. The impact of engine duty cycle on the emissions will be discussed in section 4.

The engines in all four vessels have similar cylinder bore diameters and have been commissioned after 2017. Vessels 1, 3, and 4 use engines from the same manufacturer; however, Vessels 3 and 4 have a later variant. The engines in Vessel 2 are from a different manufacturer and were installed most recently. During the course of this program, the engines all had engine control software updates to reduce CH_4 emissions, and the emissions before and after these updates were measured. This selection of vessels allows investigation of the impact on GHG emissions from the engine, engine control software, powertrain configuration, and vessel duty cycle.

Table 1: Summary of considered vessels. All vessels are coastal ferries operating in the Canadian Salish Sea. WMS: Wavelength Modulation Spectroscopy [14]; FTIR: Fourier Transform Infrared Spectrometer; FID: Flame Ionization Detector.

	Vessel			
	1	**2**	**3**	**4**
Application	RORO	RORO	ROPax	ROPax
Displacement (t)	4,810	4,857	21,958	18,747
Propulsion System	Genset + azimuth drive; Batteries for peak shaving	Genset + azimuth drive, Batteries for peak shaving and electric only propulsion	Direct drive, variable pitch propeller	Direct drive, variable pitch propeller
No. engine / No. cylinders / bore	2 / 9 / 34cm	2 / 9 / 35 cm	4 / 8 / 34 cm	4 / 8 / 34cm
Build Year	2015	2021	1992 (2018 refit)	1994 (2018 refit)
Emission measurement	WMS, FTIR	WMS, FTIR, FID	FTIR, WMS	FTIR, WMS
Power measurement	Generator output	Generator output	Engine SCADA	Engine SCADA
Exhaust Flow	Pitot Tube	Carbon balance	Carbon balance	Carbon balance

The emissions were measured through on-vessel sample extraction and analysis during seatrial and commercial vessel operation. Due to the ongoing nature of this research program, as well as vessel constraints, a range of emission and performance measurement techniques are applied and are summarized below.

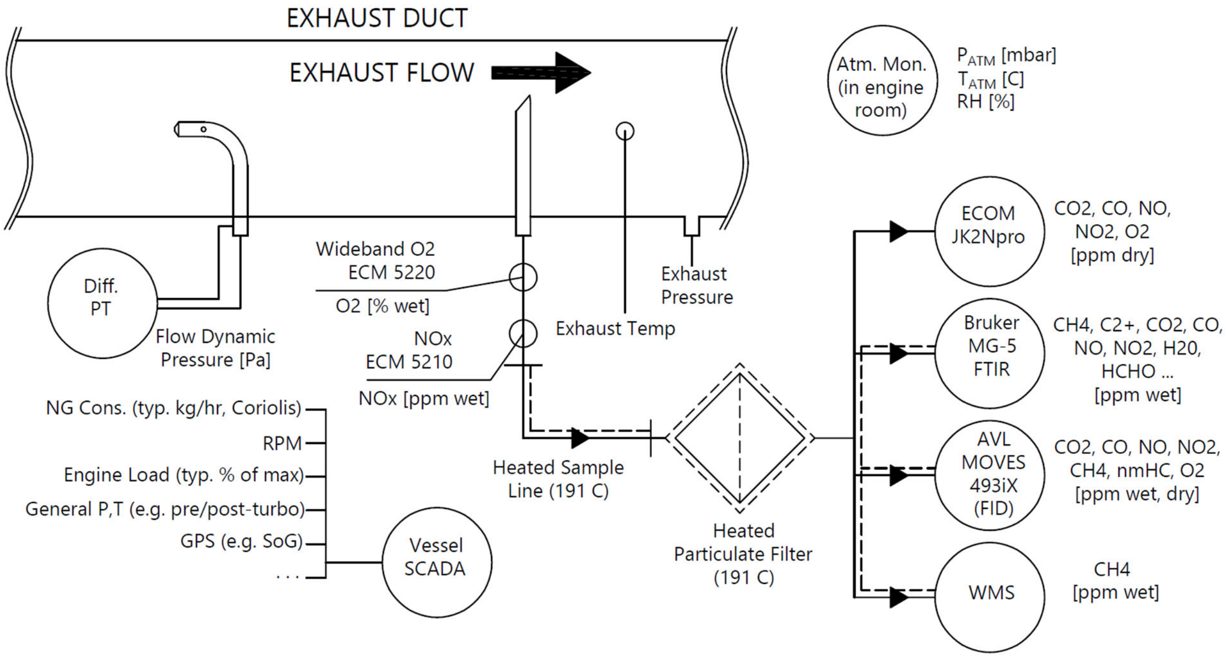

Figure 1: Typical exhaust stream emission measurement system (note that not all instruments were used for all vessels; see Table 1)

2.1 CH_4 Measurement

The emissions are characterized on a brake specific basis (g/kWhr) which requires measurement of the exhaust stream CH_4 concentration, the engine output, and the exhaust flow rate. The implemented instrumentation, measurement protocols, and analysis were based on ISO 8178 [13] and the NOx Technical Code [10], except where not possible due to equipment availability and/or vessel operation constraints. Due to the relatively recent build years and refits, all vessels have well-equipped SCADA systems which provide process data.

A representative implementation of the measurement system is shown in Figure 1. Exhaust gas is extracted from the exhaust ducting in the engine room and filtered prior to concentration measurements. All gas transport and filtering components are heated (190°C) and all CH_4 concentration measurements are carried out on a wet-basis. All equipment is placed in the engine room with vibration damping (as needed) and monitored from the engine control room via local network connection. The instrumentation is placed in the engine room to minimize gas transport times, avoid interference with passenger and/or cargo operations, and to take advantage of the hoisting infrastructure and significant ventilation typically available in the engine room. A sample installation is shown in Figure 2 (Vessel 2).

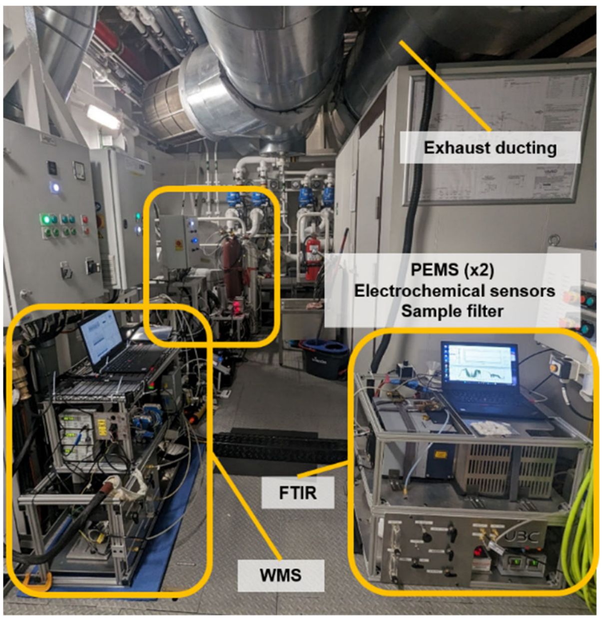

Figure 2: Representative PEMS installation for GHG emission measurement (on Vessel 2)

The exhaust stream CH_4 concentrations were measured using a Fourier Transform Infrared spectrometer (FTIR, Bruker MG5), a commercial portable emissions measurement system (PEMS, AVL MOVE 493) with a flame ionization detector (CH_4, THC), and a prototype wavelength modulation spectroscopy based CH_4 measurement system [4], [14], [15], [16]. Non-CH_4 species (incl. CO_2, H_2O, O_2, CO, NO, NO_2, C_2H_4, C_2H_6) were measured using the FTIR, PEMS, electrochemical sensors (ECM NOxCAN and LambdaCAN), and/or a low-cost PEMS (ECOM J2KN). The discussion of these species is beyond the scope of the current work. The FTIR, WMS, and FID-PEMS were all calibrated and/or span-verified at the beginning and end of each measurement day.

Each measurement campaign included at least two CH_4 measurement techniques. The FID and FTIR approaches are commonly utilized for exhaust stream CH_4 and hydrocarbon quantification; however, the FID requires hydrogen fuel for operation which is not permitted on all vessels due to safety considerations. Furthermore, CH_4 specific measurements rely on consistent performance of the catalytic cutter to isolate CH_4 from other hydrocarbons. The FTIR implemented in this study requires process N_2 gas and liquid nitrogen for sensor cooling, both of which must be managed on the vessel. Both instruments require a trained operator, and the FTIR requires expert method development to ensure accurate CH_4 quantification

A WMS based methane measurement sensor has been developed, specifically for in-use exhaust stream CH_4 concentration measurement. WMS is an infrared absorption method that combines tuneable diode absorption spectroscopy with lock-in amplification and signal normalization for noise rejection from vibration, optics fouling, and interference from species with broadband extinction spectra. Similar to other works, the WMS system can be calibrated based on prepared gas standards.

More recently, a physics-based [16] method was implemented to enable calibration free measurements. The physics-based inversion utilizes a spectroscopic simulation of the absorption process and the Levenberg-Marquardt method to calculate the sample CH_4 concentration based on the measured absorption at 1651 nm, and sample temperature and pressure. While robust, this approach carries significant computational cost and is not suitable for online inversion. To reduce the online computation time, the spectroscopic simulation was used to train a machine learning based Gaussian Process Regression model [14] for computationally inexpensive signal inversion. The machine learning WMS (ML-WMS) system was found to provide repeatable concentration measurements over multiple instrument deployments, including transportation to and installation on multiple vessels.

Figure 3 shows a representative validation of the WMS against gas calibration standards (left), as well as FTIR and FID CH_4 concentration measurements of engine exhaust (right). The strong agreement between the WMS and FTIR measurement validates the suitability of the calibration free WMS system for exhaust stream measurements. CH_4 concentration measurements from Vessels 2, 3, and 4 are taken from the FTIR dataset, while WMS data is used for Vessel 1. The root cause for the systematically higher CH_4 concentrations measured with FID is the scope of future investigation, though this may be caused by uncertainty in the catalytic cutter efficiency.

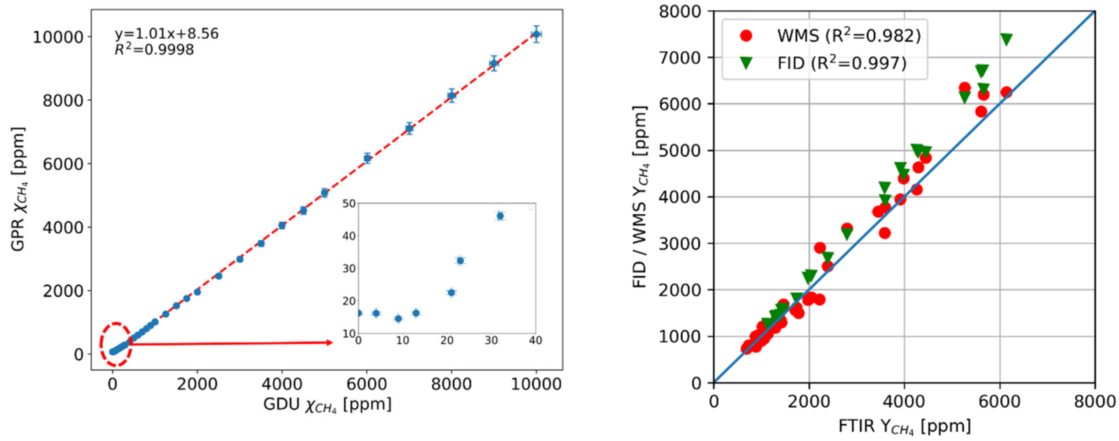

Figure 3: Validation of the WMS measurement system against gas standard mixtures prepared using a gas divider (left), and compared to an FID and FTIR for LPDF engine exhaust from all vessels (right).

It should be noted that the authors have assessed several other commercial CH_4 instruments, and while all sensors perform well against gas standards (e.g., prepared CH_4-N_2 mixtures), not all are able to accurately measure CH_4 concentration in engine exhaust, likely due to the interference of

CO_2 or H_2O, or other cross-sensitivities. The authors recommend that CH_4 measurement systems be verified specifically with exhaust gas against trusted instruments, and not just against prepared gas standard mixtures.

In addition to the emission concentrations, the engine output and exhaust flow were measured on each vessel. The measurement approach for each vessel was based on existing instrumentation on the vessel and exhaust system configuration. For Vessels 1 and 2, the engine brake power $\dot{W}_b$ was evaluated based on the SCADA reported generator power $\dot{W}_g$, and power specific generator efficiency $\eta(\dot{W}_g)$:

$$\dot{W}_b = \frac{\dot{W}_b}{\eta_g}$$

For Vessels 3 and 4, the relative engine load was recorded from the vessel SCADA system and scaled by the engine rated power.

The exhaust flow rate measurement was strongly affected by accessibility to a suitable measurement location in the exhaust duct. On Vessel 1 the exhaust velocity was measured directly using a pitot-static tube at the sample point, which was located at the end of a long straight duct section. Cross-section sweeps were carried out at all engine loads and the velocity profile was integrated to evaluate the mean exhaust velocity. The local exhaust temperature, pressure, and composition were used to evaluate the exhaust gas density. Vessels 2, 3, and 4 did not have a suitable location for pitot-static probe access (all accesses were located on ducting bends), and thus the carbon balance method was used. For this, natural gas flow rates were recorded from the vessel flowmeters, while diesel pilot flow rates were obtained from the EIAPP certificates as no diesel flowmeters were installed.

2.2 Measurement Approach

The measurements were carried out during seatrials and during commercial vessel operation. During seatrials, nominal engine loads were considered across the full engine operating region (typically 10%-100%) and at NOx Technical Code test conditions (e.g., 25%, 50%, 75%, 100%). Where the 100% engine load condition was not possible due to vessel constraints, the maximum engine allowed load was considered. The engine load was set by the vessel crew and monitored on the SCADA display to ensure stability. The measurement was started once the exhaust temperature and exhaust species concentrations were stable. On Vessels 1 and 2 the seatrials took place outside of commercial operation. For Vessels 3 and 4 the seatrials took place during commercial operation, with the measurement order designed to minimize scheduling impact by distributing low and high load conditions across multiple sailings (on the same day). A communication protocol was developed between the vessel engineering and bridge crews, and the research personnel to coordinate vessel operation and measurements. For all vessels, one or more operating conditions were repeated multiple times (at least 3) to assess the measurement repeatability. All measurements for a given engine and engine software version were completed in one day and repeated on separate days when possible, to ensure consistency.

For all vessels, low load operating conditions (<20%) were performed by dock pushing. It should be noted that dock pushing results in less stable engine operation on the direct drive vessels (3 and 4), due to the increased turbulence near the propeller. Furthermore, the authors have noted that if the engine speed (vs. power) is used to specify the engine condition during dock pushing, the engine torque on vessels with direct drive powertrains will be different than that during sailing conditions. In this case, it is necessary to also measure the engine and/or shaft torque to ensure the engine operating condition is accurately specified.

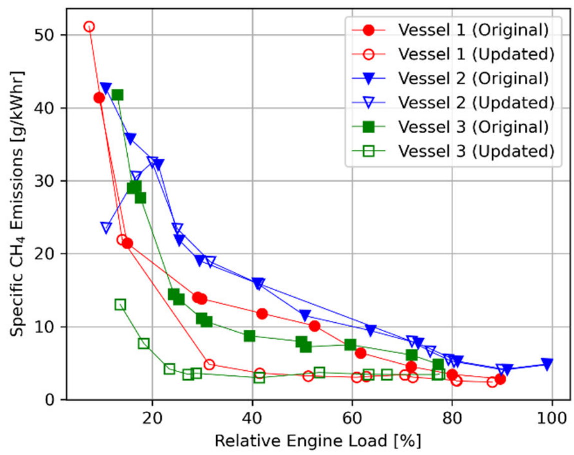

Figure 4: Comparison of brake specific CH_4 emissions from Vessels 1-4. Vessels 3 and 4 are sister vessels and have very similar emissions and only measurement from Vessel 3 are shown.

3 IMPACT OF ENGINE TECHNOLOGY ON CH_4 EMISSIONS

Across the four considered vessels, three different engines were considered (two manufacturers, with two engine versions from one of the manufacturers, see Table 1), including control software updates designed to reduce CH_4 emissions. Figure 4 provides a comparison of the brake specific emissions for all vessels, with the original and update engine control software. As has been reported in numerous other works including a recent review [9], the CH_4 emissions increase significantly at low engine loads for all vessels. This is characteristic of the slow flame speed caused by very lean operation at low loads [4]. If the engine is operated at lower loads, the GHG benefit from reducing CO_2 emissions may be negated by the CH_4 emissions.

The engine control software for all vessels was updated by the manufacturer and results in specific CH_4 emission reductions, particularly at low engine loads. Vessels 1, 3, and 4 have engines from the same manufacturer; however, Vessel 3 has a later version (2017 vs. 2018) which allows for greater CH_4 emission reduction. The software modifications utilize measures such as cylinder deactivation at low load and improved combustion phasing to reduce the air fuel ratio and to optimize combustion. With the software upgrade, the CH_4 emissions from Vessel 3 result in reduced specific CH_4 emissions at all engine loads. For vessel 1, the software update provides similar benefits; however, the reductions are less pronounced at the very lowest engine loads. The software update for Vessel 2 reduced the specific emissions at low loads, though not to the extent for Vessels 1, 3, and 4. It should be noted that the authors expect further refinements to engine software may provide additional reduction (especially for Vessel 2), and indeed other investigations have explored this potential as well [8]. Furthermore, the current work includes only engine software updates, while future strategies including fuel blending and exhaust aftertreatment may be available to further reduce CH_4 emissions (e.g., [17], [18], [19]).

Figure 4 demonstrates the significant variation in the CH_4 emissions for modern engines (newer than 2017), of the same type, size, and application. Depending on the emissions characteristics of a given engine and software version, the vessel operation and design may be adjusted for minimal CH_4 emissions. Furthermore, the significant differences imply that a single emission factor is insufficient to characterize the CH_4 emissions for all engines of a given type and size, and that these must ultimately be measured for a given engine. It should be noted that the significant differences are only for the CH_4 emissions and that the CO_2 emissions are typically proportional to the fuel consumption, as is the case for conventional hydrocarbon-based fuels.

4 IMPACT OF VESSEL OPERATION

The measured (steady state) emissions shown in Figure 4 emphasize the importance of not only considering the engine model and type, but also the actual engine duty cycle. This is particularly important for LPDF engines due to the non-linear load dependence of CH_4 (and therefore GHG) emissions. To assess the impact of the vessel operation, the daily CH_4 emission factors (EF) are estimated based on the steady-state emissions and engine operation during commercial sailings. This approach is also applied to explore best- and worst-case scenarios based on the measured data for the four considered vessels.

4.1 Emission Factor Calculation

The emission factor for a given vessel activity is estimated by assuming that the steady state, brake specific emissions measured during seatrials (Figure 4) are only a function of engine load $L(t)$ and are representative of operation during commercial operation. The emission factor, EF_i for the i^{th} day of commercial operation is evaluated using:

$$EF_i = \frac{m_{CH_4,total}}{W_{b,total}} = \frac{\int \dot{m}_{CH_4} dt}{\int \dot{W}_b dt}$$

Where $\dot{m}_{CH_4}$ is the instantaneous CH_4 mass flow rate and is evaluated at the instantaneous engine load, and $\dot{W}_b$ is the instantaneous engine power. Instantaneous engine power histories were recorded for multiple days during commercial operation.

While all vessels are ferries operating in the Salish Sea, the engine duty cycles differ due to operational constraints and vessel design. Figure 5 shows the distribution of engine loads for all of the vessels. Vessels 1 and 2 have longer loading and unloading periods than Vessels 3 and 4 (several hours vs. <1 hour) and are therefore transitioned to shore power and the engines are stopped when docked. Due to the shorter loading and unloading times for Vessels 3 and 4, the engines are used to push the vessel against the dock for the duration of the loading, which results in significant engine operation at lower loads (~20% load). The hybrid powertrain of Vessel 2 allows low engine load operation to be almost completely avoided by either using the batteries for propulsion energy, or by battery charging, which increases the engine load during periods of low propulsion demands.

It should be noted that the calculation approach presented above assumes that the instantaneous emission rate at time t is only a function of engine load, and that the steady state specific emissions are unaffected by dynamic operation. Several recent studies have presented limited time series data, which demonstrate that for approximately constant engine load, the exhaust stream CH_4

concentration may vary [6], [7], indicating limitations to the steady state assumptions.

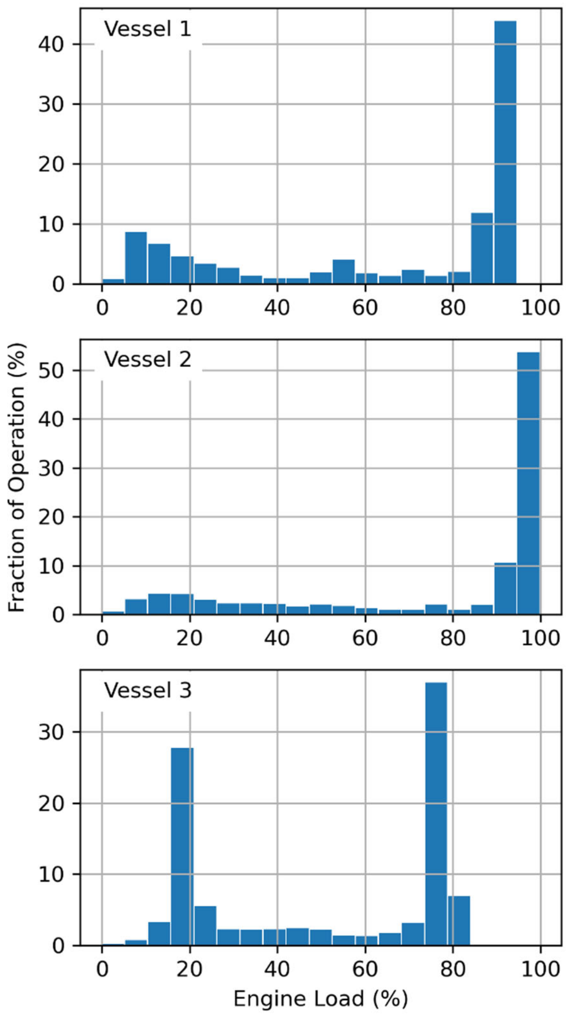

Figure 5: Engine load distributions for the considered vessels. Engine load data is taken over several weeks of commercial for each vessel with time resolution <1 minute.

4.2 Comparison of "actual" emissions

The average emission factor for individual days of commercial operation are shown in Figure 6 for all vessels, including the influence of the engine control software updates. While Vessels 1, 3, and 4 all have similar engines and similar software upgrades, Vessels 3 and 4 have higher emission factors prior to software updates due to the considerable time spent at lower engine loads during loading and unloading. With the updated software, the average daily EF for Vessels 3 and 4 is reduced by 40%. In contrast, Vessel 2 has almost no low load operation (see Figure 5); however, the higher specific CH_4 emissions result in higher daily emission factors. The emission factors shown in Figure 6 for a given vessel and engine control software have variability because of inevitable changes in vessel operation due to crew preferences, weather conditions, vessel loading, traffic, or other operational constraints. It should be noted that many of the sailings result in near-minimum emission factors, with the outliers resulting in significantly higher values. In general, the outliers result from delays or operational changes that require increased operation at lower loads. The sensitivity of the emission factors to actual operation underpins the need to consider both brake specific emissions and the vessel operation.

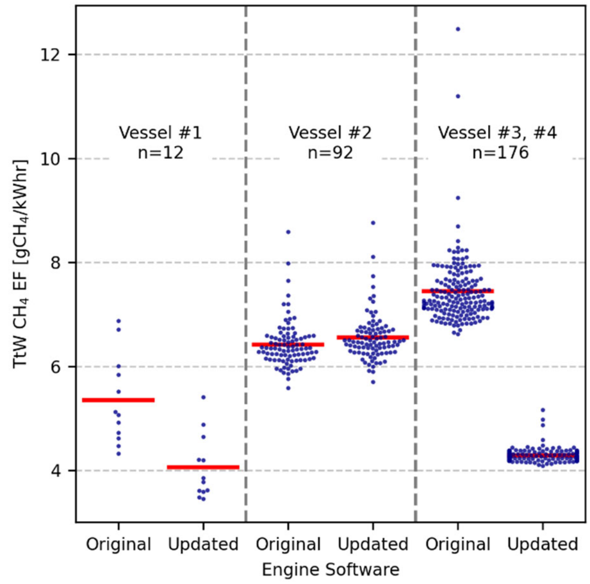

Figure 6: Distributions of calculated daily TtW CH_4 emission factors for individual days for all vessels (n indicates the number of days considered for each vessel). Data points represent the emission factor for individual days, and red lines indicate the mean value of all sailings.

A best- and worst-case EF may be evaluated using these data sets. The best-case scenario is defined here as the duty cycle of Vessel 2 with minimal low load operation, combined with the lowest brake specific emissions (Vessel 3, after update). The worst case utilizes a duty cycle with significant low load operation (Vessel 3), and the highest brake specific emissions (Vessel 2). The resulting daily emission factors are shown in Figure 7 for the same sailings considered in Figure 6. In addition to a 3.6x reduction in the TtW CH_4 emissions over the worst case (2.88 g/kWh vs 10.36 g/kWh), the best-case scenario also has significantly less emission variability. This is attributed to the consistent duty cycle with predominantly high load operation (Vessel 2), as well as the decreased CH_4 emission sensitivity to load (Vessel 3 (updated), see Figure 4). Ultimately, these two scenarios demonstrate the potential for significant CH_4 reductions by optimizing both the engine software and vessel operation. The latter can be further improved at the vessel design or refit stage e.g., by utilizing low load mitigation measures such as hybridization. Figure 6 and Figure 7 show wide ranges of TtW CH_4 emissions possible from nominally similar vessel applications because of differences in the engine and/or the vessel operation, underpinning the need for vessel and application specific determination of TtW EFs.

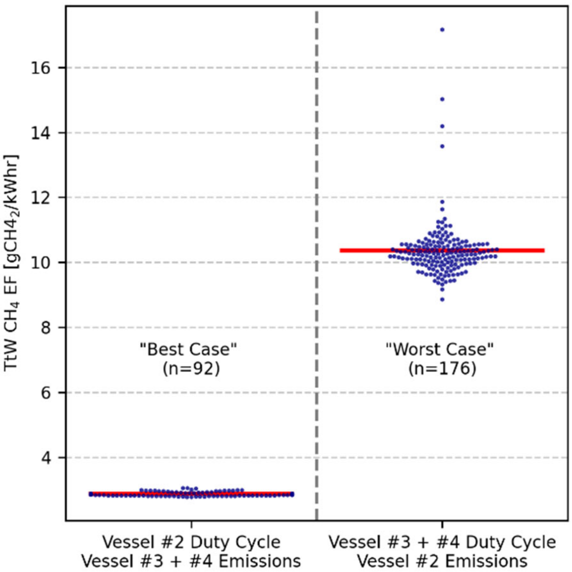

Figure 7: Estimated best- and worst-case TtW emission factors based on combinations of brake specific emissions and vessel duty cycles. Best case (left) uses powertrain hybridization to minimize load operation (Vessel 2, Figure 5) and the lowest brake specific emissions (Vessels 3 and 4, Figure 4). Data points represent the emission factor for individual days, and red lines indicate the mean value of all days.

5 CONCLUSIONS AND RECOMMENDATIONS

A collaborative ongoing program has focussed on characterizing the TtW CH_4 emissions from LPDF natural gas engines on coastal vessels. The exhaust stream emissions were measured from four different vessels with as-delivered and upgraded engine control software. The measurement and the vessel operation data (engine loading histories) were used to estimate the actual TtW CH_4 emissions factors for commercial operation. From this, the following conclusions and recommendations are made.

1. For LPDF engines of the same cylinder bore and nominally the same age, the specific CH_4 emissions vary significantly between engines, and are a strong function of the engine loading and the engine calibration.
2. For a given engine, updated engine control software can provide significant CH_4 reductions. The efficacy of the software updates vary in terms of reduction amounts, and the loads at which the reductions are realized. Furthermore, the impact of the software update on the EF depends strongly on the vessel operation and is ideally assessed for each specific vessel under actual operating conditions. For example, the software update on Vessel #2 reduced the specific CH_4 emissions at low loads; however, the vessel has negligible low load operation, resulting in minimal changes in the actual EF.
3. The actual TtW CH_4 EF can vary significantly between LPDF engines and applications due to differences in the engine specific emissions and the vessel operation. For the vessels considered here, the average daily EF ranged from 4.1-7.7 g/kWh across all vessels and software versions, while individual daily EFs ranged from 3.5-12.5 g/kWh.
4. Matching the best-case emissions with the best-case duty cycle can result in significant CH_4 reductions. For example, the best-case considered here results in an average TtW CH_4 EF of 2.9 g/kWh. In contrast, the worst-case combination, which results in an average EF of 10.4 g/kWh.
5. Engine software updates can also reduce the sensitivity of the specific CH_4 emissions to the engine load (i.e., less significant emission increases at low loads). This results in EFs that are less influenced by operational changes and may relax operational constraints. Ultimately this can reduce the actual EF, as unavoidable low-load operation will not result in significant CH_4 penalties.
6. Estimating the actual TtW emissions using specific emissions measured during steady state operation does not capture dynamic operation effects. From the limited published CH_4 emission monitoring results, there is evidence that factors other than engine load affect the TtW CH_4 emissions. Long-term CH_4 monitoring measurements are required to better evaluate actual TtW emissions under real, unsteady conditions. Such measurements are the future priority of this program and require technologies suitable high accuracy CH_4 concentration measurement, with minimal cost and operational overhead. The developed WMS system may be suitable for this.
7. The uncertainty of actual TtW emissions is affected by numerous factors unique to each vessel. These may include vessel powertrain design, emission instrument feasibility, on-vessel instrumentation (e.g., for exhaust flow determination), operational constraints or variability, or fuel properties. While existing protocols exist to minimize uncertainties, increased uncertainty relative to testbed measurement is unavoidable for actual TtW measurement activities. As such, methods

must be developed to characterize the uncertainty such that it may be used to contextualize the measurements.

While this work focussed on CH_4 emissions, the authors expect that many of the considerations will be relevant to the evaluation for other non-CO_2 EF (e.g., N_2O) for other candidate fuels. It will be necessary to characterize the impact of engine operation and technology, vessel design, and vessel operation on the specific emissions and actual TtW emission factor.

6 NOMENCLATURE

EF: Emission Factor

FID: Flame Ionization Detector

FTIR: Fourier Transform Infrared

GHG: Greenhouse Gas

LPDF: Low Pressure Dual Fuel

MGO: Marine Gas Oil

PEMS: Portable Emissions Measurement System

TtW: Tank to Wake

WMS: Wavelength Modulation Spectroscopy

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