GHG and Air Quality Emission Characterization for Alternative Marine Fuels

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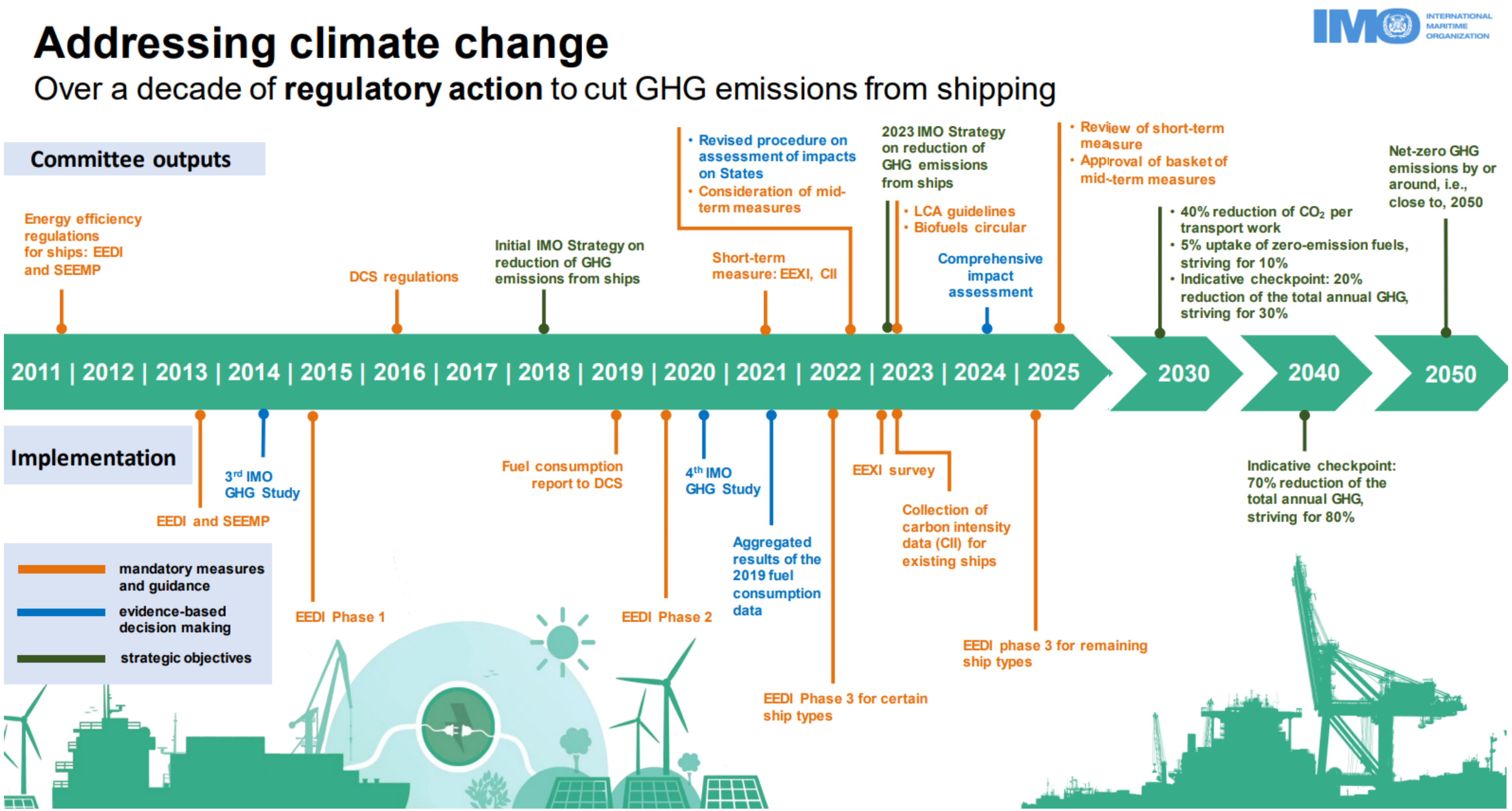
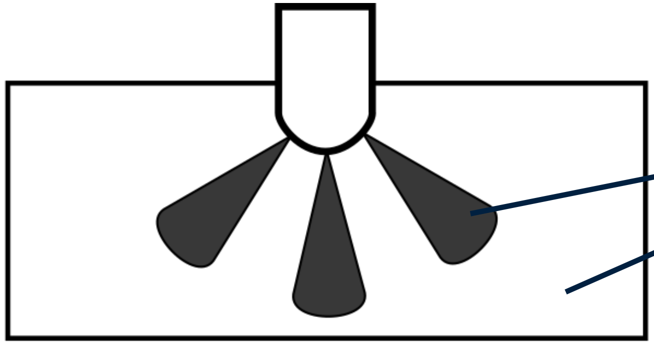
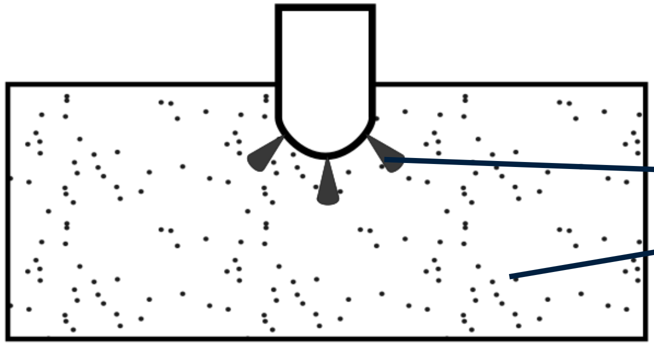
IMO's APPROACH TO GHG REDUCTION



Dual Fuel Combustion

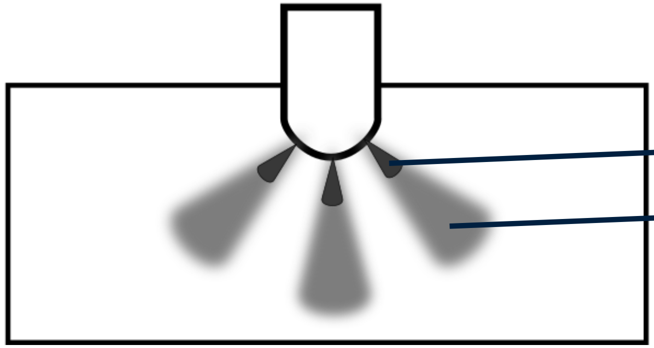


Diesel Combustion
Diesel (liquid)
Air



Low Pressure Dual Fuel (LPDF)
Liquid pilot fuel for ignition
Pre-mixed gaseous fuel
Natural gas, Hydrogen, etc

Retrofits/Conversions
Heavy duty vehicles
Stationary engine
Marine engines



High Pressure Direct Injection (HPDI)
Liquid pilot fuel for ignition
Direct injected gaseous fuel
Natural gas, hydrogen, etc

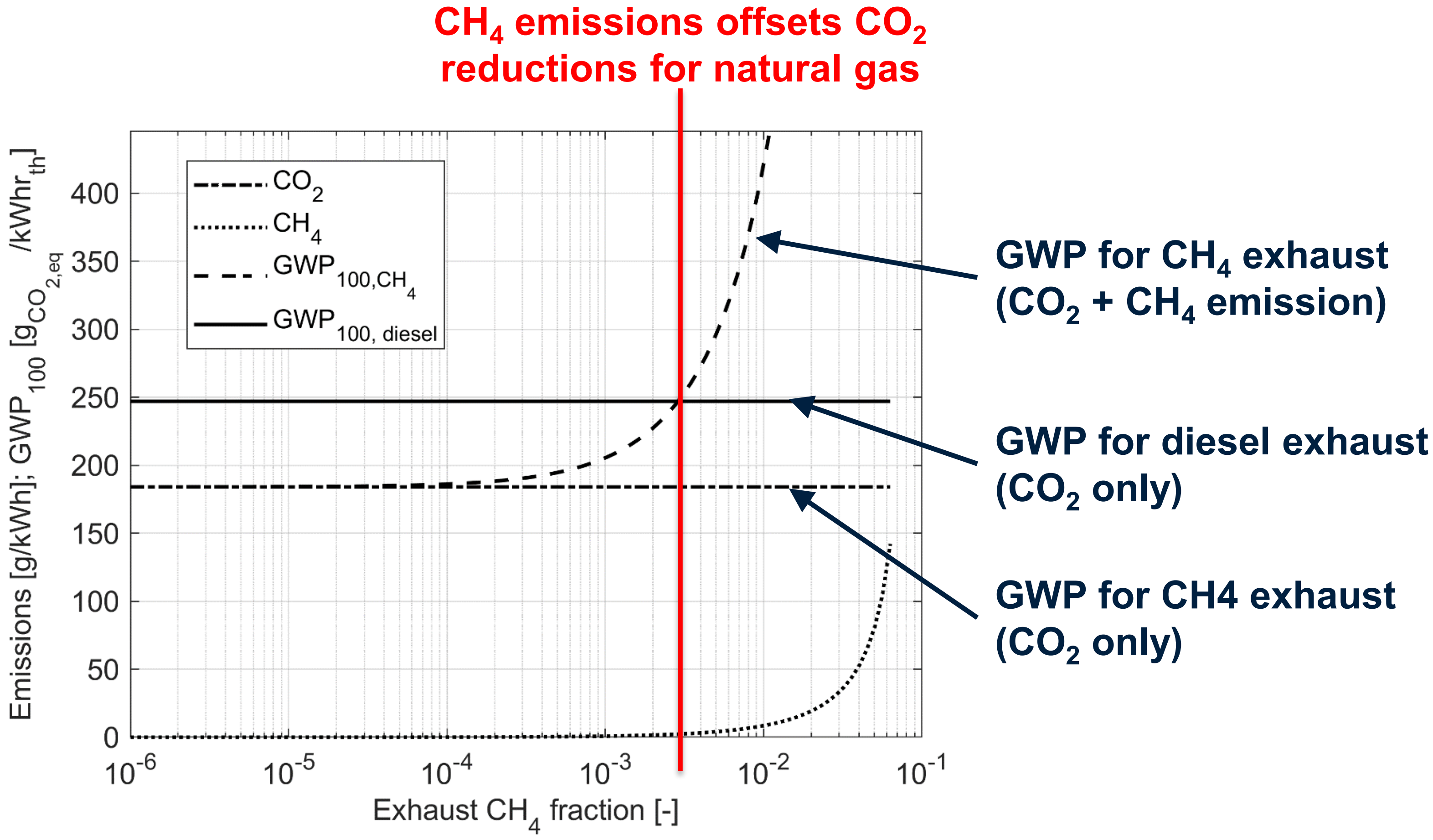
Heavy duty vehicles
Marine engines

HPDI: High Pressure Direct Injection
LPDF: Low Pressure Dual Fuel

CASE STUDY: GHG Emissions from a NG LPDF Marine Vessel

OBJECTIVE: Evaluate and minimize actual Tank to Wake GHG exhaust emissions for LPDF natural gas vessels

- LPDF provides CO_2, NO_x, SO_x, and PM reductions
- Any CH_4 slip will negate CO_2 savings and can result in higher GHG emissions relative to diesel



CH_4 Emissions

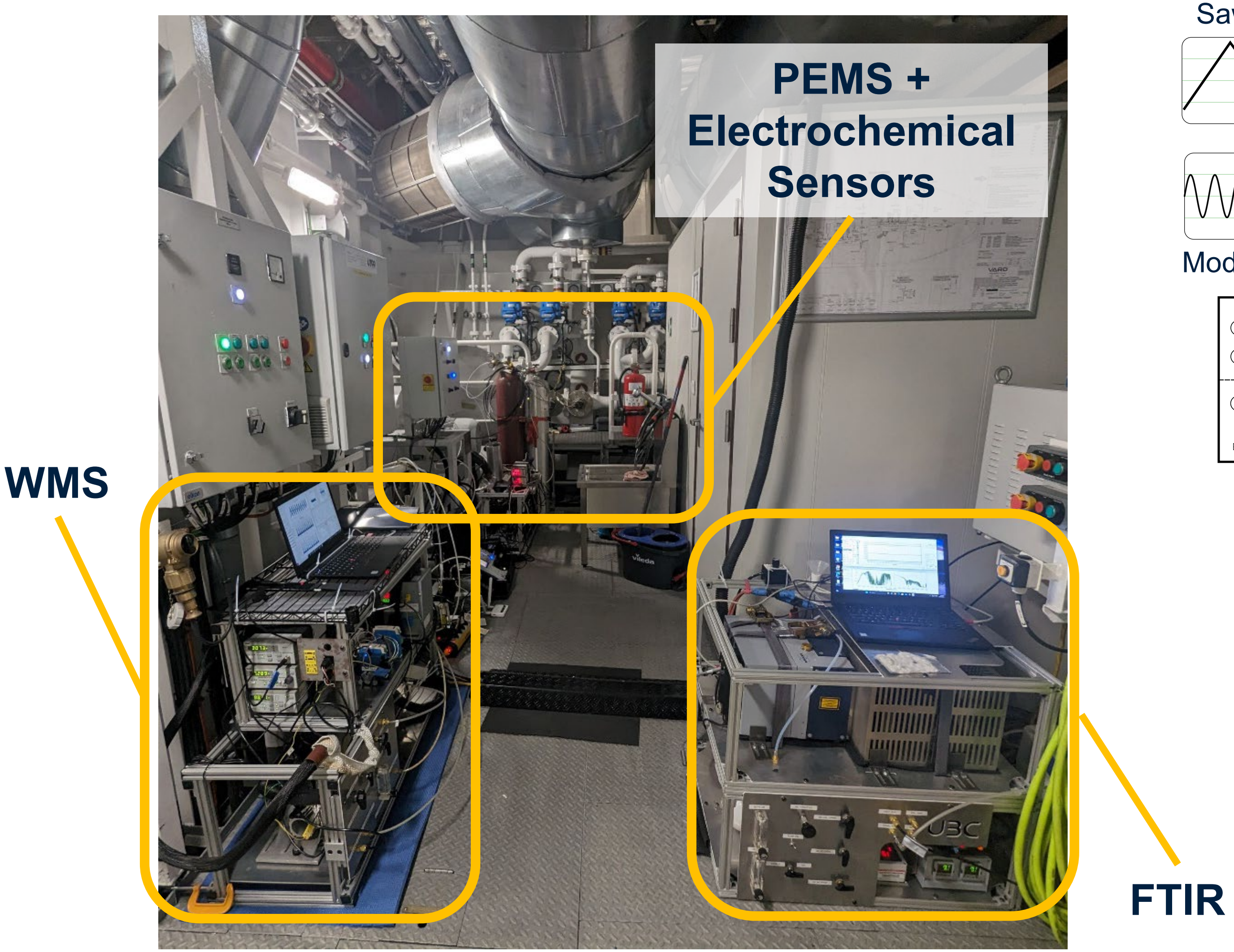
CASE STUDY: GHG Emissions from a NG LPDF Marine Vessel
Methodology

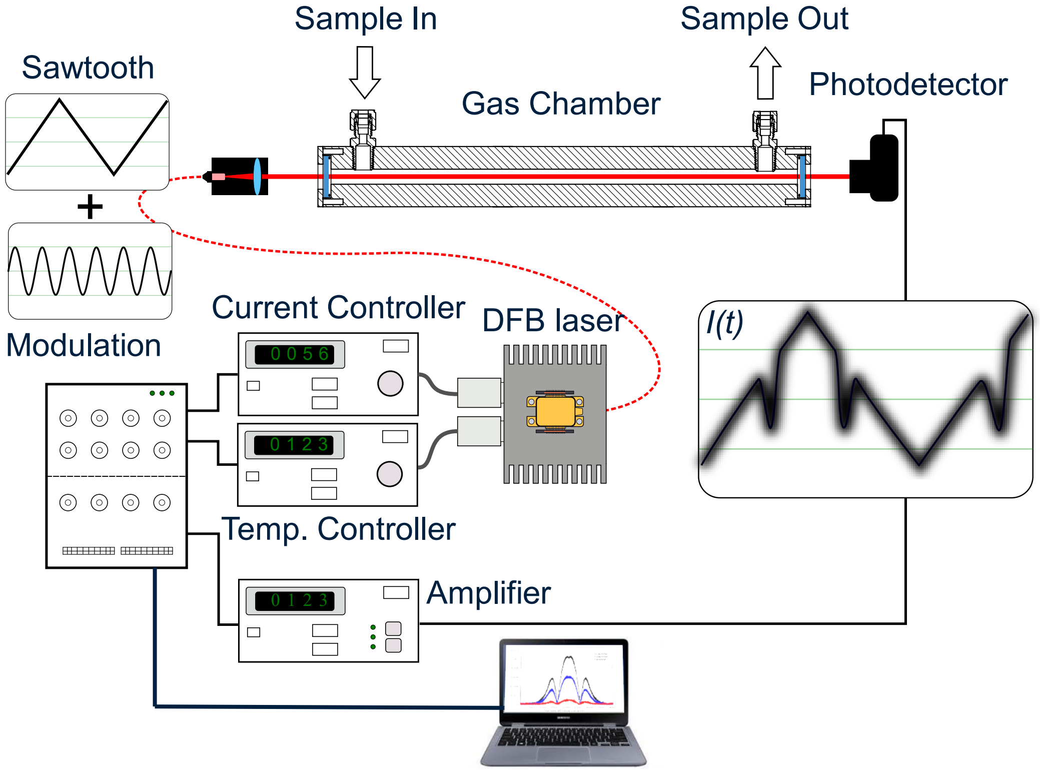
Instrument	Measurand	Comment
AVL 493 iX PEMS (incl. FID)	CO_2, CO, O_2 NO, NO_2 CH_4, nmHC	H2 fuel needed Not CH_4 specific
Bruker MG5 FTIR	CO_2, CH_4, CO, NO, NO_2, H_2O, …	Cost Process gasses / LN_2 Significant training
Commercial IR absorption System	Low cost Multi-species Turnkey	Low cost, turnkey; can be inaccurate for exhaust CH_4
WMS (IR absorption)	CH_4	Calibration free Not (yet) commercially available Requires training
Bag + off vessel FTIR/GC/MS	Multispecies Uses reference instruments	Slow Expensive (instrument or service) No time resolution

SEASPAN RELIANT
2x Wärtsilä 9L34DF Engines
(2x4.3MW; 4-stroke; med. speed)
LNG and Diesel Fuel Systems
Battery Bank (468 kWh)

CASE STUDY: GHG Emissions from a NG LPDF Marine Vessel

Methodology

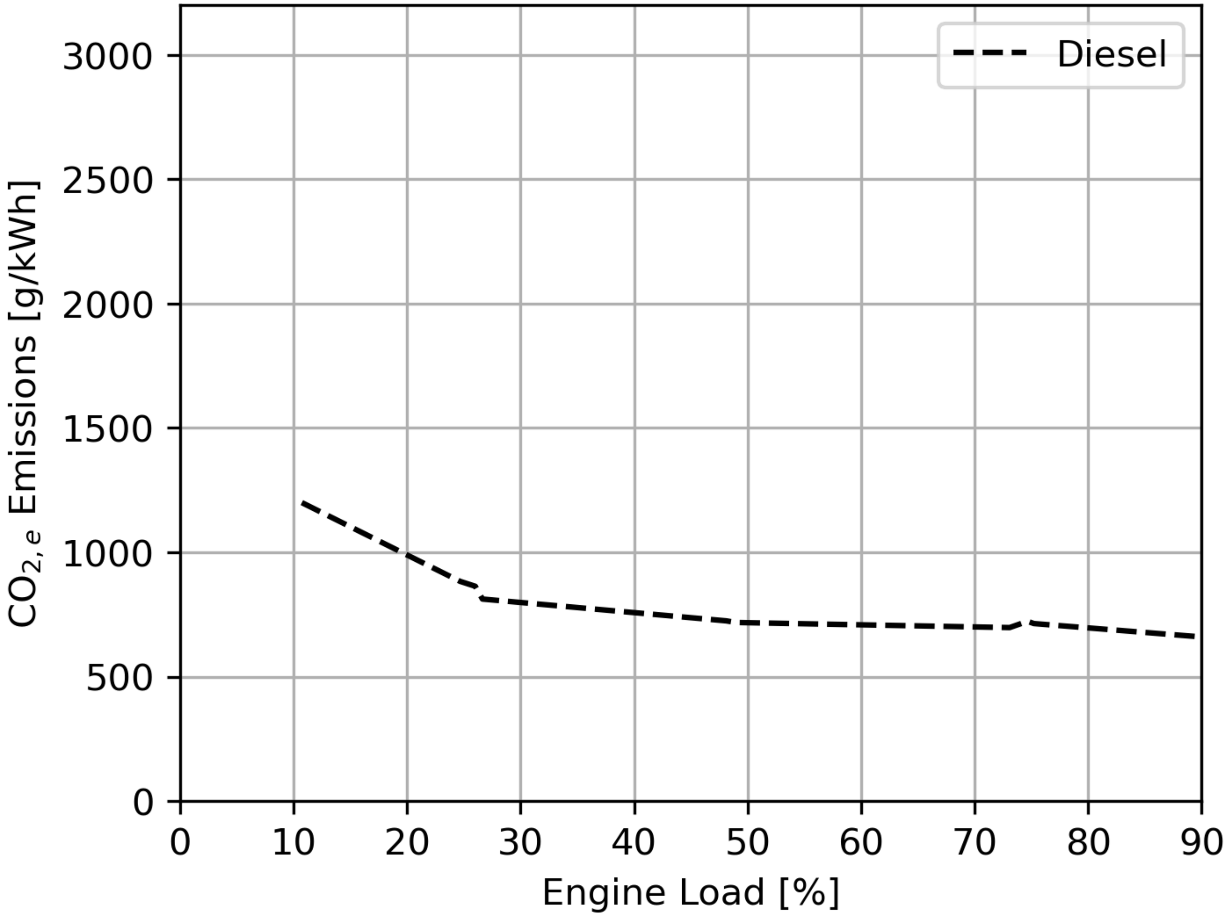




Wavelength Modulation Spectroscopy (WMS) for “calibration-free” CH_4 Measurement

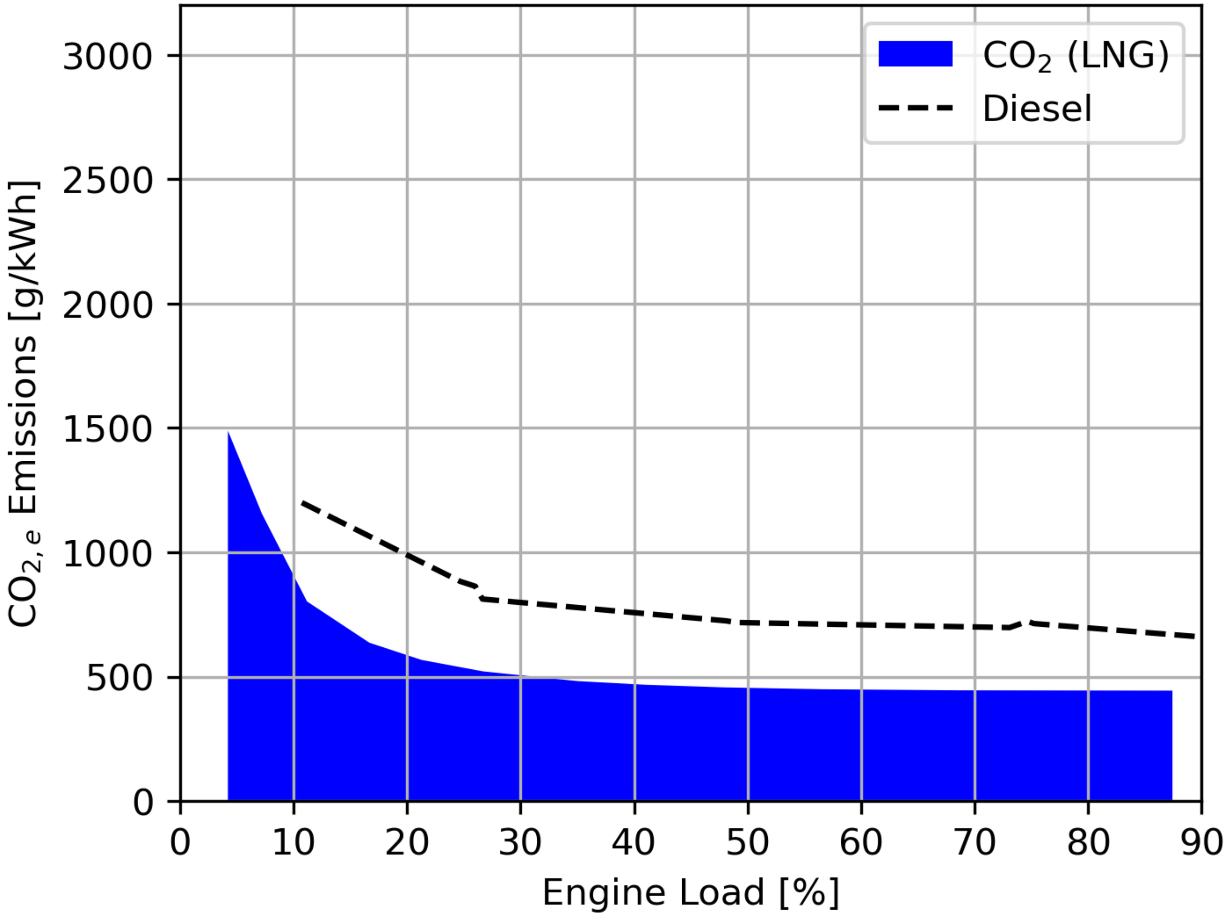
Sommer, et al. Environmental Science and Technology. 2019
Sommer, et al. CIMAC 2019
Cohen-Sacal, et al. SAE 2021
Jaeger, et al. CICS 2022
Mhanna,et al. CICS 2024
Mhanna et al. under preparation
Jaeger, et al. under preparation

2018: Tank to Wake GHG Emissions – Diesel



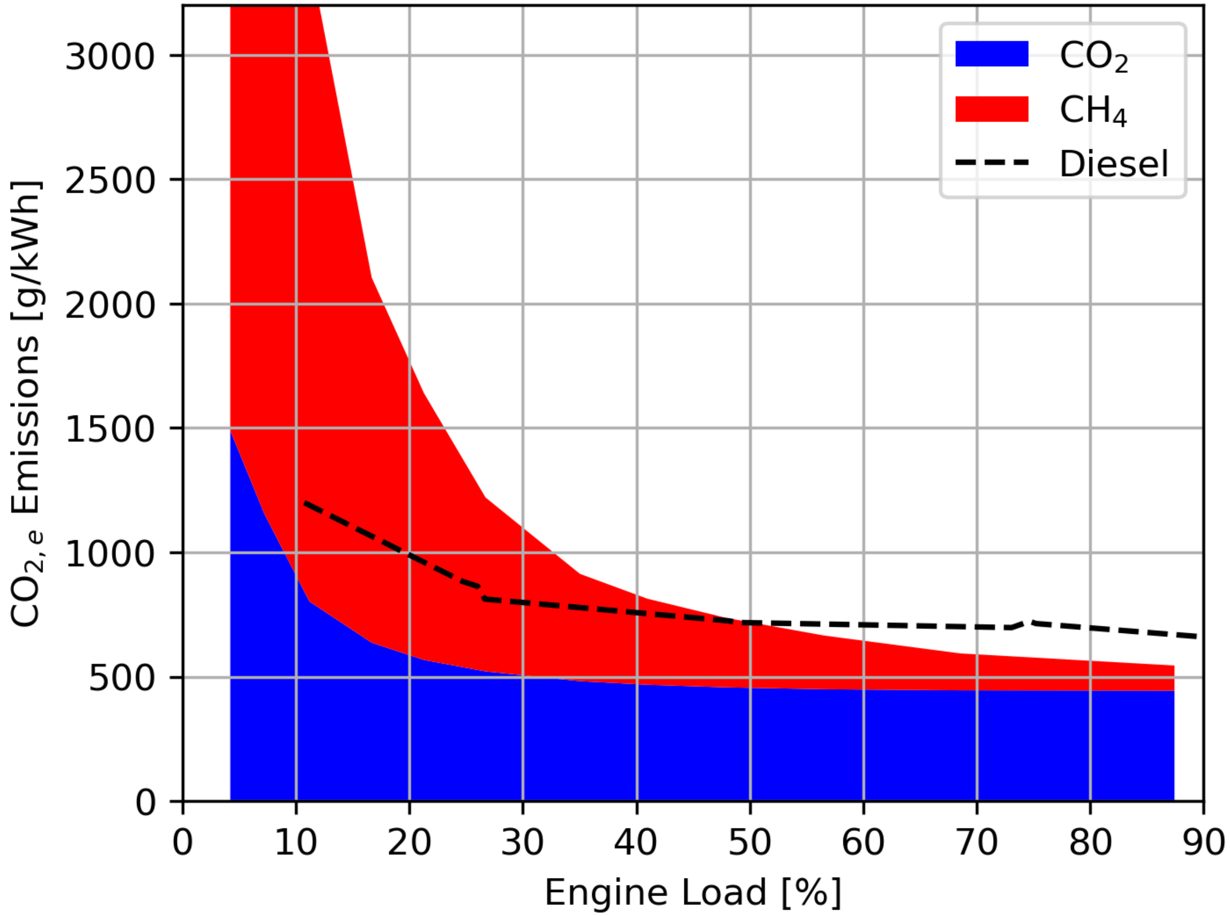
Sommer, et al. Env. Sci. Tech. 2019
Sommer, et al. CIMAC 2019
Peng, et al. Env. Poll. 2020
Rochussen, et al. Fuel. 2023

2018: Tank to Wake GHG Emissions – Diesel vs LNG (CO_2)



Sommer, et al. Env. Sci. Tech. 2019
Sommer, et al. CIMAC 2019
Peng, et al. Env. Poll. 2020
Rochussen, et al. Fuel. 2023

2018: Tank to Wake GHG Emissions – Diesel vs LNG ($CO_2 + CH_4$)



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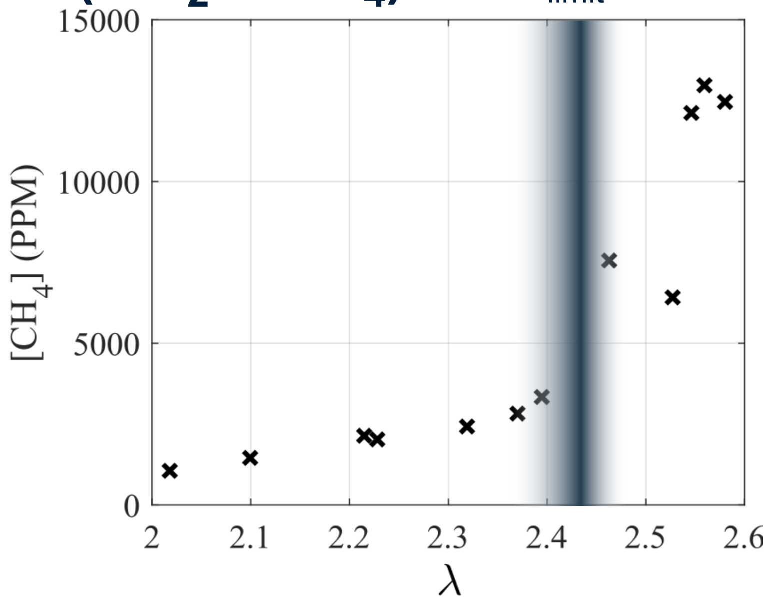
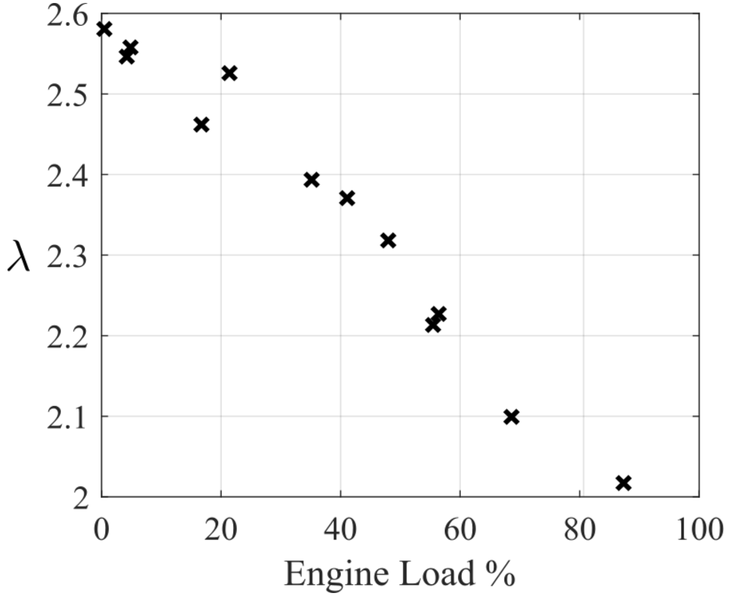
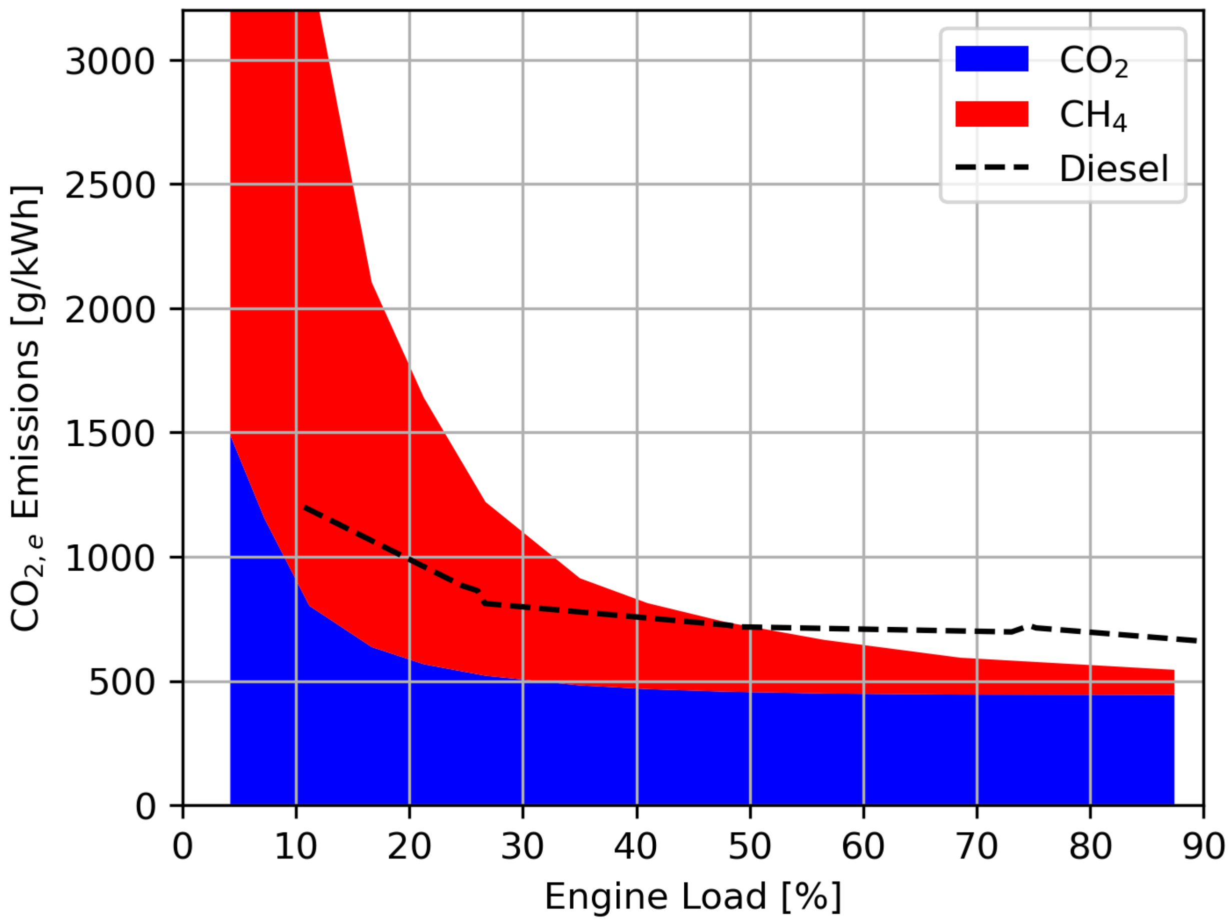




TODAY: Tank to Wake GHG Emissions – Diesel vs LNG (CO_2 + CH_4)



Modified engine control strategy developed by engine manufacturer to reduce CH_4 emissions

Measures include:

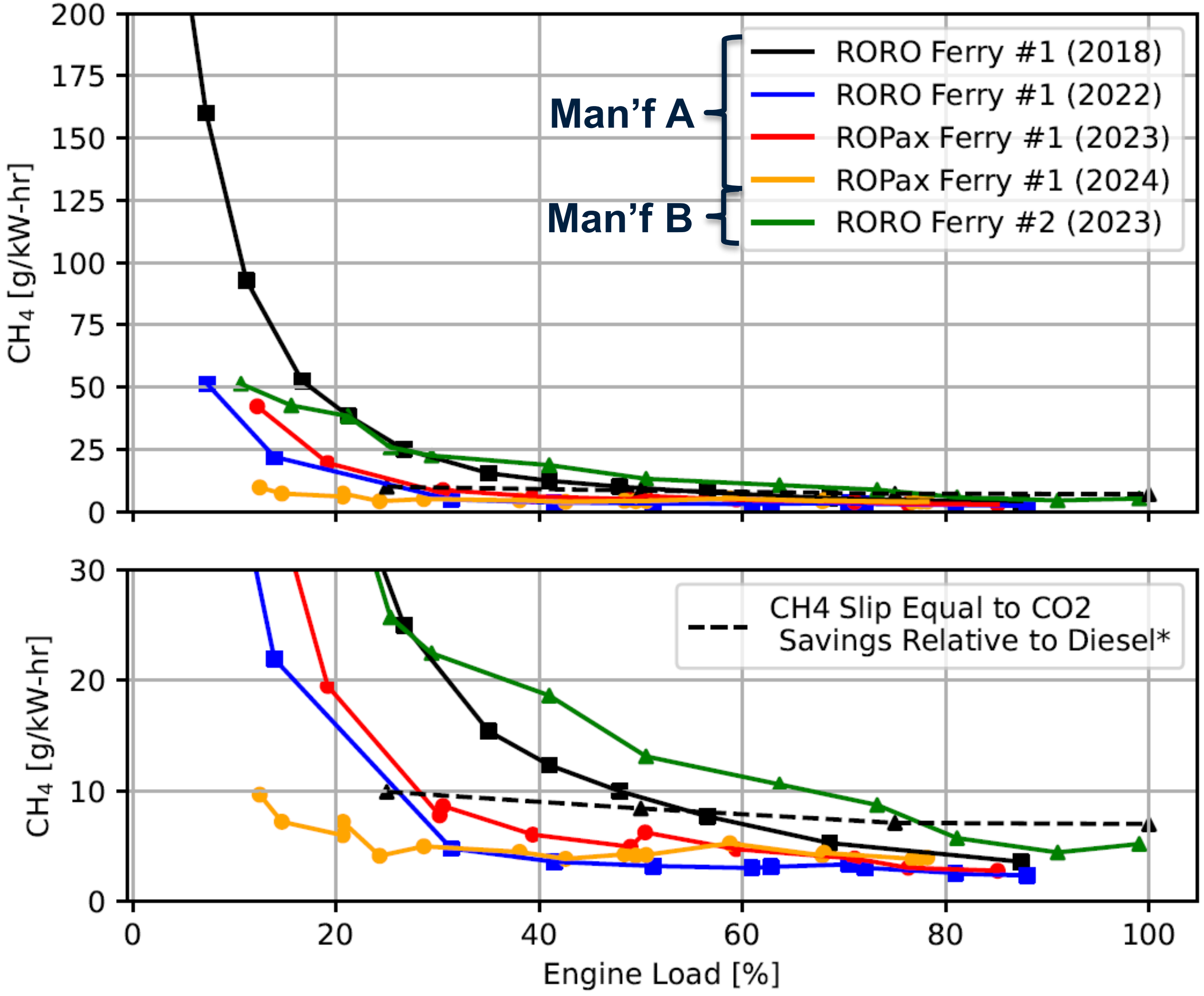
- Cylinder deactivation
- Decreased air fuel ratio at low loads
- Optimized pilot injection

Overall Tank to Wake GHG savings with natural gas operation relative to diesel

Very low load CH4 emissions still problematic

Sommer, et al. Env. Sci. Tech. 2019
Sommer, et al. CIMAC 2019
Peng, et al. Env. Poll. 2020
Rochussen, et al. Fuel. 2023

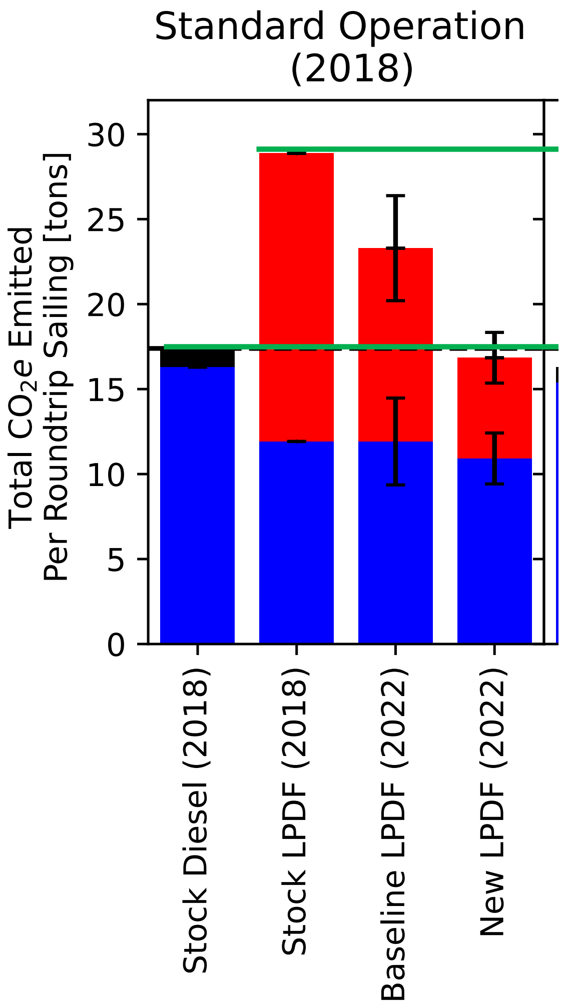
COMPARISON OF CH_4 EMISSIONS FOR MARINE LPDF ENGINES

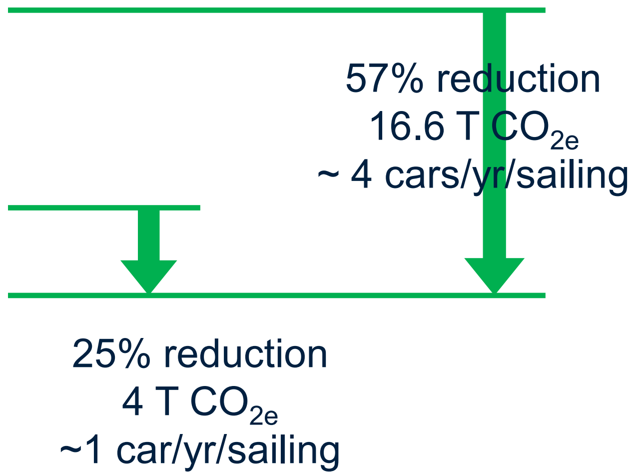


- All engines are medium speed, 4-stroke, low pressure dual fuel (LPDF) with similar cylinder bore (~340mm)
- RORO #1:
  - Hybrid drive (genset+batt+emotor)
  - 2018: As delivered
  - 2022: Cylinder deactivation
  - 2023: + pilot and air path optimization
- RORO #2:
  - Hybrid drive (genset+batt+emotor)
  - 2023: As delivered
- ROPax #1:
  - Direct drive (shaft + variable pitch prop)
  - 2023: As delivered
  - 2024: Cyl. deac + pilot and air path optim.
- **Emissions depends on engine manufacturer, engine software, and vessel type**

RORO: Roll on, roll off
ROPax: Roll on + passenger

Combined Technological and Operational Measures for GHG Reduction





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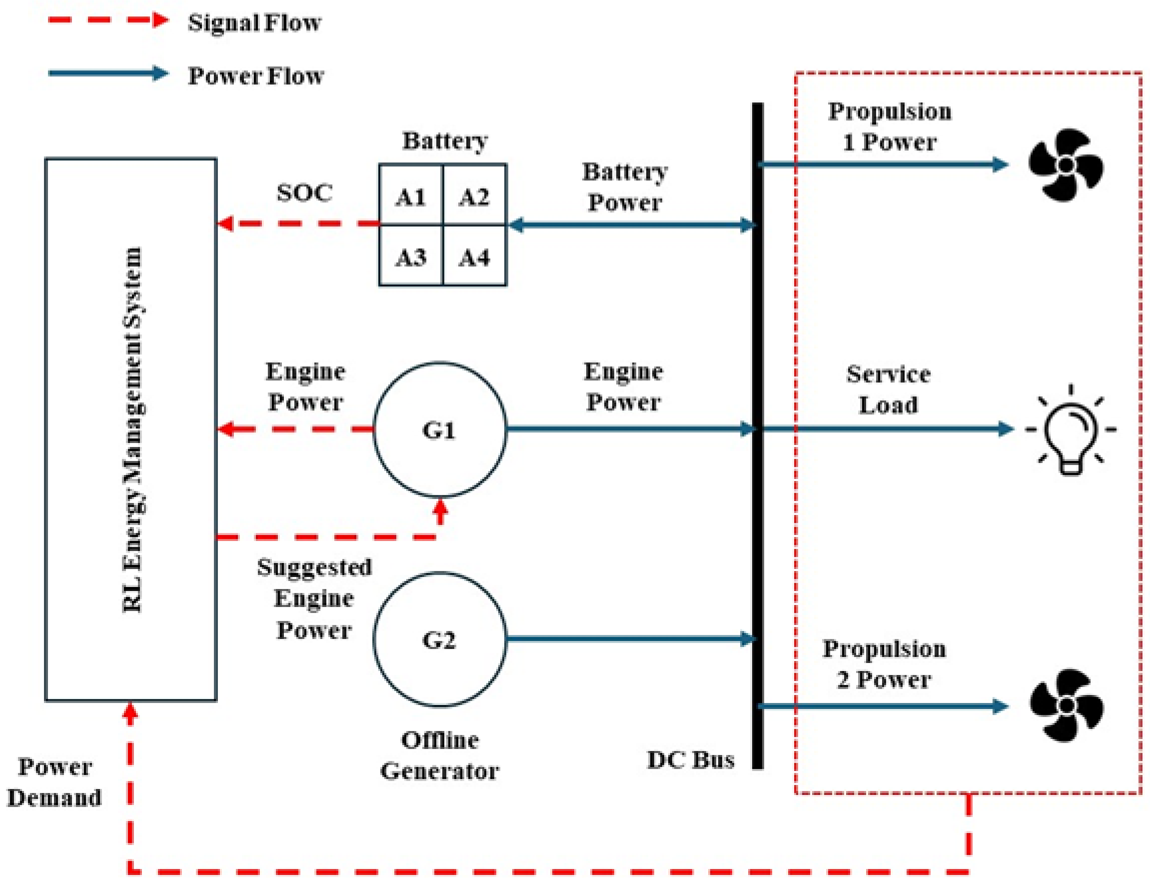
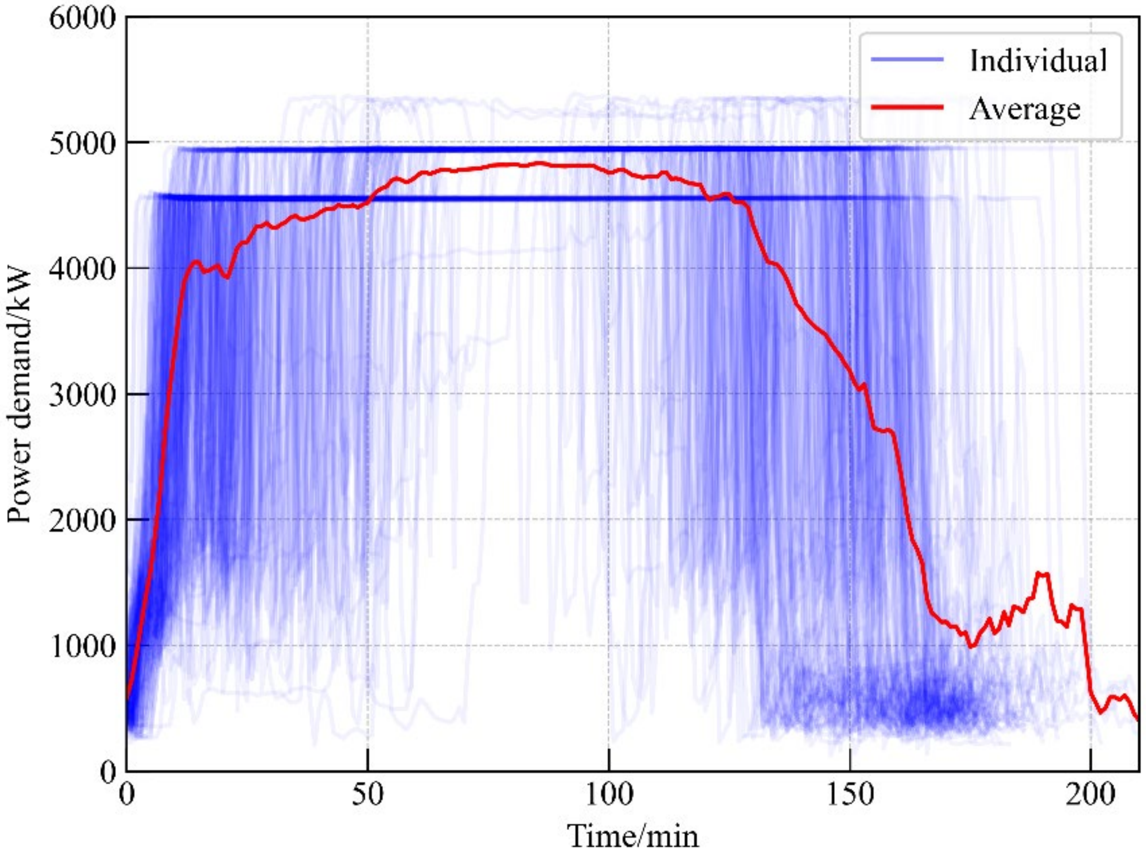
Peng, et al. Env. Poll. 2020
Rochussen, et al. Fuel. 2023

Optimization of Power Management (NG-LPDF- Hybrid Vessel)
Reinforcement Learning for GHG Reductions

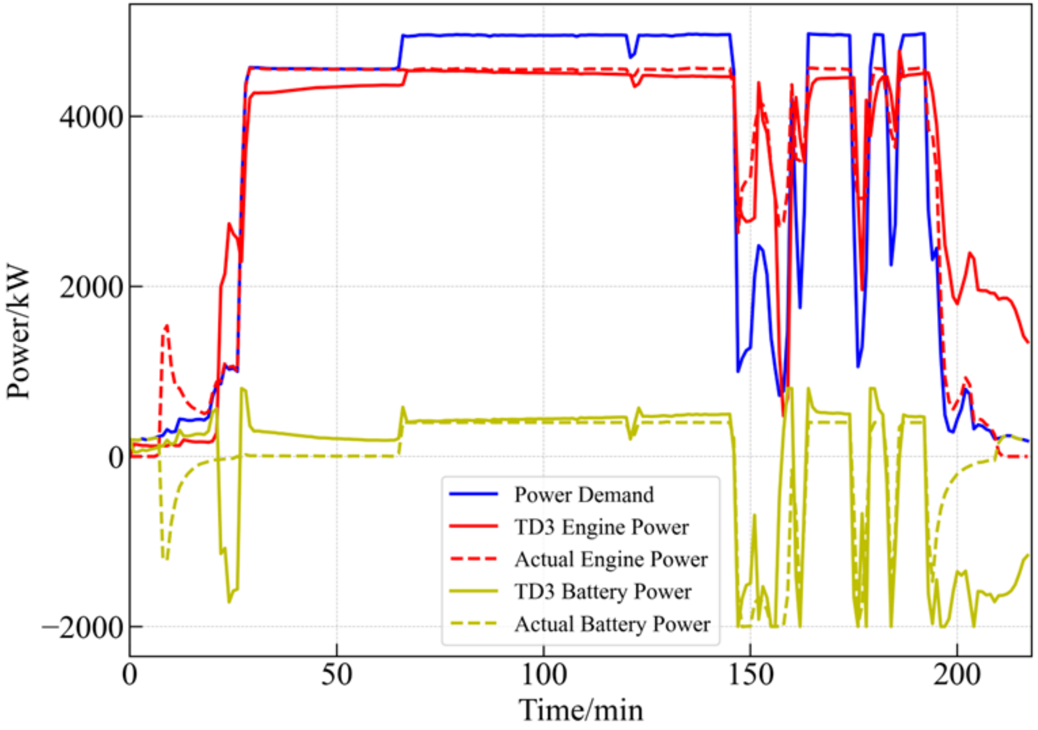




Measured emissions (steady state) and engine power histories (>300 sailings) used to train RL algorithm to identify instantaneous power distribution for minimum total GHG

Abdalla, et al. ADCHEM, 2024
Abdalla, et al. Under preparation.

Optimization of Power Management (NG-LPDF- Hybrid Vessel)
Reinforcement Learning for GHG Reductions



Sample RL-based power distribution for one-way sailing

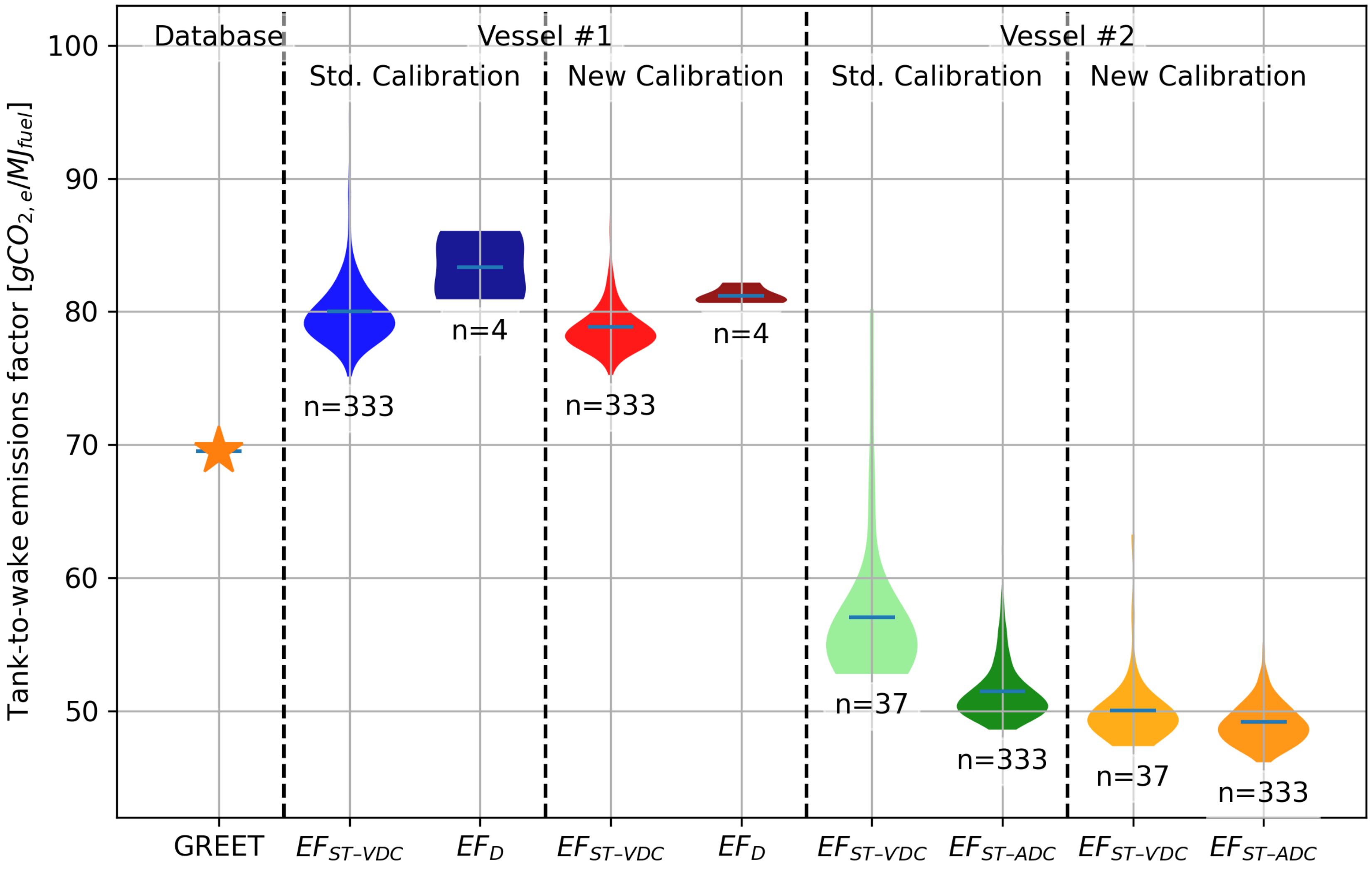
Dataset & Algorithm	Methane Emissions Reduction (%)	Carbon Dioxide Emissions Reduction (%)
RL - TD3 (train)	25.8	-1.3
OO – SLSQP (train)	34.2	-1.2
RL - TD3 (test)	27.2	-1.3
OO – SLSQP (test)	33.0	-1.3

RL – TD3: Reinforcement Learning – Twin Delayed Deep Deterministic
OO – SLSQP: Offline Optimization – Sequential Least Squares Programming

Summary of predicted emission reductions using RL optimization, based on actual total vessel power demand for 300 cycles

Abdalla, et al. ADCHEM, 2024
Abdalla, et al. Under preparation.

Comparison of Tank to Wake CH_4 Emissions Factors ($g_{CO2,e}$/MJ)



Becker et al. CICS 2024
Becker et al. Under Preparation

Tank to wake emissions vary considerable between similar vessels

Actual value is dependent on engine+vessel technology AND operation

GREET: Reference emission factor (Marine Module 2022)

ST-VDC: Emission factor calculated based on measured steady state emission data and instantaneous engine load

ST-ADC: Emission factor calculated based on measured steady state emission data and modified duty cycle

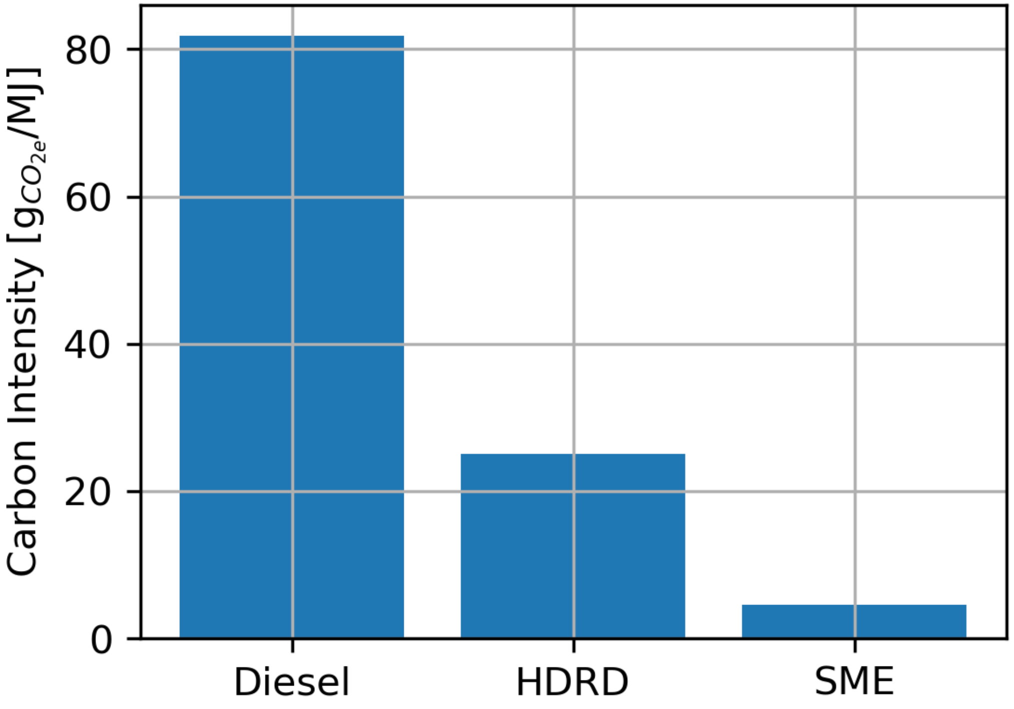
D: Emission factor measure directly for limited sailings

LIFECYCLE GHG EMISSION REDUCTION: Biofuels and Renewable Diesel

Biofuel (SME) and renewable diesel (HDRD) implemented on commercial vessels can provide “drop-in” solution for decarbonization of legacy vessels

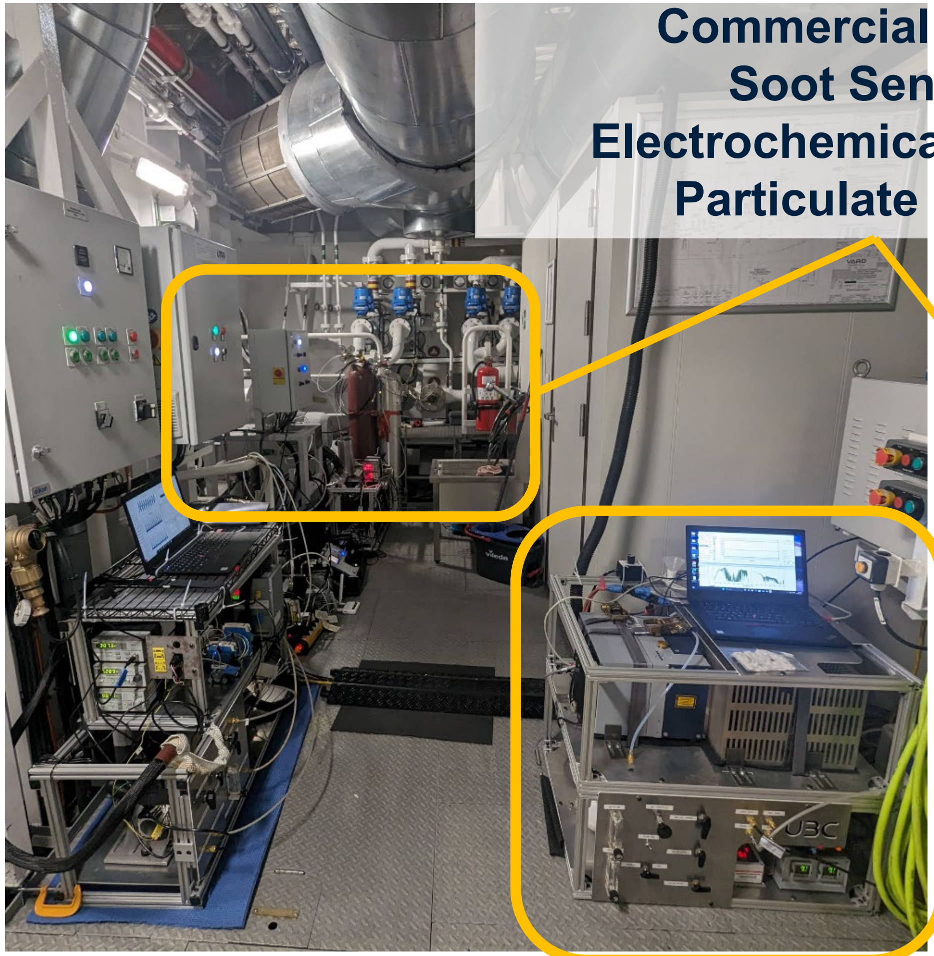
Pilot studies provide much-needed operational and emissions data for policy and fleet development

On-vessel measurement carried out for SME (RORO ferry) and HDRD (harbor tug) for seatrial and commercial operation.

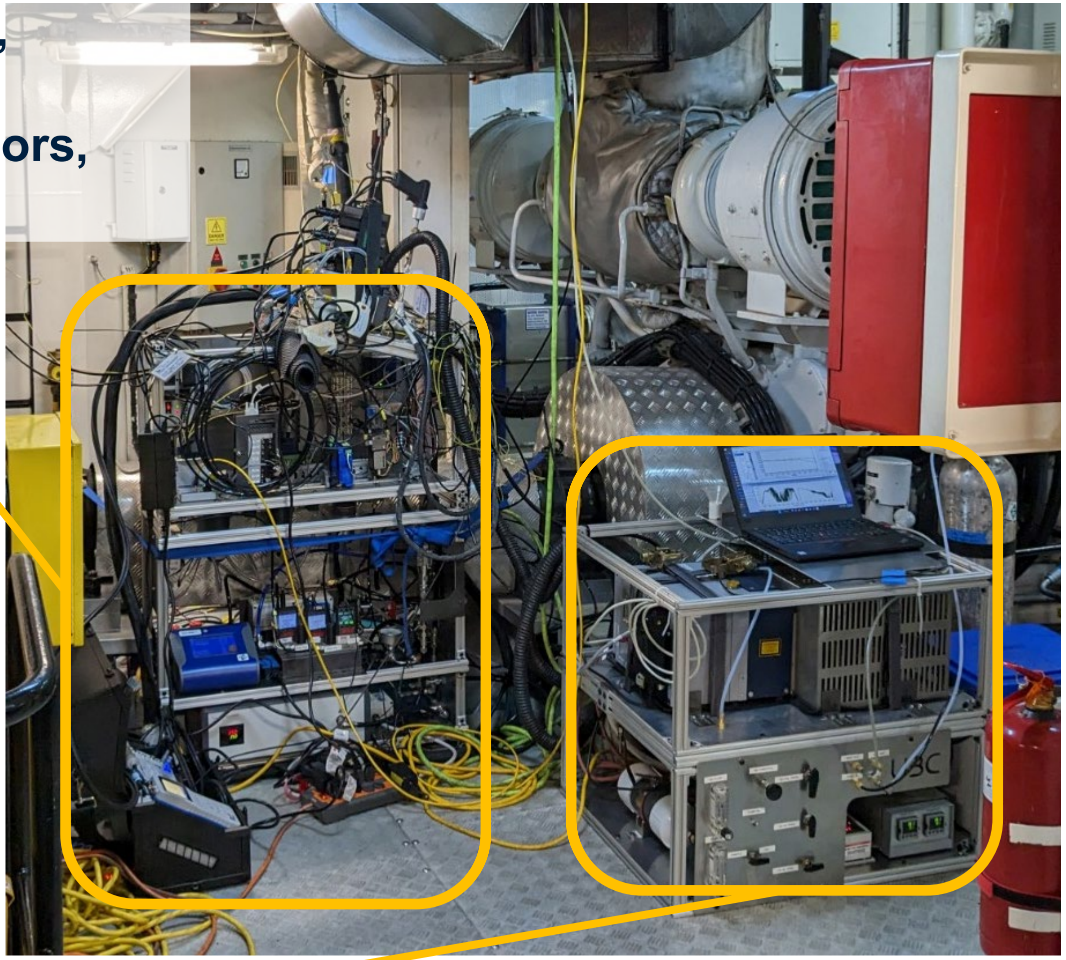


IN-USE EMISSION MEASUREMENTS – Instrumentation Installations

Commercial PEMS, Soot Sensor, Electrochemical Sensors, Particulate Matter



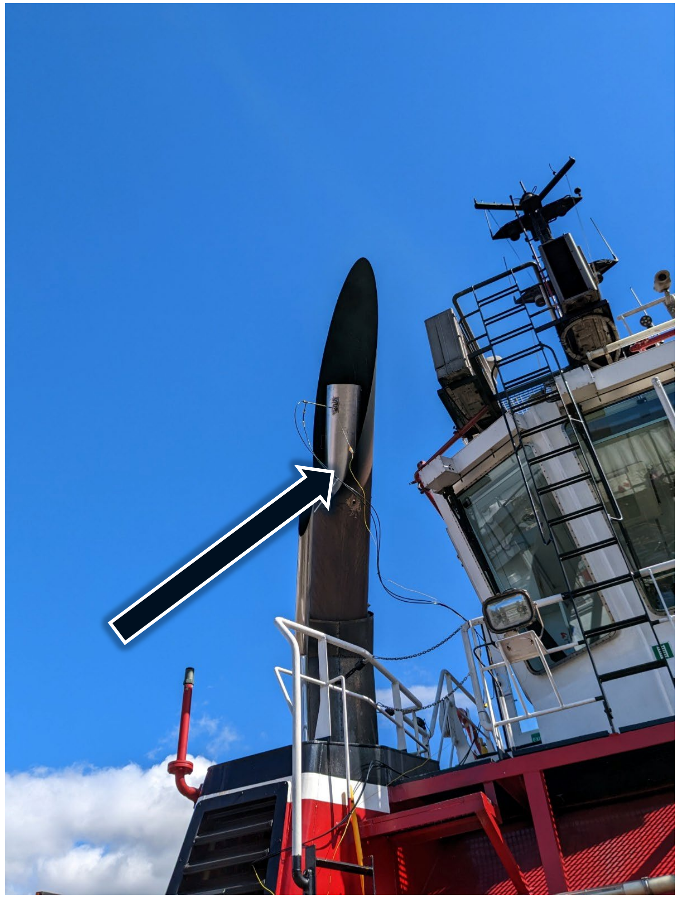
Seaspan Trader RORO Ferry



Harbor Tug

FTIR

IN-USE EMISSION MEASUREMENTS



Exhaust modifications for accurate emission rate measurements

RORO Ferry – unloaded seatrials
Constant engine speed, variable load

Tug – bollard pull
Propeller curve

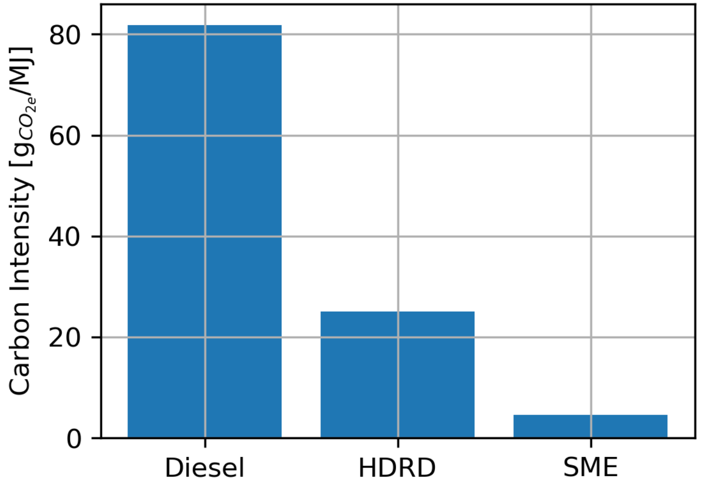
LIFECYCLE GHG EMISSION REDUCTION: Biofuels and Renewable Diesel

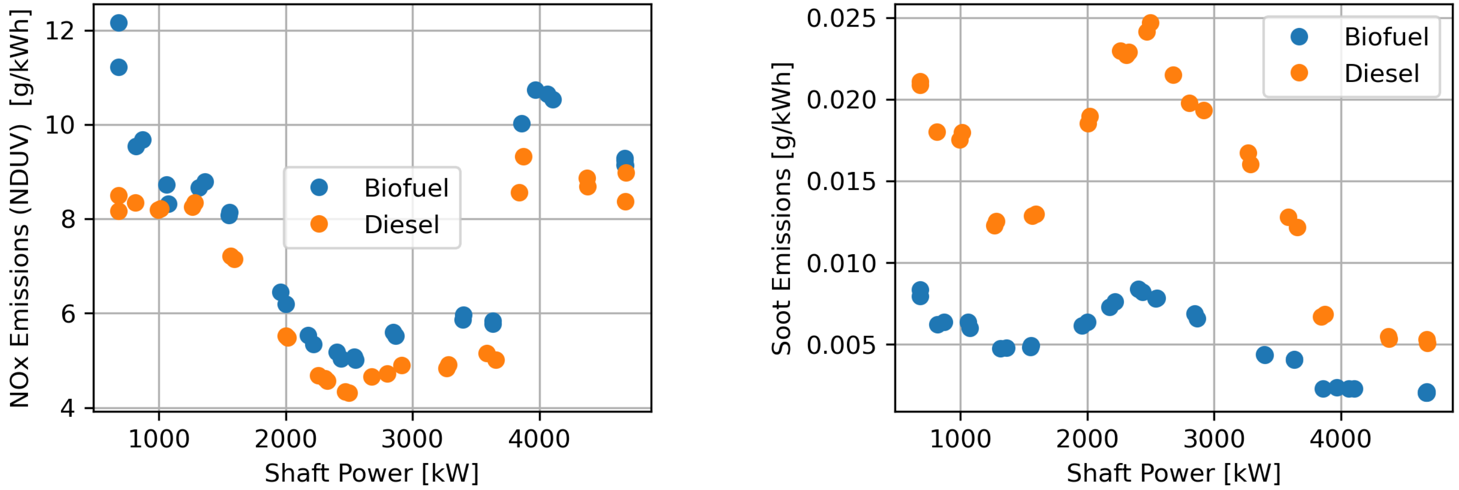
Soybean Methyl Ester (SME) relative to diesel (RORO):

- Significant carbon intensity reduction
- Significant PM reduction
- NOx increase

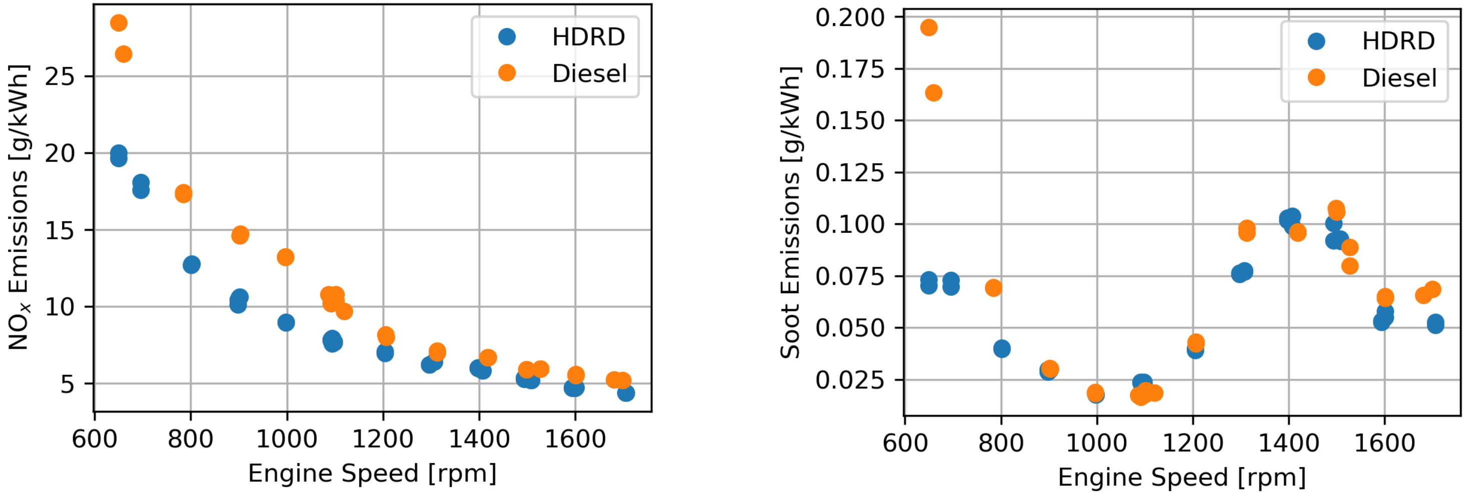
HDRD relative to diesel (harbor tug):

- Carbon intensity reduction
- NOx reduction
- PM unchanged





RORO Ferry operated with Diesel and biofuel (SME)



Harbour Tug operated with Diesel and HDRD

UBC Urban Freight Emissions Program

Environment and Climate Change Canada

UBC

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

Vehicle Measurements
GHG + Air Pollutants
Conventional + Low Carbon Fuels

Freight System Modelling
Total GHG + Air Pollutants

Corridor Measurements
Air and non-exhaust pollutants
Toxicity

Regional Emissions and Dispersion Modelling
Total GHG + Air Pollutants

Case Study
Vehicle optimization

Case Study
Impact of fuels

Case Study
Policy interventions

KNOWLEDGE EXCHANGE WITH STAKE- AND RIGHTSHOLDERS FOR INFORMED DECISION MAKING

THANK YOU!

Seaspan: Harly Penner, Ahmed Khan, Daryl Lawes, Matt Vi … kler, Peter Lister, Luke Pyper

Crews: Seaspan Reliant, Seaspan Trader, Seaspan Raptor, Sea… f Var… of Oak Bay

UBC: Jeremy Rochussen, Nicolas Jaeger, Mark Guan, Troy Hurren, Nishan Sapkota, Isaa… ayan Yeremi, Jeff Son, Jeff Yeo, Gibson Clark, Anand Kumar, Hamed Nikookar, Mhanna Mhanna;
Steve Rogak, Amanda Giang, Bhushan Gopaluni

Funding: ECCC (Climate Action Awareness Fund, Salish Sea Marine Emiss…
NSERC (Alliance, CRD, Discovery Grant programs)
CFI Innovation Fund
Transport Canada Innovation Center
Seaspan Ferries, BC Ferries, FortisBC, Solaris