Air Quality Benefits of Switching a Freight Ferry from Diesel Fuel to Natural Gas

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Published/In-prep work:

1. Sommer, D. E. et al. Characterization and Reduction of In-Use CH4 Emissions from a Dual Fuel Marine Engine Using Wavelength Modulation Spectroscopy. Environ. Sci. Technol. (2019). doi:10.1021/acs.est.8b04244
2. Trivanovic, U. et al. Size and morphology of soot produced by a dual-fuel marine engine. J. Aerosol Sci. (2019). doi:10.1016/j.jaerosci.2019.105448
3. Corbin, J. et al. Characterization of particulate matter emitted by a marine engine operated with liquefied natural gas and diesel fuels. Atmos. Environ. (2019). Doi:10.1016/j.atmosenv.2019.117030
4. Peng, W. et al. Air Quality Benefits of Switching a Marine Vessel from Diesel Fuel to Natural Gas. (In prep)

A Collaborative Effort

UCR College of Engineering- Center for Environmental Research & Technology	Weihan Peng, Jiacheng (Joey) Yang, Qi Li, Wayne Miller
Canada NRC·CNRC	Stéphanie Gagné, Joel Corbin, Brett Smith, Prem Lobo
UBC THE UNIVERSITY OF BRITISH COLUMBIA	Una Trivanovic, Steve Rogak, David Sommer, Patrick Kirchen

Ship owner and their crew

With the financial, logistical and other support from:

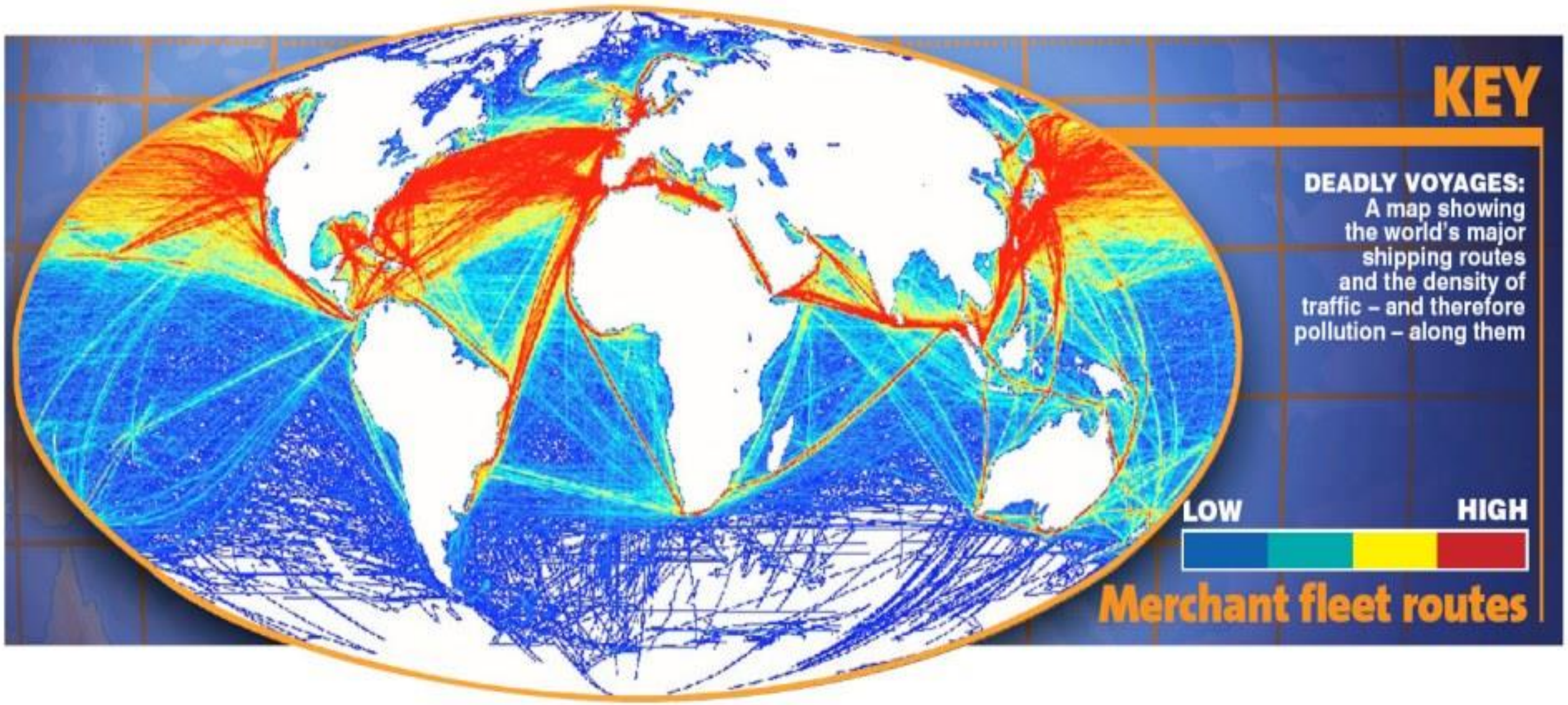
Transport Canada Transports Canada

- Transport Canada
- US MARAD
- SCAQMD
- CARB
- Wärtsilä

CALIFORNIA AIR RESOURCES BOARD

South Coast AQMD

Background – Global Shipping



- Represents 80% of the volume and 70% of the value of international trade[1].
- Emissions such as NOx, SOx, PM and BC contributes to air pollution in atmosphere.
- Linked with increased mortality in coastal regions, with an estimated 60,000 deaths from cardiopulmonary and lung cancer per year[2].

1. United Nations Conference on Trade and Development (UNCTAD), Review of Maritime Transport 2015
2. Corbett, J. J., Winebrake, J. J., Green, E. H., Kasibhatla, P., Eyring, V., & Lauer, A. (2007). Mortality from ship emissions: a global assessment. *Environmental science & technology*, *41*(24), 8512-8518. https://www.epa.gov/enforcement/marpol-annex-vi

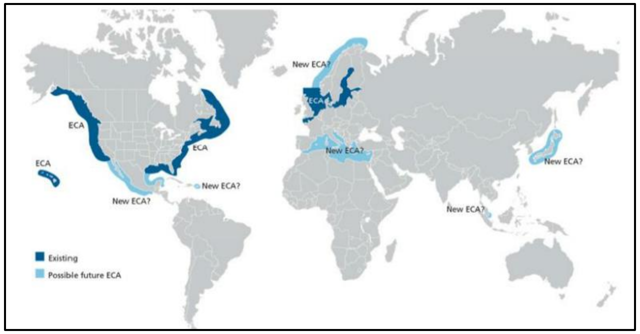
*Figure is obtained from www.marinetraffic.com.

Strategies to Control Marine Emissions

MARPOL Annex VI

Decision

Emission Control Areas



Switch to MGO

Bunker Prices ($/metric tons)	HFO	MGO
Global Average	477.00	758.50
Americas Average	470.00	755.00
APAC Average	510.00	794.50
EMEA Average	462.00	720.50

*Information adopted from Ship&Bunker on September 9th, 2018

Install Control Devices (e.g. Scrubber)

Switch to NG Engine

NG: Natural Gas

UCR

Analysis Needed when Switching Diesel Fuel to Natural Gas

Particle
- $PM_{2.5}$
- Black Carbon (BC)
- Organic/Elemental Carbon (OC/EC)

Criteria Gases:
- NO_x
- SO_x
- CO

Greenhouse Pollutants:
- CO_2,
- CH_4
- BC

Toxics:
- HCHO
- PM

- Air Quality
- Global Warming
- Health Effects

Approach

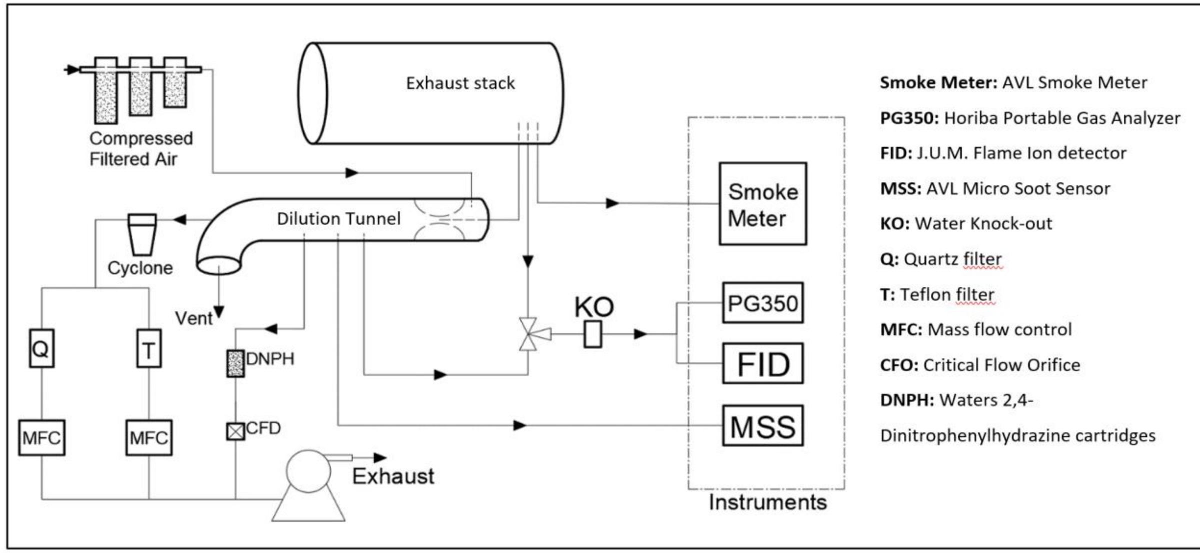
Ultra-low Sulfur Diesel

Natural Gas (>92% methane)

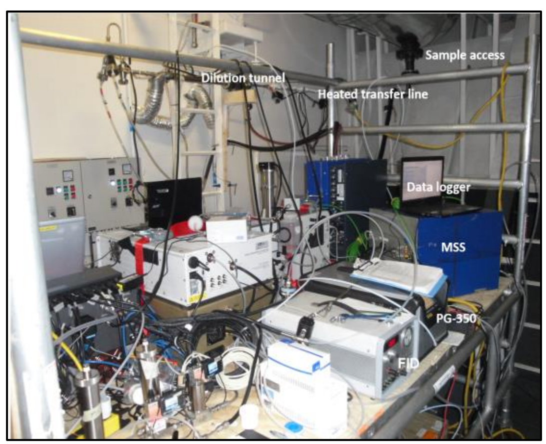
Engine Information

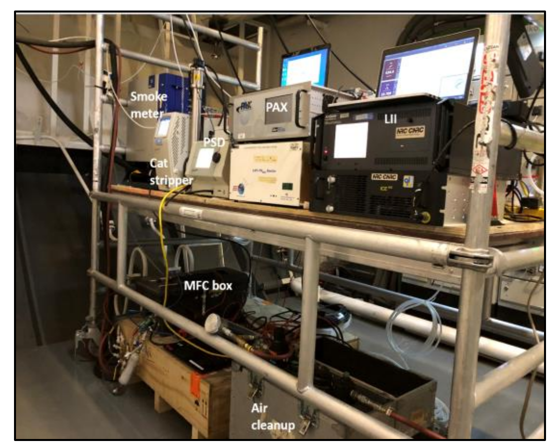
Parameter	Value
Power	4320 kW
Net IMEP	22 bar
Bore and stroke	340 and 400 mm
Displacement	36.3 l/cyl
Speed	720 rpm
Cylinders	9
Intake valves	2
Exhaust valves	2
NG injection	indirect

Corbin et. al. 2019



Experiment Setup Schematics





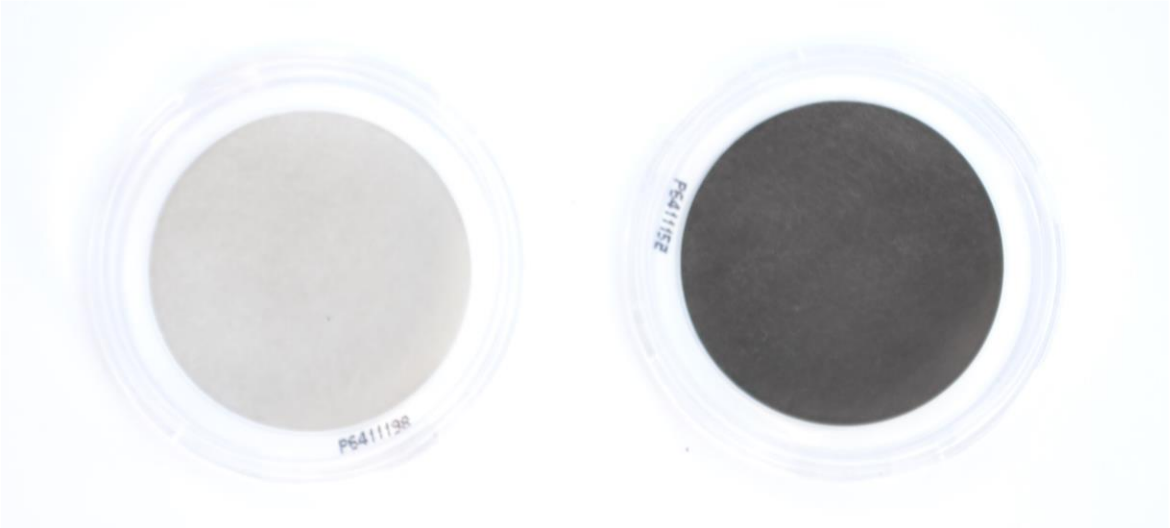
Summary

PM2.5

CO2

Black Carbon

NOx



NG 50min

Diesel 5min

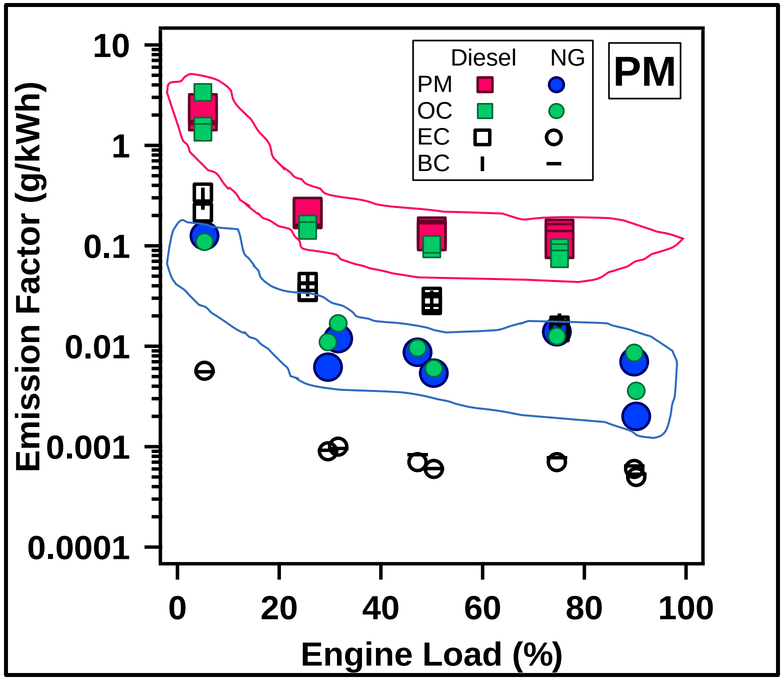
HCHO

CH4

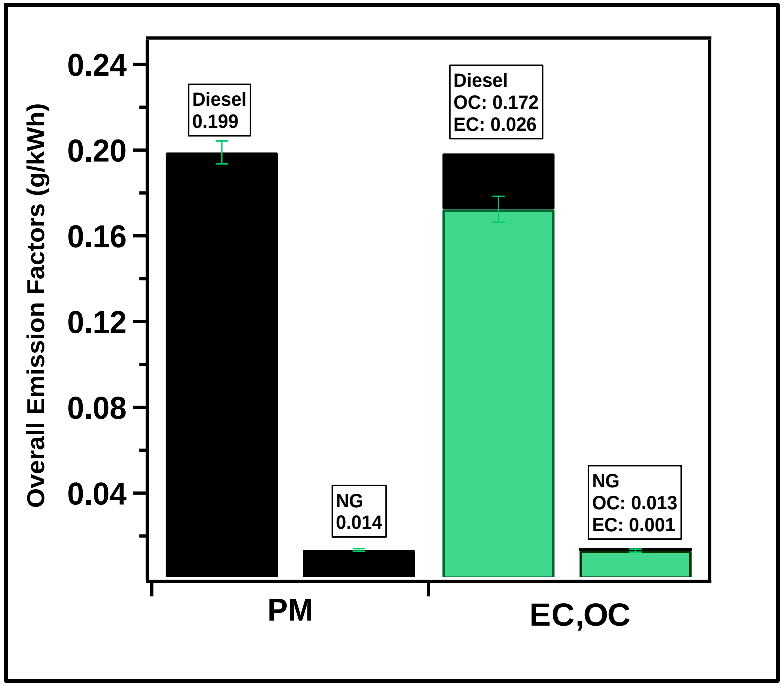
CO

Air Quality (Particles)

Modal Emission factor



Overall Weighted Emission factor



- When switching from diesel fuel to NG:
  - Modal emission factors of $PM_{2.5}$ were to **>1 order of magnitude lower.**
  - $PM_{2.5}$ and BC were **reduced by 93% and 97%** respectively when switching from diesel fuel to NG.
  - Organic carbon accounts for 87% (diesel) and 93%(NG) of total carbon.

Particle Size Distribution

Corbin et. al. 2019

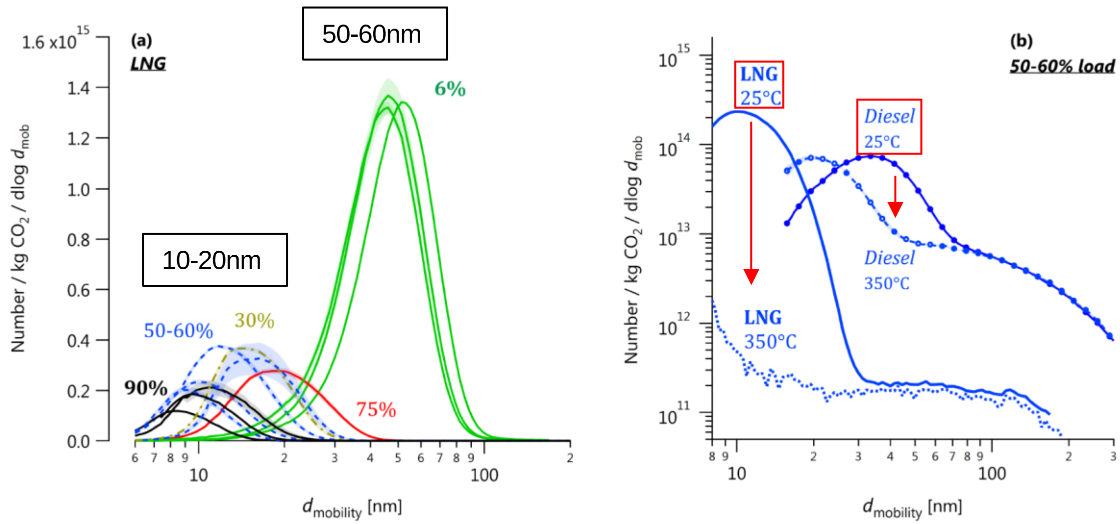
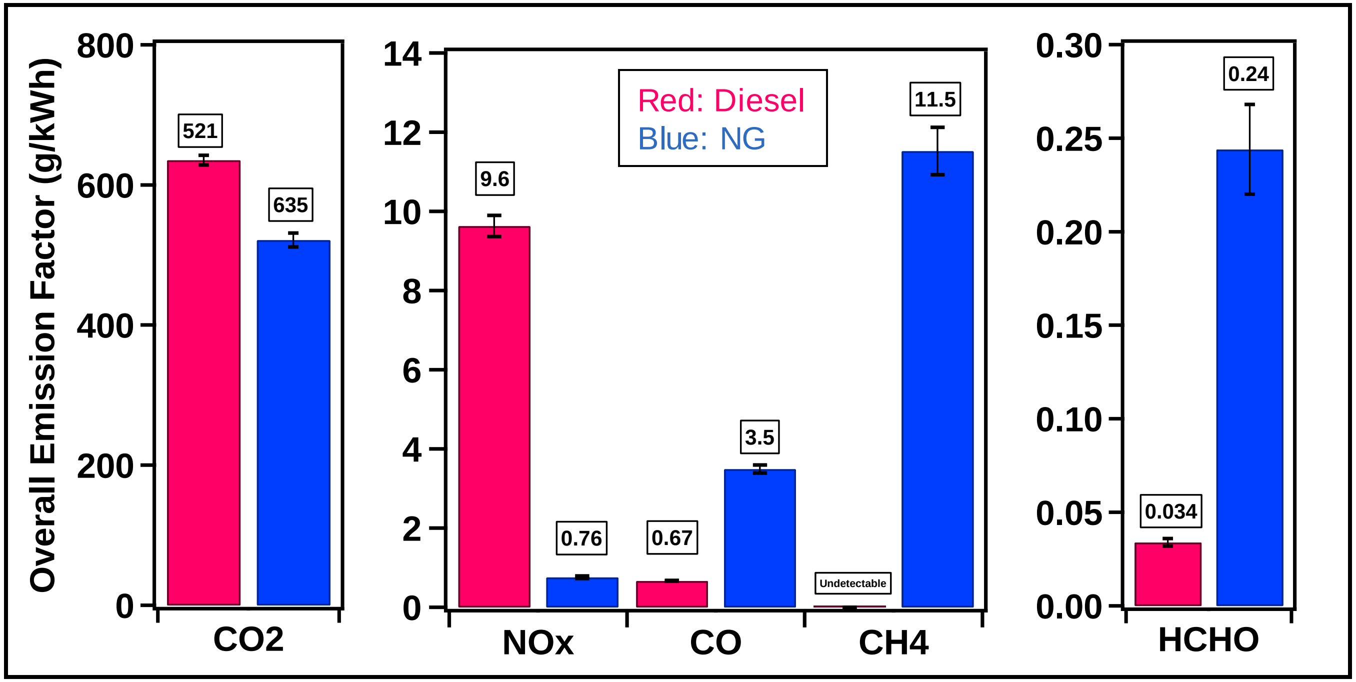


Figure 2: (a) Mobility size distributions as a function of engine load in LNG mode. (b) Mobility size distributions at 50% load for diesel and LNG modes, with and without the removal of volatiles at 623 K by the catalytic stripper. Note that, since (b) shows that the majority of particles in (a) were volatile, the larger sizes observed at 6% load can be understood to indicate that volatile (organic) emissions were higher at 6% load, as discussed in the text. For the same reason, smaller sizes would have been measured at higher dilution ratios. Note also that the mobility diameter of a soot particle is larger than that of an equivalent-volume sphere due to shape effects [44].

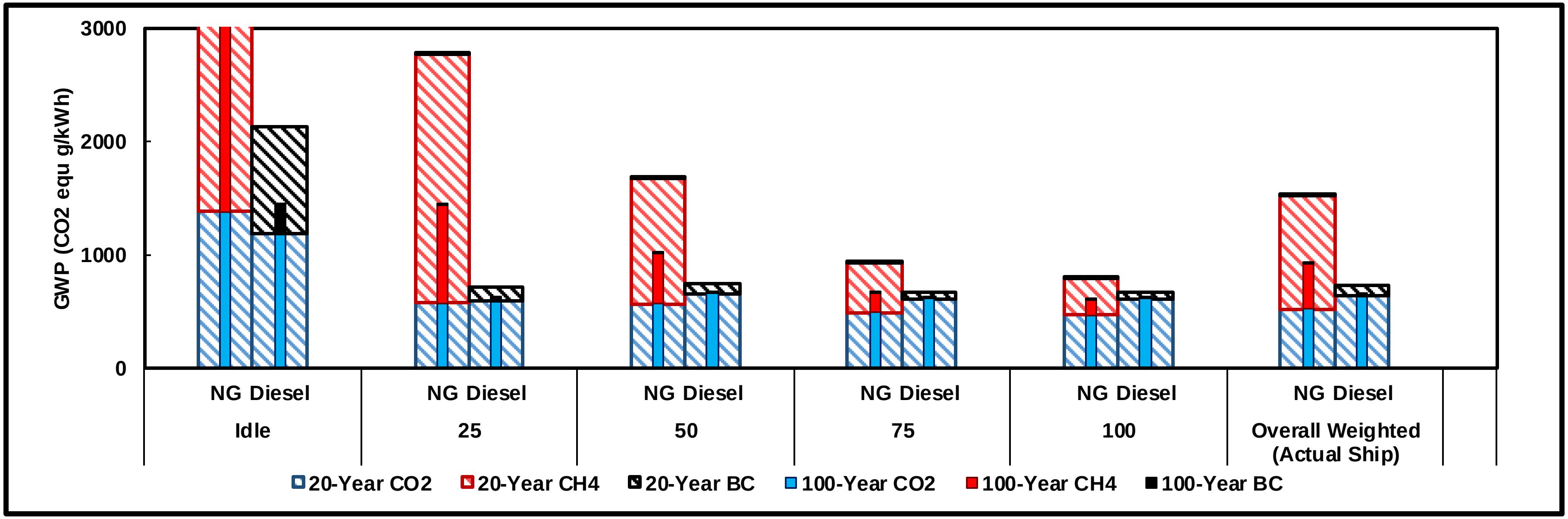
- Particles from NG exhaust peak at **10-20 nm** at **engine load > 30%** and **50-60nm at idling**.
- At 50-60% engine load, NG particle emissions above 20nm is significantly lower than diesel.
- Particles from NG emissions mainly composes of **volatiles**.

Air Quality (Gases)



- When switching from diesel fuel to NG:
  - **CO_2 and NO_x was reduced** by ~20% and 92% respectively.
  - **CO and HCHO was increased** by >4 and >6 times respectively.
  - CH_4 emission factor was 11.5 g/kWh while no detectable CH_4 was measured from diesel exhaust.

Global Warming Potential



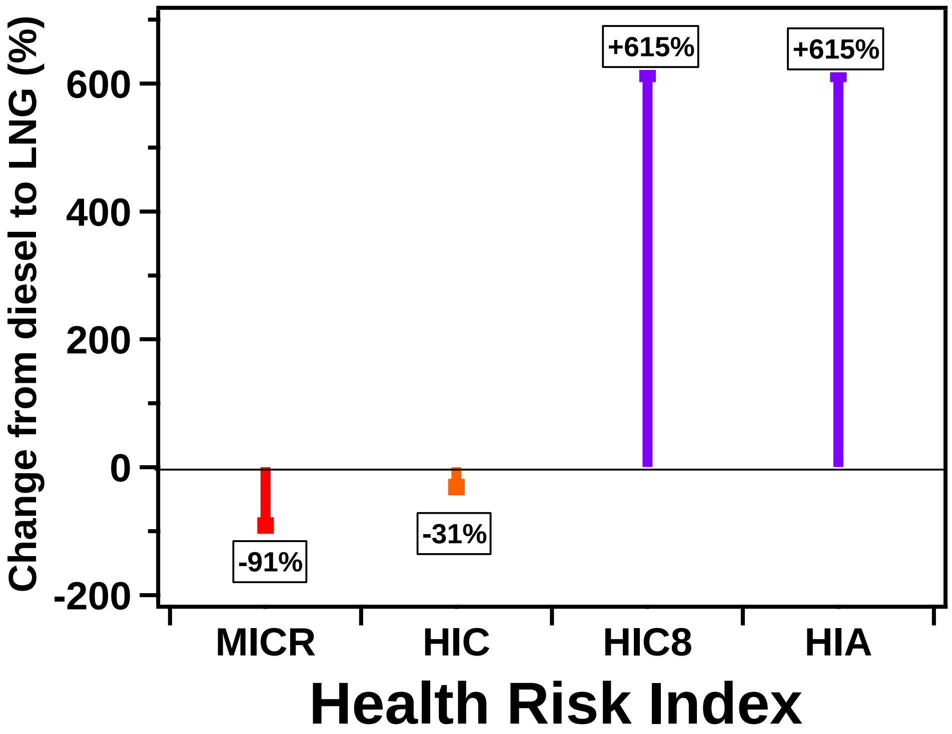
✓ Compounds: CO_2, CH_4, BC.
✓ Time horizontal: 20-year vs 100-year.
✓ Engine load: idle, 25%, 50%, 75%, 100% and overall average

- When switching from diesel fuel to NG:
  - **Overall GWP from increase of CH_4 outweighs reduction of CO_2.**
  - **100-year GWP of CH_4 and BC decreased by more than 50% compared to 20-year GWP** due to shorter lifetime in atmosphere.
  - At lower engine loads, CH_4 accounts for major fraction of GWP. **At >75% engine load, GWP from NG is at similar level with diesel.**

Health Risk Assessment

- Maximum Individual Cancer Risk **(MICR)**
- Non-Carcinogenic
  - Chronic Hazard Index **(HIC)**
  - 8-Hour Chronic Hazard Index **(HIC8)**
  - Acute Hazard Index **(HIA)**

2015 OEHHA Guidelines
2017 SCAQMD Risk Assessment Procedures V 8.1



- When switching from diesel fuel to NG:
  - **Cancer risk and chronic health risk (long-term non-carcinogenic) were reduced largely** due to PM reductions.
  - **Shorter-term health risks in local areas were increased significantly** due to HCHO increases. (e.g. 95% remove efficiency)

Mitigation

1. Plugging in Shore-power at idle

2. Cylinder-Deactivation

3. Oxidation Catalyst at exhaust

Metric	Index	Actual	Shore Power	Cylinder Deactivation	Oxidation Catalyst
Hazards Risks	MICR	-91%	-94%	-91%	-93%
	HIC	-31%	-57%	-42%	-91%
	HIC8	615%	345%	496%	-64%
	HIA	615%	345%	496%	-64%
Climate Impacts	GWP20	109%	37%	78%	109%
	GTP20	96%	33%	69%	96%
	GWP100	38%	4%	25%	38%
	GTP100	-11%	-20%	-13%	-11%

Conclusion

- Switching to NG reduced $PM_{2.5}$, BC, NOx, CO_2 by 93%, 97%, 92% and 20% respectively, however, increased CO and HCHO by >4 and >6 times and CH_4 emission factors to >11 g/kWh.
- Organic carbon account for 93% of total carbon of NG exhaust particles while 85% for diesel.
- The large increase of CH_4 increase GWP from NG but at >75% engine load, 100-year GWP from both NG and diesel are comparable.
- The decrease of PM reduced the cancer risk and long-term non-carcinogenic effects but the increase of HCHO increased shorter-term health effects, which can be controlled significantly with proper after-treatment (e.g. oxidation catalyst).

Thank You

Published/In-prep work:

1. Sommer, D. E. et al. Characterization and Reduction of In-Use CH4 Emissions from a Dual Fuel Marine Engine Using Wavelength Modulation Spectroscopy. Environ. Sci. Technol. (2019). doi:10.1021/acs.est.8b04244
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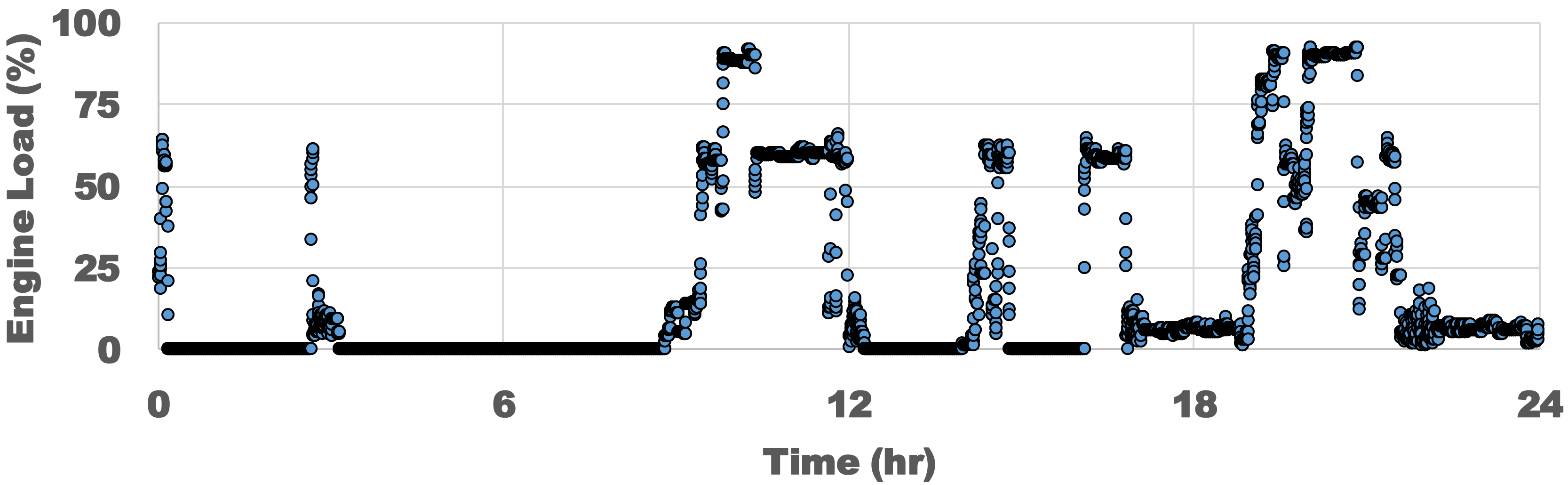
SCAN ME

a	Engine Load				
	Idle	25%	50%	75%	100%
Actual Vessel Cycle	0.32	0.09	0.06	0.31	0.22
Standard E2 Cycle	0.00	0.15	0.15	0.50	0.20



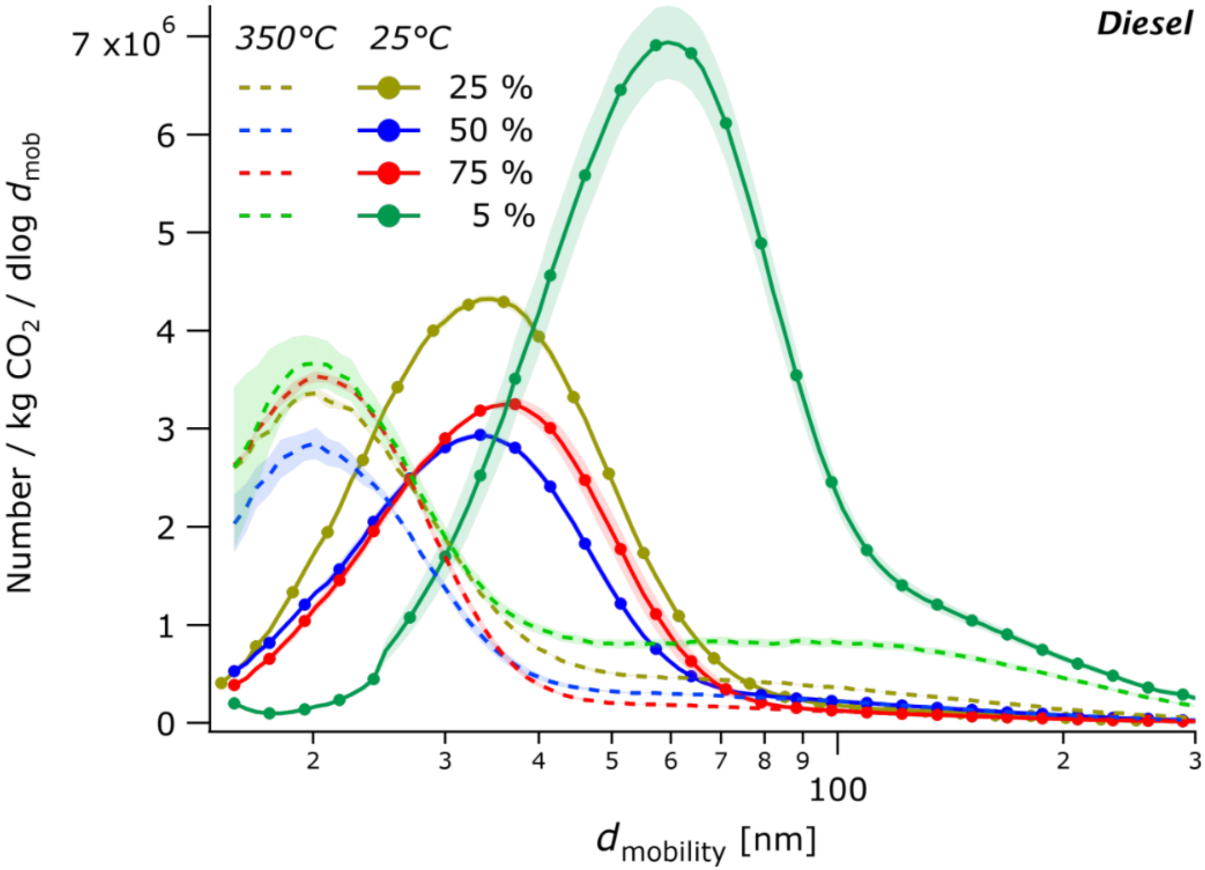


Figure S6: Mean mobility-size number distributions for diesel combustion as a function of engine load. Solid lines show sixfold-diluted samples, dashed lines show samples denuded at 623 K. Shading shows standard error of the mean.

Health Risk Assessment

MICR = Cancer Potency (CP) x Dose (D) x 10^{-6}

Where:

Dose = Concentration x Exposure

Concentration = GLC = $(Q_{tpy}$ x $\chi/Q)$ x MWAF

CEF_R = $(Exposure_{0.25\text{-}0}$ + $Exposure_{0\text{-}2}$ + $Exposure_{2\text{-}16}$ + $Exposure_{16\text{-}30})$ x EF_R / AT

$Exposure_{AgeBin}$ = DBR_{AgeBin} x ED_{AgeBin} x ASF_{AgeBin} x FAH_{AgeBin}

$Exposure_R$ = CEF_R x MP_R

CEF_W = DBR_W x ED_W x EF_W / AT

$Exposure_W$ = CEF_W x MP_W x WAF

Parameters	Cancer Potency	REL		
		Acute	8-hr	Chronic
Compounds	(mg/kg-d)^-1	ug/m3	ug/m3	ug/m3
Formaldehyde	0.02	5.50	9.00	9.00
PM from diesel	1.10	0.00	0.00	5.00

	MICR	HIA	HIC8	HIC
LNG	4355.14	7.78	4.76	5.76
Diesel	133077.69	3.17	1.94	37.59
Difference	-0.97	1.46	1.46	-0.85

Total $HIC_{\text{target organ}}$ = $\{[Q_{tpy,TAC1}$ x (χ/Q) x MP_{TAC1} x MWAF]/Chronic $REL_{TAC1}\}_{\text{target organ}}$ +
$\{[Q_{tpy,TAC2}$ x (χ/Q) x MP_{TAC2} x MWAF]/Chronic $REL_{TAC2}\}_{\text{target organ}}$ + ...

Total $HIC8_{\text{target organ}}$ = $\{[Q_{tpy,TAC1}$ x (χ/Q) x WAF x MWAF]/8-Hour $REL_{TAC1}\}_{\text{target organ}}$ +
$\{[Q_{tpy,TAC1}$ x (χ/Q) x WAF x MWAF]/8-Hour $REL_{TAC2}\}_{\text{target organ}}$ + ...

Total $HIA_{\text{target organ}}$ = $\{[Q_{lbph,TAC1}$ x $(\chi/Q)_{hr}$ x MWAF]/Acute $REL_{TAC1}\}_{\text{target organ}}$ +
$\{[Q_{lbph,TAC2}$ x $(\chi/Q)_{hr}$ x MWAF]/Acute $REL_{TAC2}\}_{\text{target organ}}$ + ...

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