IN-USE MEASUREMENTS TO QUANTIFY MARINE METHANE SLIP IN LNG DUAL-FUEL ENGINES

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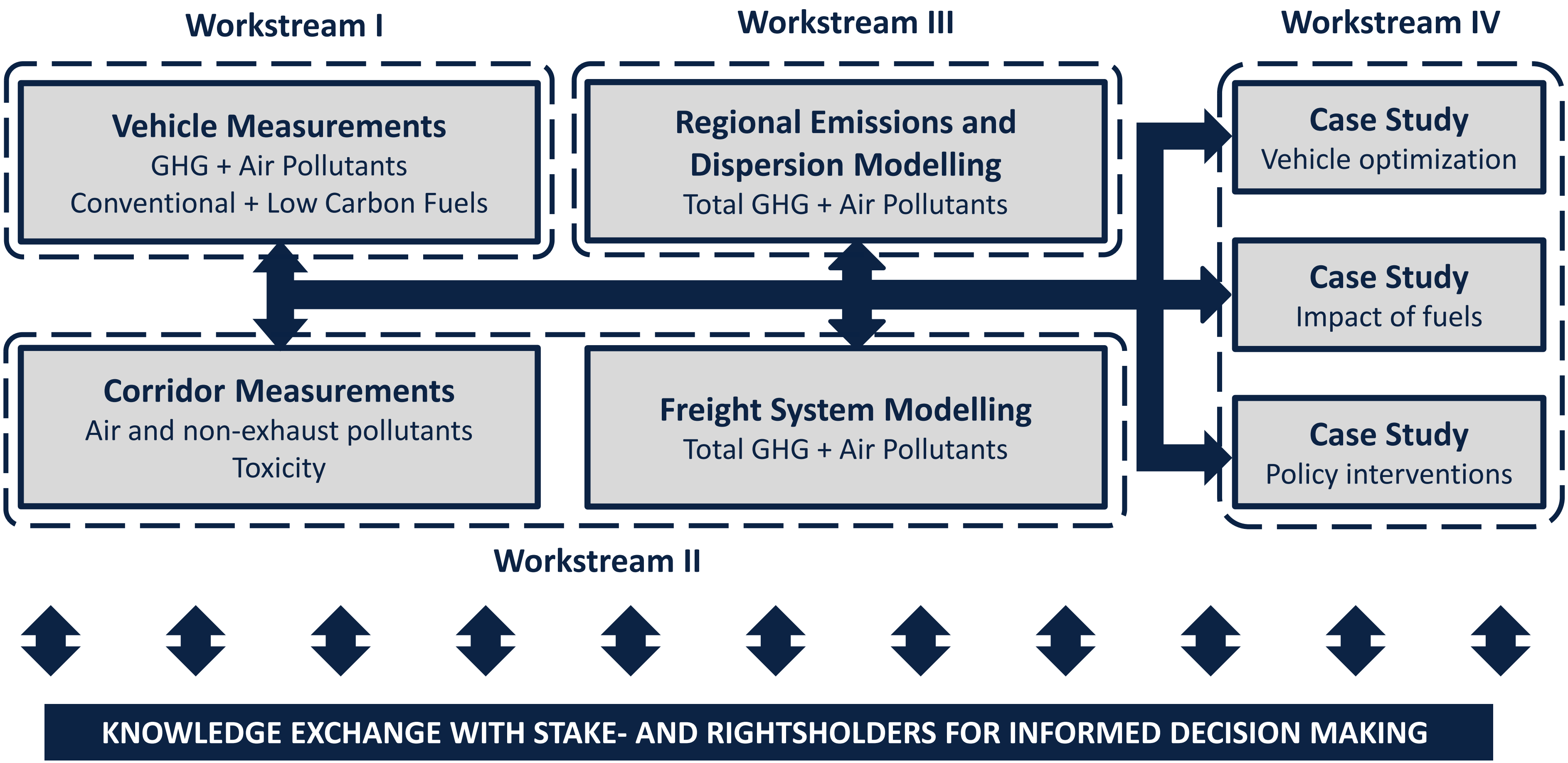
UBC URBAN FREIGHT EMISSIONS PROGRAM

(ENVIRONMENT AND CLIMATE CHANGE CANADA)

Generate data, tools, and strategies to mitigate the greenhouse gas and air quality pollutants from urban freight vehicles



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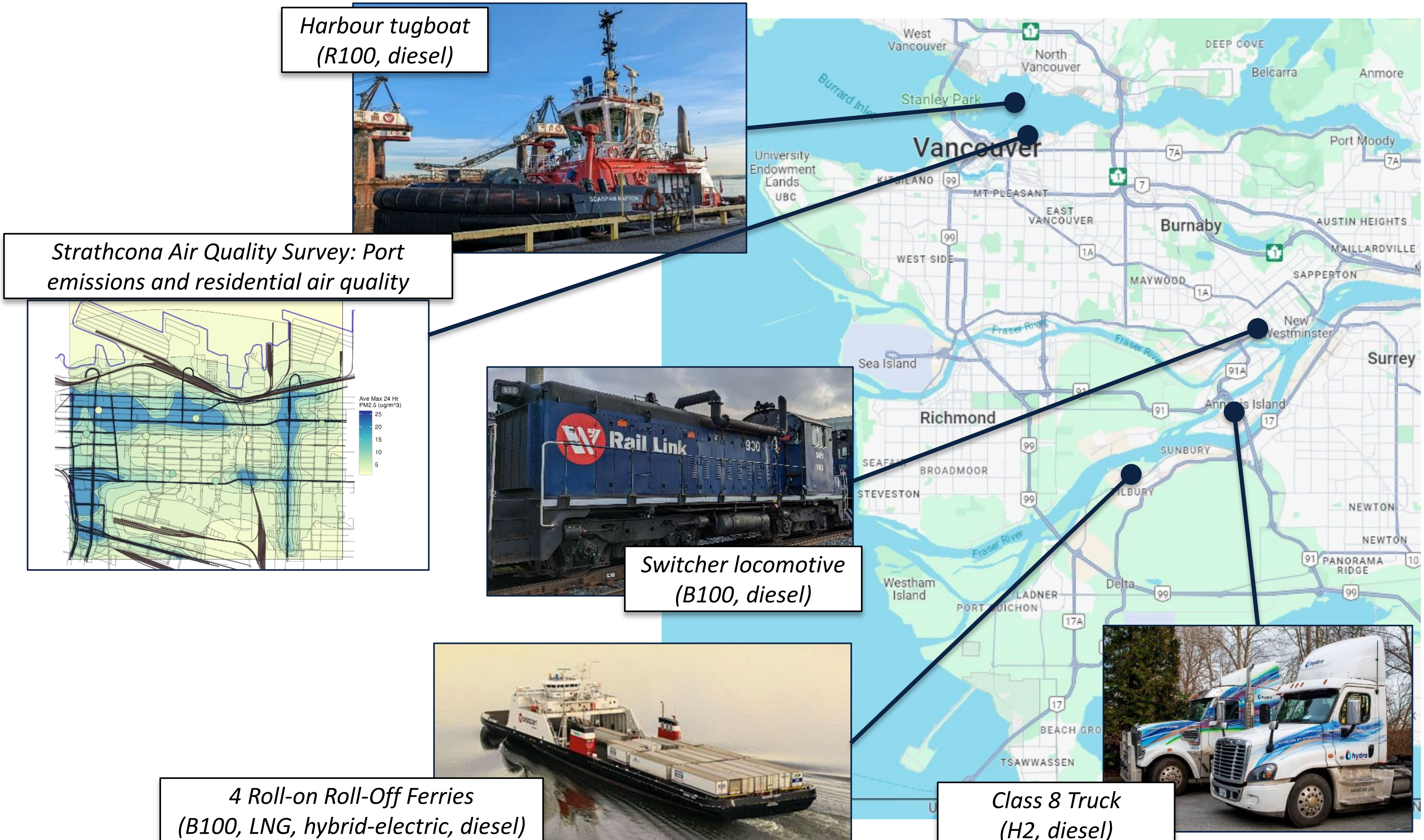
INVESTIGATING DECARBONIZATION AND AIR QUALITY IMPROVEMENTS FROM HEAVY FREIGHT OPERATIONS NEAR OUR COMMUNITIES



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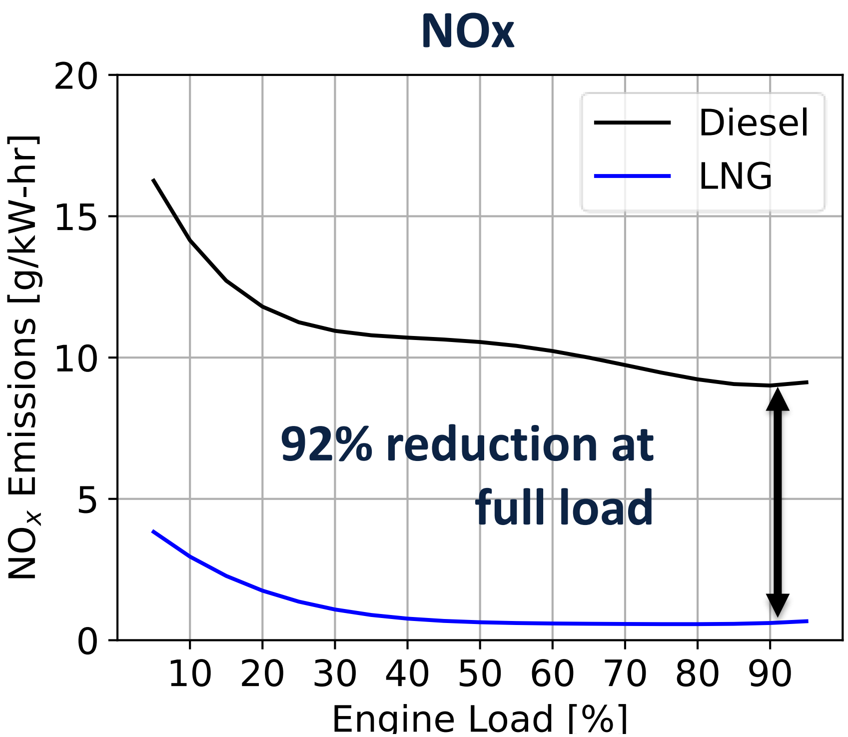
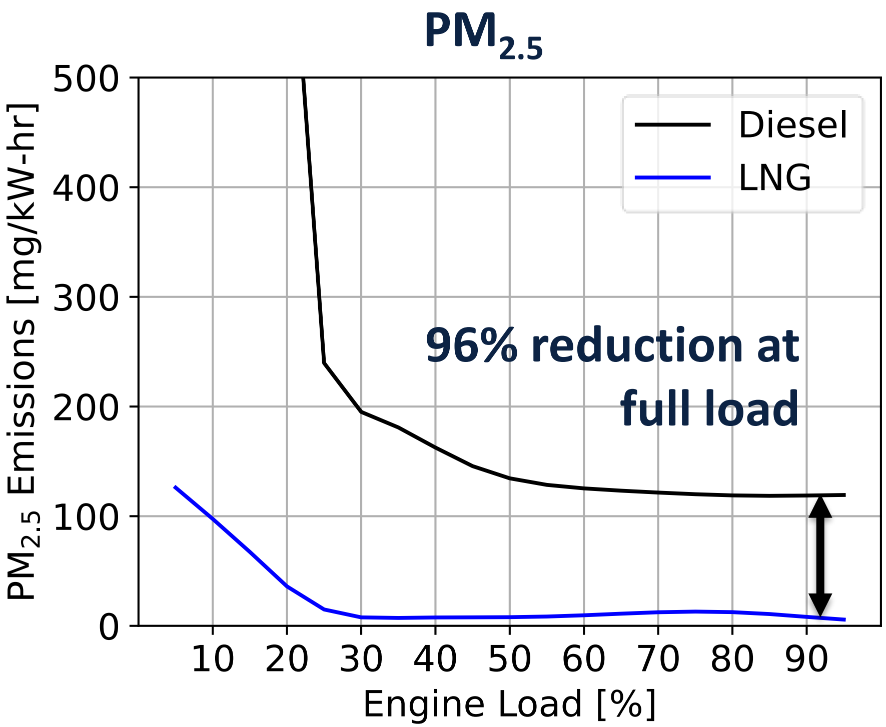
LNG Provides a Significant Air Quality Benefit over Diesel (Roll-on Roll-Off Ferry; RORO)

Air Quality: Each roundtrip sailing on LNG instead of diesel is equivalent to removing ~40k miles worth of NOx and ~47k miles of $PM_{2.5}$ from a class 8 truck

Under all circumstances, there will be air quality benefits to this fuel switching





Peng, Weihan, et al. Environmental Pollution 266 (2020): 115404.

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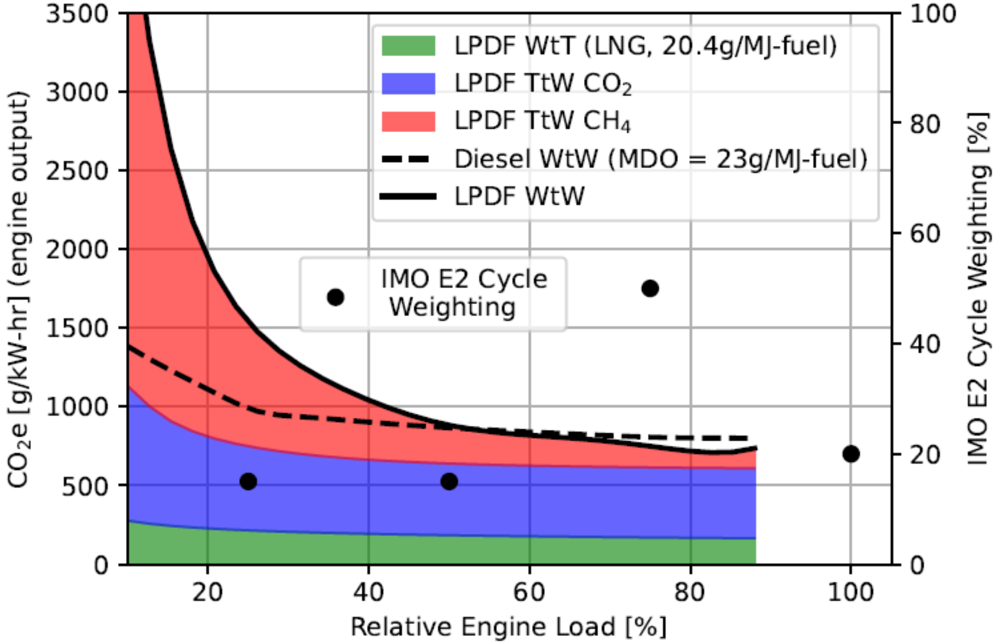
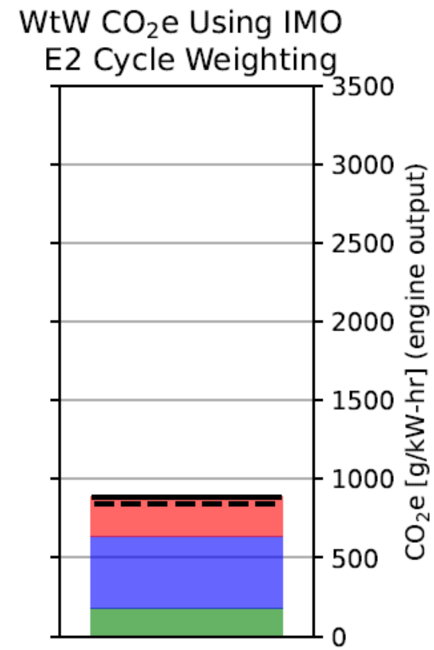
Methane Slip is Critical to Well-to-Wake Emissions Analyses and Fuel-Switching GHG Analysis





- Methane slip is very load-sensitive and can be a much more significant source of GHG than upstream (WtT) emissions
- LCA and GHG models typically use a single legislation-weighted emission factor (EF) to represent marine applications
  - **Can this be representative of the class of medium-speed LPDF engines?**
  - **How much confidence/uncertainty are there in these values when used for selecting fuels or propulsion technologies?**

In-use emissions measurements on a LPDF RORO ferry (Seaspan Trader, 2023)

GWP_{CH4} = 28 (100yr)

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Selection of Real-World Data for Emission Factor (EF) Calculation

A) Instrumentation / methods:

i) 1065 compliant PEMS,

ii) lab-grade FTIR,

iii) custom methane sensor (WMS);

iv) flow-measurement: pitot-tube, IMO NOx Technical Code carbon balance

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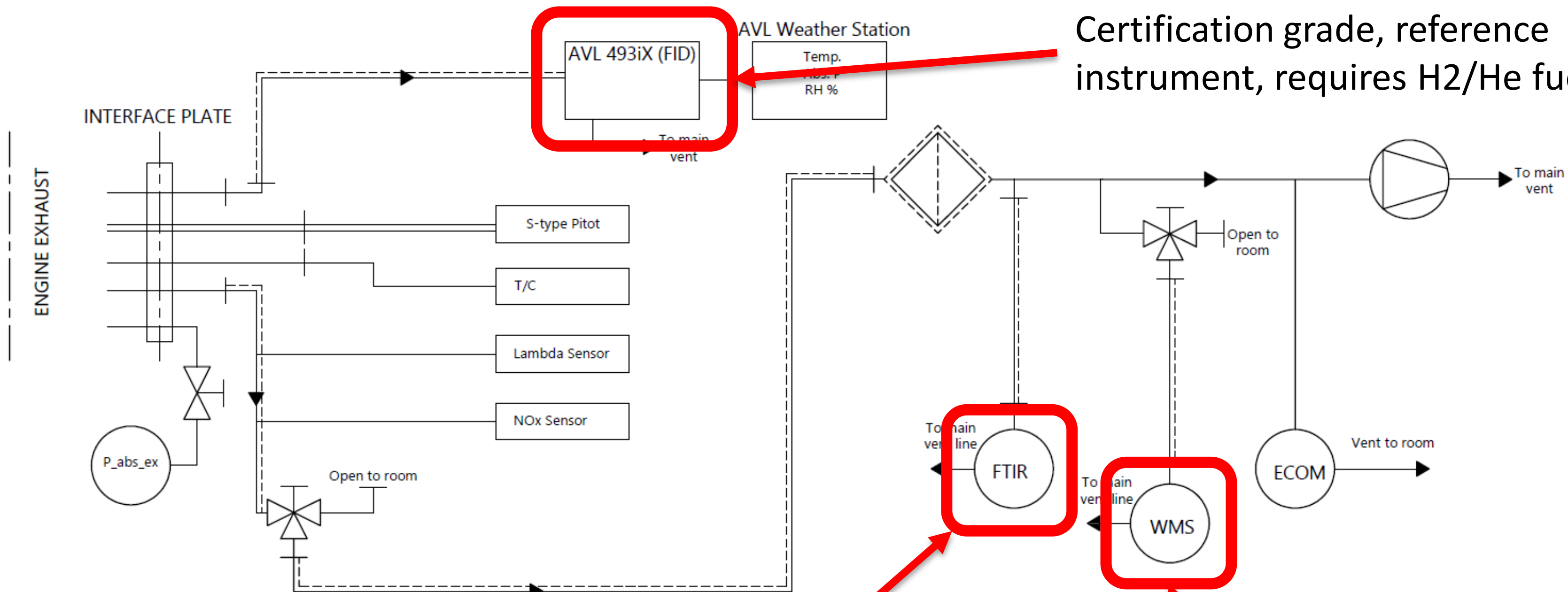
FIELD COMPARISON OF CH4 ANALYZER PERFORMANCE

Simultaneous measurement of exhaust emissions from an in-use LPDF RORO ferry during: i) steady-state sea-trials, ii) dynamic commercial operations



Certification grade, reference instrument, requires H2/He fuel

Flexible monitoring of conventional and unconventional species, currently being upgraded for field application

Wavelength Modulation Spectroscopy (WMS): Custom design, CH4-selective, high SNR and low cost, suitable for long-duration emissions logging

Engine load: Vessel SCADA, NG flowrate: Vessel SCADA (Promass80 Coriolis meter), Diesel flowrate not measured, Exhaust flow: S-type pitot tube

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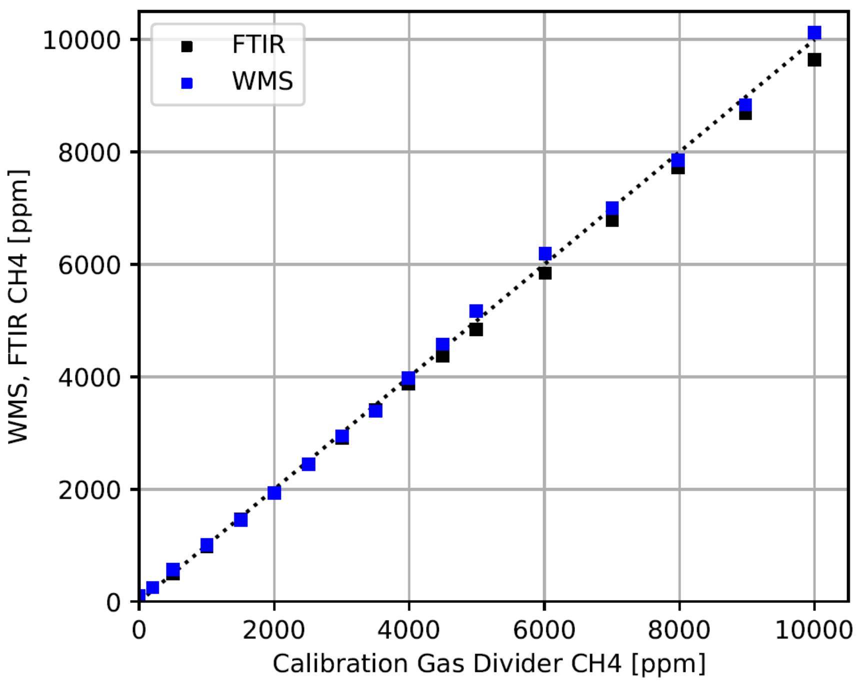
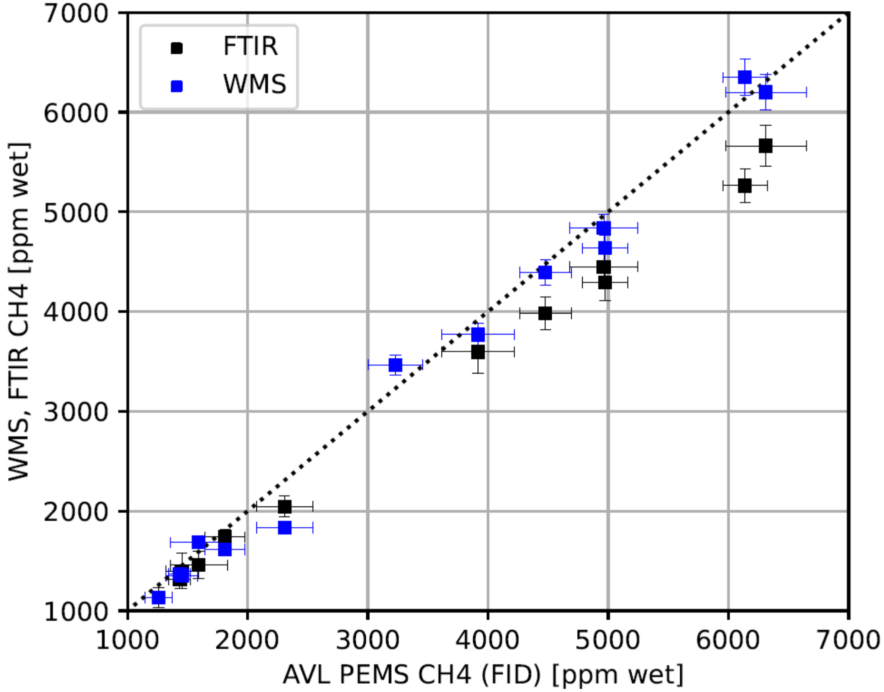
Measurement Uncertainty: Instrument & Exhaust Process Variability

Laboratory Calibration



Field Comparison



- Measurement error is higher in the field measurement than the dry calibration.
- Using error propagation, the largest source of uncertainty in the field measurements was identified as the intra-measurement variability (horizontal error bars);
  - e.g. imperfect load control during 'steady-state', propeller-pitch control feedback, etc.

Error bars are 95% confidence interval calculated using intra-measurement variability and instrument precision.

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The Role of Other Instruments in Calculation of Emissions Factors

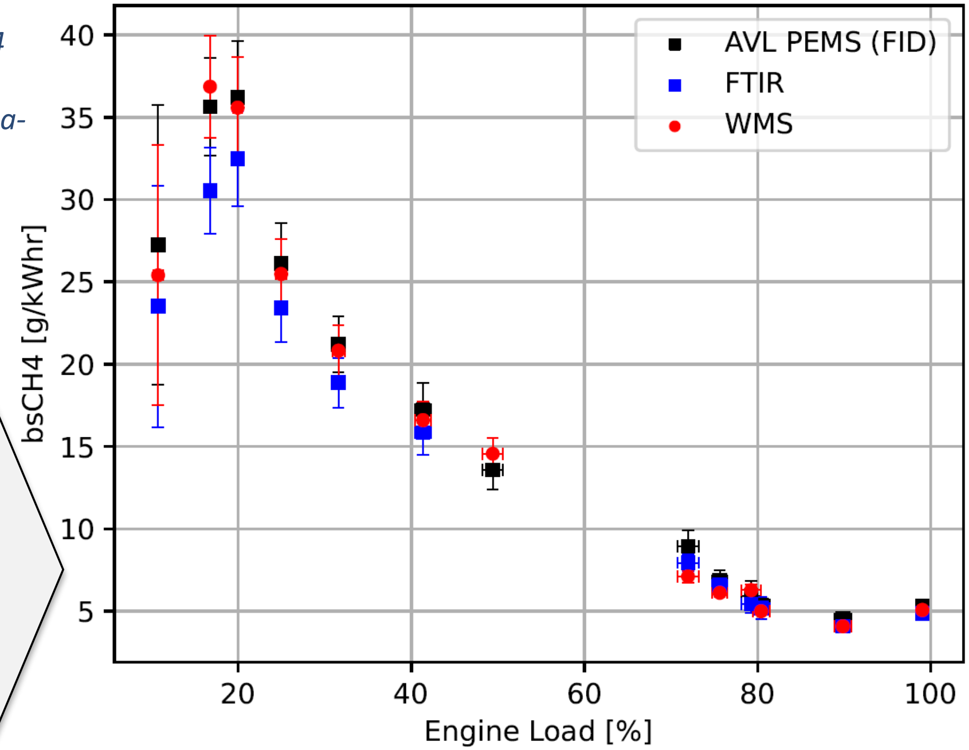
Measured Inputs for EF Calculation:

- CH4 concentration
- Engine output
- Exhaust flowrate
  - NG flowrate
  - Diesel flowrate
  - Pitot tube
  - Fuel composition
- Major exhaust species
  - CO2, O2, HC
- Atmospheric conditions
  - RH, P, T

Calculation of EF

(g-CH4/kWhr)

[Steady-state bsCH4 emission factors measured during sea-trials of RORO ferry (2023)]



Stack up of uncertainty from instrument accuracy, and <u>process variability</u> for every measured input parameter; **high methane slip conditions also have high uncertainty**

Error bars are 95% confidence interval calculated using intra-measurement variability and instrument precision.

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Reductions in Methane Slip with Improving Engine Technology

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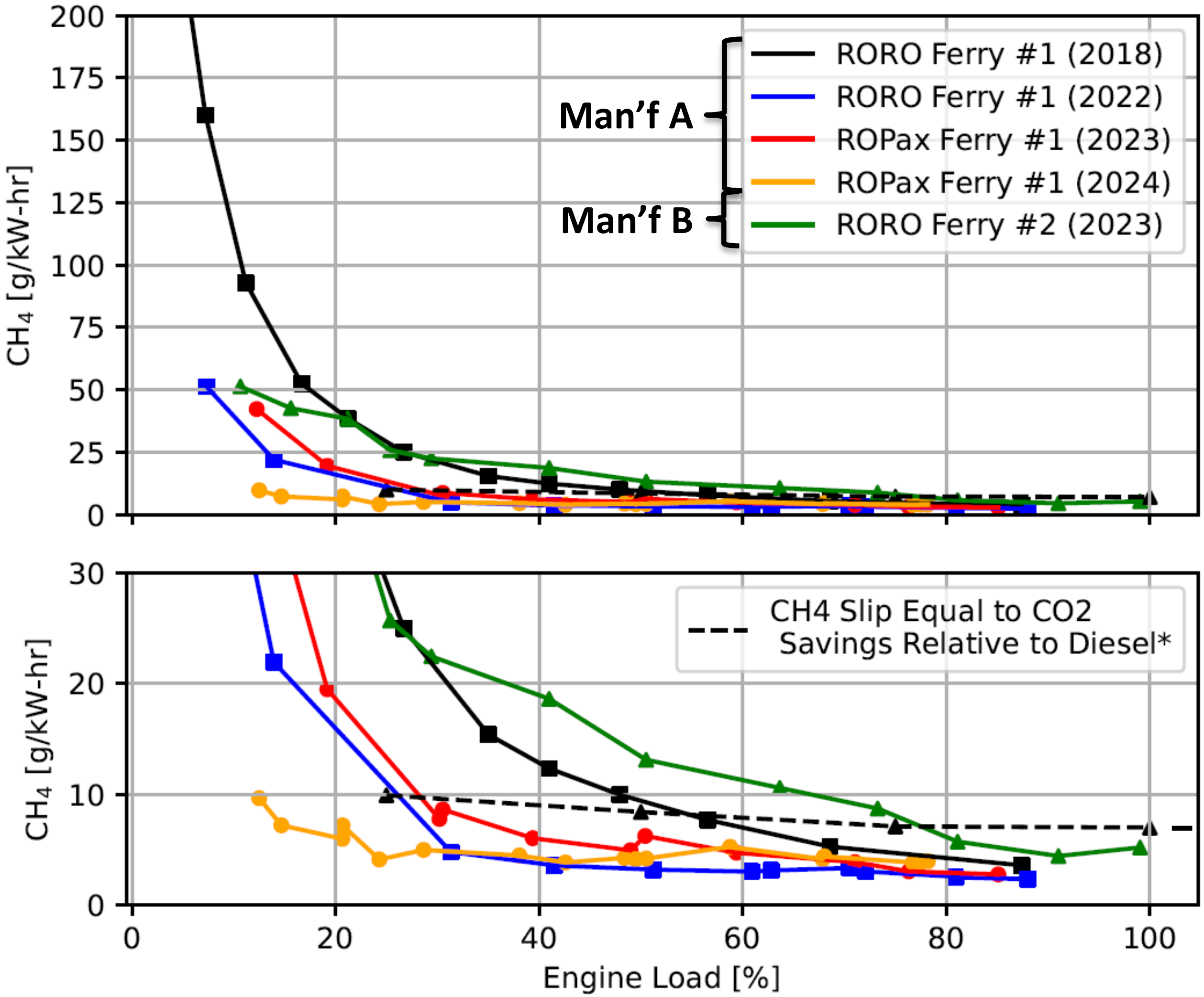

- Methane slip reductions achieved in Man’f A engines a result of UBC-Seaspan in-use measurements and updated engine calibrations (skip-fire, pilot control, air/fuel control) developed by Man’f A
- Methane slip reduction updates produce increased NOx, however engines remain well below Tier-III limits (IMO E2)
- **Current state-of-the-art LPDF has lower GHG emissions across entire load range compared to diesel**

** CH4 slip to offset CO2 savings calculated based on manufacturer B test-bed CO2 emissions data for diesel and gas mode operation, GWP_{CH4}=28*

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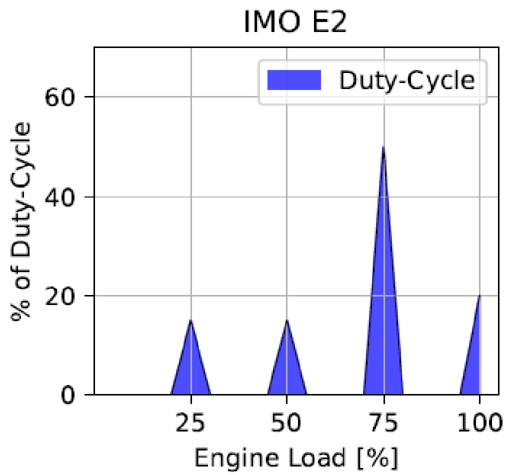
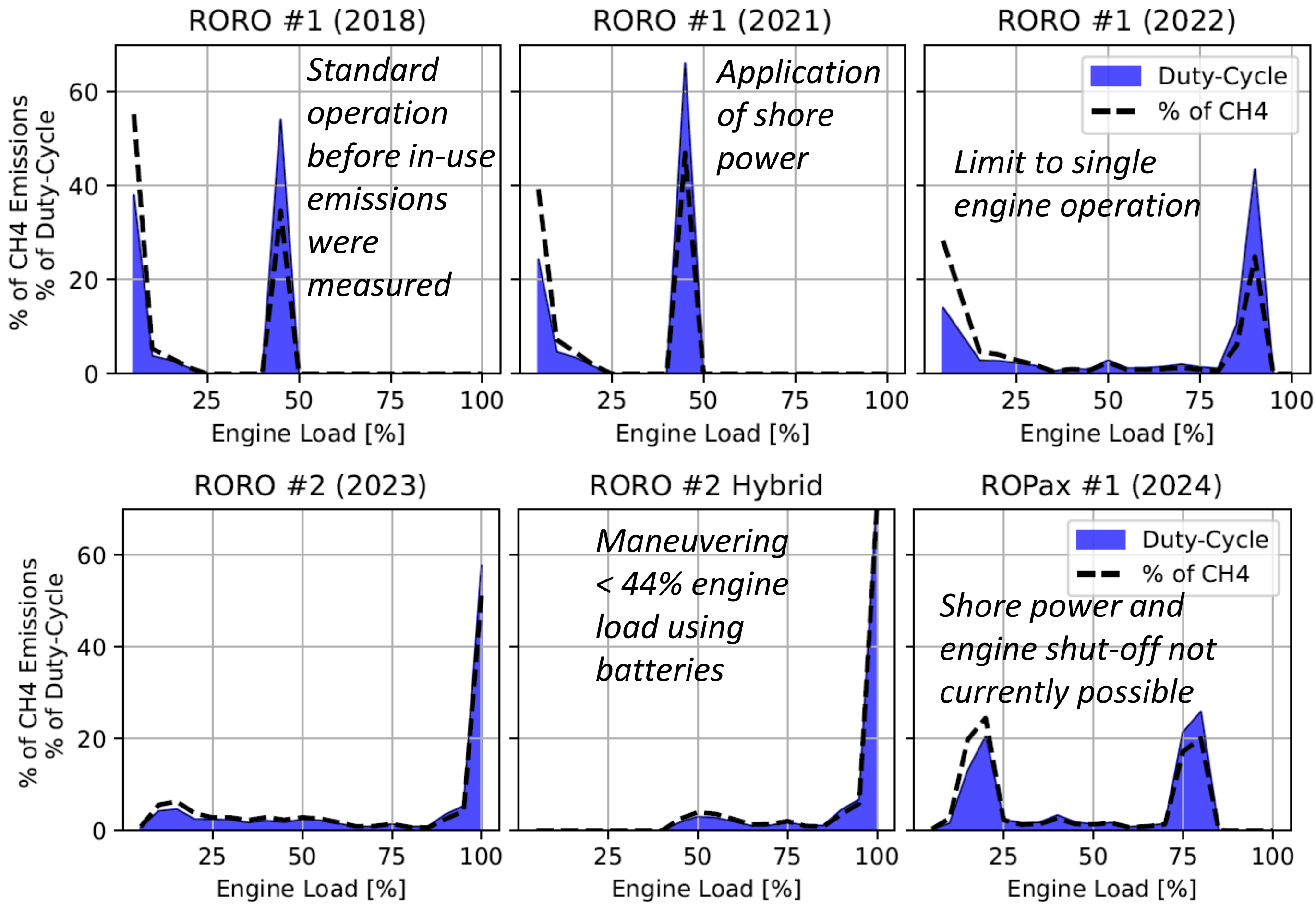
Diversity of Real-World Duty-Cycles For RORO Ferries in BC



All of these duty-cycles are measured from service between Vancouver Island and BC mainland



- Short-haul operations have a characteristic bi-modal distribution, but there is still very significant differences between different applications
- Unlike CO_2, CH_4 emissions do not scale ~linearly with engine load or fuel consumption

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Combining Real-World Emissions and Measured Duty-Cycles to Calculated Weighted - Emission Factors

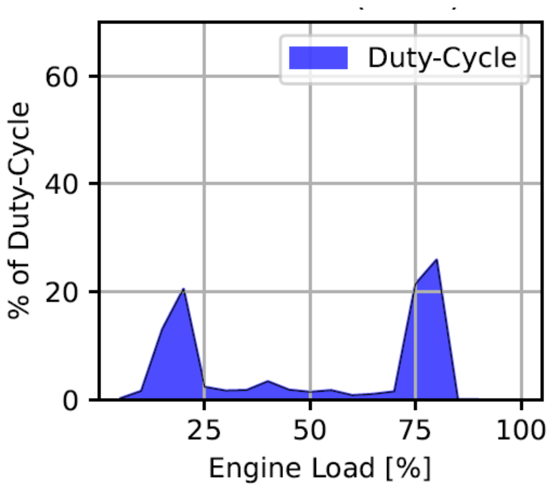
mechanical engineering

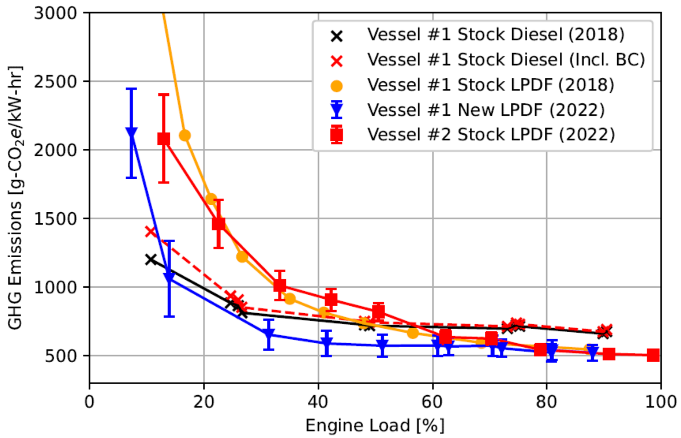
Duty-Cycle Weighting + In-use emissions measurements = TtW Emission Factor, EF

Duty-Cycle Weighting
- Application-specific (measured)

In-use emissions measurements

(g-CO2/kWhr, g-CH4/kWhr)
- Engine & calibration – specific
- Interpolate emissions as a function of engine load





TtW Emission Factor, EF

EF(Engine, Duty-Cycle) +/- $\sigma_{meas.}$

Nominal EF is a function of the considered engine and the application specific duty-cycle

Measurement uncertainty and variability is propagated from raw instrument measurements to final calculated EF

Note that this analysis assumes steady-state emissions measurements are representative of dynamic operations' emissions (experimentally evaluating this assumption for marine vessels is the focus of on-going research)

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Range of Calculated TtW CH4 Emission Factors for A RORO Ferry in BC, Using Recent Data

		TtW GHG EF: g-CH4/kW-hr				
		LPDF Engine & Calibration				
		RORO #1 (2018)**	RORO #1 (2022)	RORO #2 (2023)	ROPax #1 (2023)	ROPax #1 (2024)
Duty-Cycle*	RORO #1 (2018)	84.7 ± 0.0	23.7 ± 4.1	32.4 ± 3.9	22.1 ± 5.1	6.6 ± 1.7
	RORO #1 (2021)	61.7 ± 0.0	17.7 ± 3.0	28.2 ± 3.2	17.6 ± 4.1	5.8 ± 1.5
	RORO #1 (2022)	41.6 ± 0.0	13.5 ± 2.3	19.1 ± 2.2	13.9 ± 3.2	5.6 ± 1.5
	RORO #2 (2023)	15.5 ± 0.0	6.0 ± 1.0	12.4 ± 1.2	7.6 ± [illegible]	[illegible]
	RORO #2 Hybrid	4.5 ± 0.0	2.5 ± 0.4	6.1 ± 0.4	3.4 ± 0.8	4.1 ± 1.1
	ROPax #1 (2024)	23.1 ± 0.0	8.9 ± 1.6	21.1 ± 1.9	11.6 ± 2.8	5.1 ± 1.4
	IMO E2	8.7 ± 0.0	4.0 ± 0.7	11.0 ± 0.8	5.1 ± 1.3	4.1 ± 1.1

EF(Engine , Duty-Cycle) +/- $\sigma_{measurement}$

*Note that extrapolation outside of measured operating ranges was required for this analysis

** Incomplete instrument uncertainty data

Using application specific data (engine-specific emissions and application-specific duty-cycle) can yield up to two orders of magnitude difference in the TtW GHG emission factor

- **Measurement uncertainty is ~ 7-30%**

Quality emissions measurements are important, however they must be combined with application-specific duty-cycle weightings and engine-specific data for actionable analysis of LNG LPDF marine engines

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SUMMARY

- Engine-out CH4 slip is a critical limitation of NG-fueled marine engines that must be balanced against the NOx and PM reduction benefits

- In the last ~6 years there has been rapid and significant reductions in engine-out CH4-slip with new engine calibrations being offered
    - Emission inventories are rapidly becoming out of date, significantly limiting LCA and emission modelling activity accuracy
    - Current state-of-art LPDF engine has lower g-CO2e/kW-hr for nearly all operating conditions relative to diesel

- Quality exhaust concentration instrumentation is fundamental to reliable in-use emissions analysis, however test-conditions (e.g. load stability) and other measured parameters (e.g. fuel flow-rate) may introduce more significant uncertainty

- Calculated GHG emission factors for marine LPDF engines are <u>very</u> sensitive to the engine (and any applied calibrations) and the duty-cycle
    - RORO ferries operating between Vancouver Island - BC mainland and equipped with medium-speed LPDF engines can have a factor of 6 different Tank-to-Wake GHG emission factors

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CONCLUSIONS

- More granularity is needed in marine emissions LCA and modelling tools (e.g. GREET, GHGenius) for calculations to be actionable by policy-makers and fleet-operators
    - A single value for emission factors introduces too much uncertainty for LPDF engines where g-CO2e/kWhr are very sensitive to duty-cycle
    - More rapid uptake/utilization of recent in-use emissions measurements is needed to maintain emission inventory utility

- A shift in marine emissions measurement methodology is needed: Continuous emissions monitoring approach using lower-cost sensors and remote reporting to relevant jurisdictions
    - Most accurate duty-cycle, dynamic effects accounted for, immediate turn-around of data to decision- and policy-makers

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