Local Air Benefits by Switching from Diesel Fuel to LNG on a Marine Vessel

Final Report

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CARB

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Disclaimer

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Executive Summary

Background: Current environmental regulations require cleaner fuels and lower emissions for all maritime operations. Natural gas is a fuel that has been shown to meet the cleaner fuel requirements for maritime applications, despite data on natural gas in this capacity being quite limited. It is unknown what the future of maritime regulations will require or if natural gas can meet those requirements. This project provided an opportunity to directly compare the emissions from a modern duel-fuel marine engine running on liquefied natural gas (LNG) with emissions from diesel fuel.

Approach: The University of California, Riverside (UCR) teamed with the National Research Council -Canada (NRCC) and the University of British Columbia (UBC) to measure a wide range of chemical and physical properties of emissions from LNG and diesel fuels at loads specified in the engine certification cycle. Using standard methods, UCR measured the emissions of criteria and toxic air pollutants, as well as other contaminants that impact climate change such as black carbon (BC) and methane. Additionally, UCR generated activity profiles for the vessel operating within the Strait of Georgia to calculate real-world emission factors. Finally, a deeper analysis of the emission data was carried out to gauge the health and climate change impacts associated with the fuel change.

Results: The overall emission factors for both LNG and diesel fuels were below the certification levels. Especially notable was the reduction of 93% in particulate matter (PM) and 92% in NOx that was observed after switching from diesel to LNG. The ISO weighted NOx emission factor for LNG was 0.63 g/kWhr (8.94 g/kWhr for diesel). This value offers a mitigation strategy for port communities where high NOx levels drive ozone levels above the federal standards. The health hazard for PM outweighed formaldehyde toxicity over both the long and short term exposure. An analysis of global warming potential (GWP) impacts is complex, especially when considering the energy usage for both the fuel cycle and the vessel operation. This analysis considered energy usage solely for vessel operation. For snow and ice areas, the 97% reduction in black carbon will slow ice melting. However, the unburned methane dominates the GWP for both short and long term exposure.

Implications: LNG offers significant benefits within local communities by reducing criteria pollutants and improving public health. However, global impacts are dominated by the release of short-lived climate pollutants, such as methane. Several strategies show promise to mitigate the methane exhaust and leakage emissions associated with LNG, which will require further investigation. Other dual-fuel engines would also need to be tested to determine accuracy and consistency of results.

Emissions from the Latest LNG Engine Technology

1 Background

Background

Recent regulations from the International Maritime Organization (IMO) and other regulating bodies significantly lowered the permissible emissions of smog and soot forming entities in the exhaust gases from ships. For example, the sulfur content of fuels in Emission Control Areas (ECAs) is now limited to 0.1 weight percent, bringing the threshold down from 3.5 weight percent. Vessel owners are offered the alternative of installing an exhaust gas scrubber to control exhaust sulfur oxides to levels that would be equivalent to using a fuel with 0.1 weight percent sulfur. The regulation is of importance considering that all of the coastline of the United States and Canada is classified as an ECA area.

One approach to meeting the low sulfur fuel requirement is to burn natural gas and fortunately both the United States and Canada have rich reserves of natural gas. While natural gas sold as liquefied natural gas (LNG) may be cost competitive to other ECA fuels, there are additional expenses associated with shifting to widespread use of LNG, including the cost of fueling infrastructure, and for some owners, repowering existing vessels with engines that can operate on LNG. Other countries in Europe and in Asia, primarily China, are converting to LNG so there is global interest in knowing more about the emissions from ship engines burning LNG.

The objective of this analysis was to measure in-use criteria emissions from the same engine when burning either LNG or diesel fuels at the load points specified for certification testing. These emission measurements, to our knowledge, would provide the first independent comparison using the same fuels.

This project was completed with the collaboration of UCR, the National Research Council of Canada (NRC), the University of British Columbia (UBC) and a ferry vessel owner. The LNG engine that was powering the ferry vessel provided an ideal emission testing platform.

Completion of the project was divided into three tasks with deliverables.

Task 1 - planning phase; included the kick-off meeting where all parties agreed on the overall approach and responsibilities. Next step was laboratory tests at UCR to ensure the equipment was functioning properly and ready for field deployment. Last step was packaging and transporting the near 400kg of equipment in containers that met international standards to ensure the equipment arrived on time at the test site.

Task 2 - testing phase; included the on-site building of a sampling line and setting up equipment on the vessel for measurement of real-world emissions using both LNG and diesel fuels.

Task 3 – reporting phase; included organization and execution of meetings, reports, publications, and technology transfer to the scientific community.

With Tasks 1 and 3 being mainly administrative, the following sections focus on the results of UCR's emission measurements.

2 Approach

This section describes the results from the test vessel when operating on LNG and diesel fuels. In-depth details of the analytical methods are described in the project proposal and included in Appendix 1.

2.1 Test article

The test vessel was a steel mono-hull, roll-on/roll-off (RO/RO) cargo ferry built in 2017 that was designed to reduce emissions of criteria pollutants and greenhouse gases. Selected specifications for the vessel: 6,750 deadweight tonnage (dwt), 7 m draft, 148.9 m length, 26 m width, and a capacity of 59 -53 foot trailers. This class of RO/RO vessel was designed to cover short distances and is not the same as the larger ocean-going RO/RO vessels, which have a capacity of 23,786 dwt (3.5 times larger).

The test vessel is the first LNG-battery hybrid RO/RO ferry vessel operating in North America. It is powered by two Wärtsilä 34DF dual-fuel engines and a 1,050 V, 546 kWh Corvus Energy Storage System (ESS) consisting of 84 AT6500 advanced lithium polymer batteries. The battery system, integrated with an Elkon power distribution system, is used as a spinning reserve and for port maneuvers.

The main propulsion system is comprised of twin 9L34DF LNG-diesel dual fuel engines by Wärtsilä, coupled to constant-speed generators with Wärtsilä LNG Pac fuel systems. The 34DF engine design comes in five configurations the 6L, 8L, 9L, 12V, and 16V options where the "L" is an inline design with 6, 8, and 9 cylinders and the "V" is a V-cylinder design with 12 and 16 cylinders. The Wärtsilä 9L was used in this study. The 34DF is a 4-stroke, non-reversible, turbocharged and inter-cooled dual fuel engine with direct injection of liquid fuel and indirect injection of gas fuel. The engine can be operated in either the gas or diesel mode. In the gas-mode the diesel pilot fuel supplies ~1% of the total fuel energy at normal operating loads and <10% when at idle. For this project, the engine serial number that was tested was PAAE-2740430, and the engine model year was October 2015.

Table 2-1 Selected Properties of the Main Propulsion Engine

Brand	Model	Cylinder	Speed	Max Power	Displacement
Wärtsilä	9L34DF	#	rpm	MWatt	liter/cyl
		9	720	4.32	36.3

Table 2-1 above shows selected properties of the main propulsion engine. EPA[1] identifies marine engines with a displacement of >30 liters/cylinder as Category 3, and the applicable NOx standards are specified in Table 1 of §1042.104: "NOx Emission Standards for Category 3 Engines (g/kW-hr)." NOx certification standards are calculated from *n*, the maximum in-use engine speed, in RPM. At 720 RPM, the Tier 2 standard is 9.69 g/kWhr and the Tier 3 standard is 2.42 g/kWhr.

[1] CFR Title 40 Part1042—Control of emissions from new and in-use marine compression-ignition engines and vessels; Table 1 to §1042.104 https://www.ecfr.gov/cgi-bin/text-idx?node=pt40.36.1042&rgn=div5#se40.36.1042_1104

2.2 Test conditions

Testing can be performed in-service, in-use, or pulling against a dock. This testing was performed during normal in-service operation for moving cargo.

2.2.1 Operating loads

Emissions were measured while the vessel operated as close as possible to the four certification loads specified in the ISO 8178-4, "E-2 cycle" [2] used for Heavy-Duty, Constant-Speed Engines for Ship Propulsion and shown below in Table 2-2. Measurements at the certification loads were used to calculate the modal and overall emission factors, which were compared to published certification values. Some deviation from the E-2 cycle values was expected as vessels in service may need to adjust speed in order to adhere to the published arrival and departure schedules. Aside from sea trials, engines rarely operate at 100% loads. Throughout this project, the top load was 90%. For the 75%, 50%, and 25% load points, the loads were within approximately 10% of the certification load value. Because the vessel spent a considerable amount of time at idle speed, measurements were collected at idle in addition to measurements at the four modes in the E-2 cycle. Repeat measurements at the same loads were collected when possible.

TABLE 2-2 TARGETED ENGINE OPERATING CONDITIONS FOR THE TESTING

	Rated speed				
Torque, %	100	75	50	25	Idle
Weighting factor	0.2	0.5	0.15	0.15	0

2.2.2 Fuels

Testing was carried out with both LNG and a commercial low-sulfur (<15ppm) #2 diesel fuel for on-road use in the Vancouver area. LNG was supplied from the nearby Fortis BC Tilbury LNG plant located in an industrial area near the Fraser River. Composition and heating value for the LNG is shown in Table 2-3.

TABLE 2-3 COMPOSITION AND SELECTED PROPERTIES OF THE LNG

Specification/ Component	UNITS	LNG
Methane	mole %	91.88
Ethane	mole %	5.94
Propane	mole %	1.85
i-Butane	mole %	0.20
n-Butane	mole %	0.14
Heating Value	MJ/m3	40.71

[2] Reciprocating internal combustion engines – Exhaust emissions measurement – Part 4 Test cycles for different engine applications. ISO 8178-4, 1996.

2.3 Sample system

A key element of the project was designing and building a sample line that could be fitted to the existing knock-out (KO) section for removing water that had entered the exhaust line. The ferry owner requested that existing lines that penetrate the exhaust be utilized rather than drilling new holes to create new lines. The KO section consisted of a valve and drain lines to remove the water from the exhaust as seen in Figure 1. For access convenience we elected to sample from the left side.

Team members from the University of British Columbia worked with the vessel operator to remove the valve from the KO system and added a blank flange with four connections to the sampling lines, as shown in Figure 2. A transfer line was built from the exhaust to the dilution tunnel. The same dilution tunnel was used throughout the project to ensure a consistent dilution ratio for all test results.

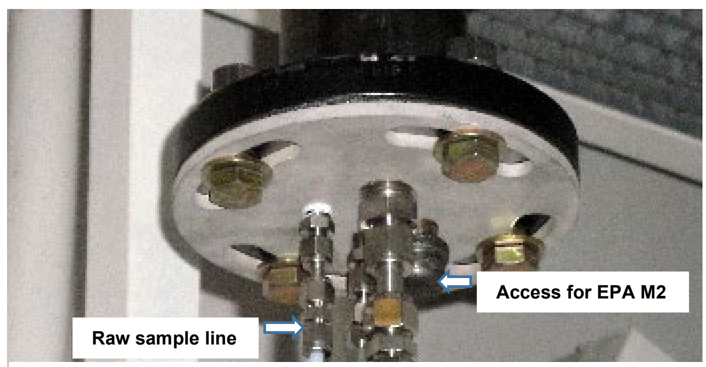


FIGURE 2 MULTIPLE SAMPLE PORT ACCESS DESIGN

Due to the distance between the sampling port and the measurement instruments, a long transfer line was built from the sampling port to the dilution tunnel, as shown in Figure 3. UCR typically connects directly to the exhaust stack without out using a transfer line to minimize PM losses. Several features were designed into the transfer line to minimize PM losses and manage the sample. First a large inside diameter was selected for the transfer line to minimize pressure drop; second, the transfer line was heated to minimize thermophoretic PM losses and prevent condensation of moisture before reaching the dilution tunnel; and third, the probe end that was inserted into the exhaust flow was cut at 45 degrees and faced directly into the flow to provide a boost in pressure and flow.

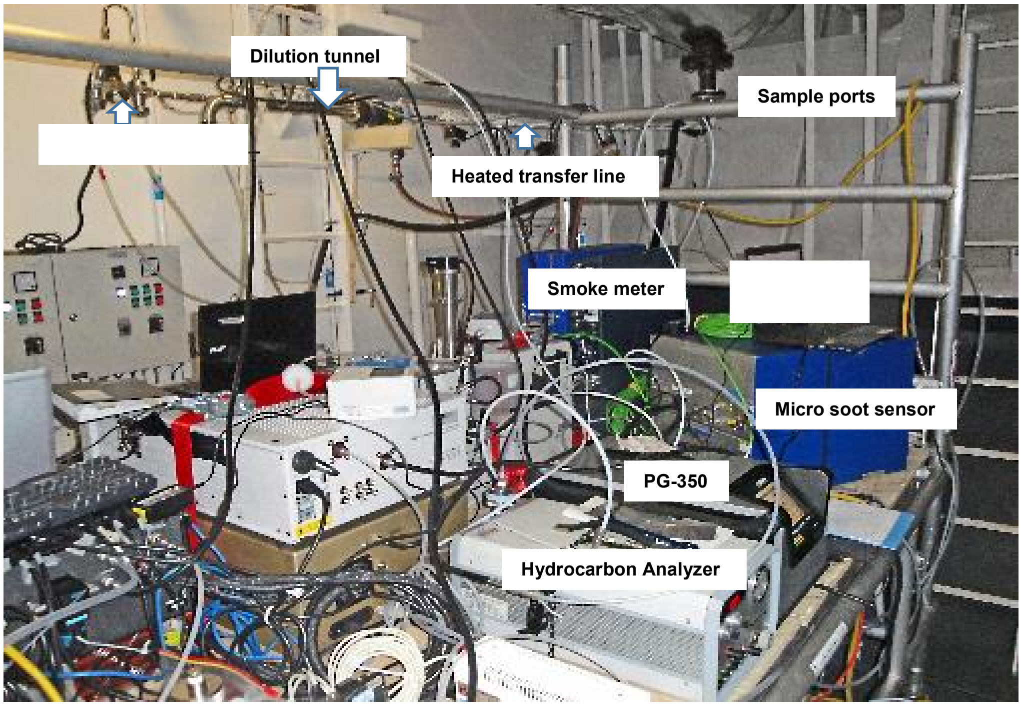


FIGURE 3 LAYOUT OF THE DILUTION TUNNEL SYSTEM AND THE ANALYTICAL INSTRUMENTS

As shown in Figures 3 and 4, staging was assembled, and a thick plywood section was laid across the supporting members of the staging to hold the instruments. All instruments were securely fastened to the plywood for stability while underway. The platform supported specialized equipment from both UCR and NRC.

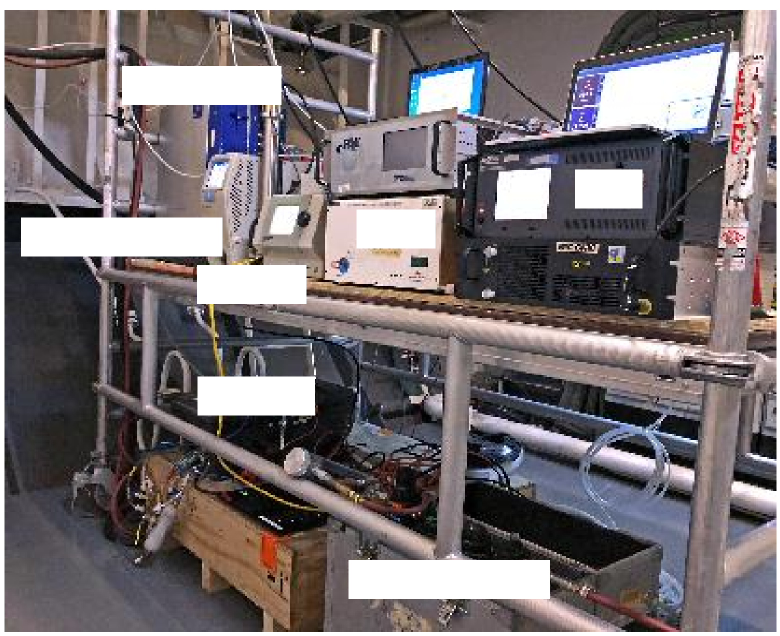
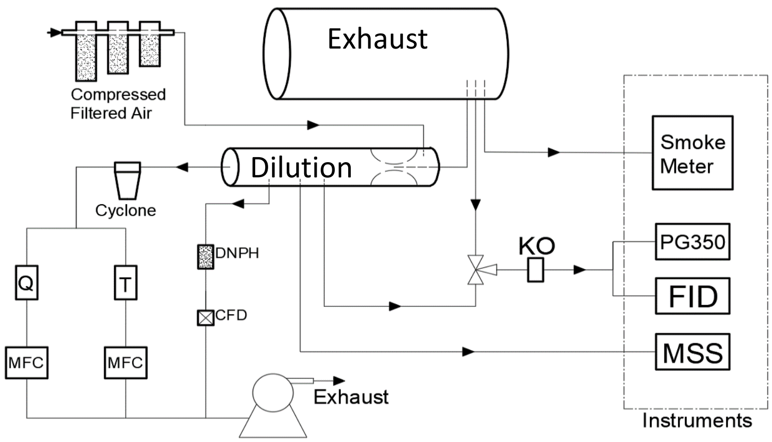


FIGURE 4 OPPOSITE VIEW OF STAGING AND INSTALLED EQUIPMENT



Smoke Meter: AVL Smoke Meter
PG350: Horiba Portable Gas Analyzer
FID: J.U.M. Flame Ion detector
MSS: AVL Micro Soot Sensor
KO: Water Knock-out
Q: Quartz filter
T: Teflon filter
MFC: Mass flow control
CFO: Critical Flow Orifice
DNPH: Waters 2,4-Dinitrophenylhydrazine cartridges
Cyclone separator: removes PM >10 μm

FIGURE 5 SCHEMATIC SHOWING LAYOUT OF UCR EQUIPMENT

Figure 5 shows a schematic layout of the setup. After the equipment was installed and operating properly, collection of measurements of the real-world exhaust emissions while the vessel burned LNG or diesel fuel began.

2.4 Exhaust flow

It was essential to accurately measure the mass flow rate of the exhaust in order to calculate emission rates and emission factors based on mass. Although there are four accepted methods for measuring flow rate, only EPA Method 2 was applicable for this project. With EPA Method 2, a type S Pitot tube is used to measure the differential pressure between the counter-flow (static pressure) and parallel-flow (dynamic pressure) directions. Measurement of the differential pressure and temperature were repeated several times at each load as shown below in Figure 6. Results were consistent with the literature provided by the manufacturer in terms of exhaust flow as a function of load.

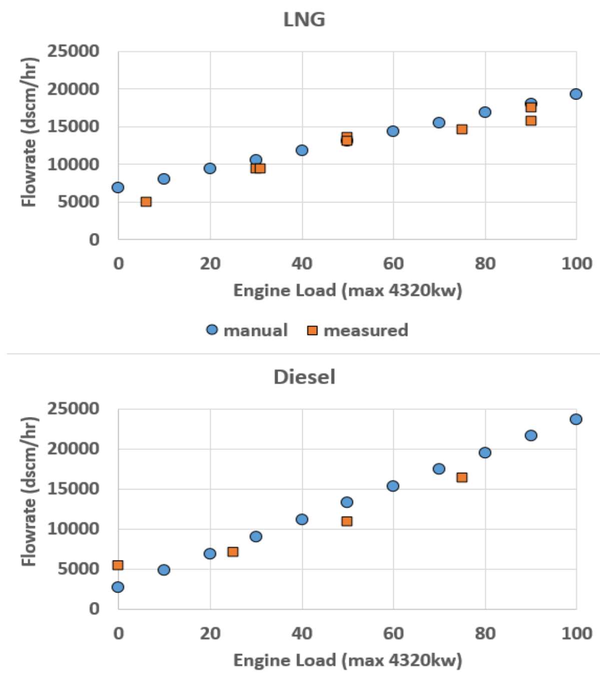


FIGURE 6 FLOW EXHAUST RATE IN DRY STANDARD CUBIC METER PER HOUR

2.5 Emissions factor calculations

The emission factor at each mode was calculated from the measured gaseous and $PM_{2.5}$ concentrations, the reported engine load in kilowatts (kW) and the calculated mass flow in the exhaust. An overall single emission factor representing the engine was determined by weighting the modal data according to the ISO 8178 E2 requirements and summing them. The equation used for the overall emission factor is as follows:

$$A_{WM} = \frac{\sum_{i=1}^{i=n} (g_i \times WF_i)}{\sum_{i=1}^{i=n} (P_i \times WF_i)}$$

Where:

A_{WM} = Weighted mass emission level (CO, CO_2, $PM_{2.5}$, or NO_x) in g/kW-hr
g_i = Mass flow in grams per hour,
P_i = Power measured during each mode, and
WF_i = Effective weighing factor.

3 Results

The results and impact of the emissions are presented in this section.

3.1 Gaseous emissions

The gaseous emissions of CO, NOx, CO_2, CH_4, total hydrocarbons and carbonyls were measured following methods outlined in the International Standards Organization (ISO) 8178-1 and ISO 8178-2. A Horiba PG-350 instrument measured the concentrations of NOx, CO, CO_2, O_2 and SO_2 and a J.U.M. Flame Ionization Analyzer Model 3-200 (JUM FID), using a hydrogen carrier gas, measured the concentration of total hydrocarbons in one mode and concentration of methane in the other mode. During the project, daily calibrations of the Horiba were performed with EPA protocol gas (1% accuracy standard for use with emissions measurements for new engines)[3] for NOx, CO_2 and CO span values, which is typical for in-use testing procedures. For the JUM FID, UBC's methane protocol gas was used to calibrate the FID data for methane to directly compare the output of the instruments. The carbonyl compounds, especially formaldehyde (HCHO), were measured using EPA Method TO-11a[4]. Samples were collected on 2,4-dinitrophenylhydrazine (DNPH) coated silica cartridges and analyzed using a high-performance liquid chromatography (HPLC) instrument. The collection time for HCHO on the DNPH coated cartridges was estimated using Dräger tubes such that sample breakthrough would be minimized. The sampling times were on the order of minutes for LNG exhaust at idle as compared with tens of minutes for diesel exhaust, due to the higher concentrations of carbonyls in the LNG exhaust.

3.1.1 CO_2 and NOx

Carbon dioxide (CO_2): Modal emission factors are about the expected value of 600g/kW-hr when the diesel engine was operated at the normal operating loads, as shown in Figure 7. The emission factor at ~5% load was nearly 30 times higher as the engine operates with much lower efficiency at low loads. The CO_2 emission factors for LNG were lower than diesel since the hydrogen to carbon mole ratio is doubled for methane. Burning the extra hydrogen in methane requires less carbon and fuel to be burned.

Nitrogen oxides (NOx): Modal emission factors with LNG were one order of magnitude lower than those for diesel for loads >5%. The ISO weighted emission factors (loads > 5%) for LNG and diesel were 0.63 g/kWhr and 8.95 g/kWhr, respectively. When idling, the emission factor of NOx was about 4g/kWh for LNG and 16 g/kWhr, approximately 80% less than with diesel fuel. These results were expected as the duel fuel engine was certificated for NOx as Tier 3 with LNG and Tier 2 with diesel fuel. However, both the LNG and diesel NOx emission factors did not change significantly when engine load was > 25%.

[3] US EPA (2012) "Traceability Protocol for Assay and Certification of Gaseous Calibration Standards" (PDF) (174 pp, 1.7 M, About PDF) Publication No. EPA/600/R-12/53.

[4] Determination of in Ambient Air Using Adsorbent Cartridge Followed by High Performance Liquid Chromatography (HPLC), January 1999. https://www.epa.gov/sites/production/files/2019-11/documents/to-11ar.pdf

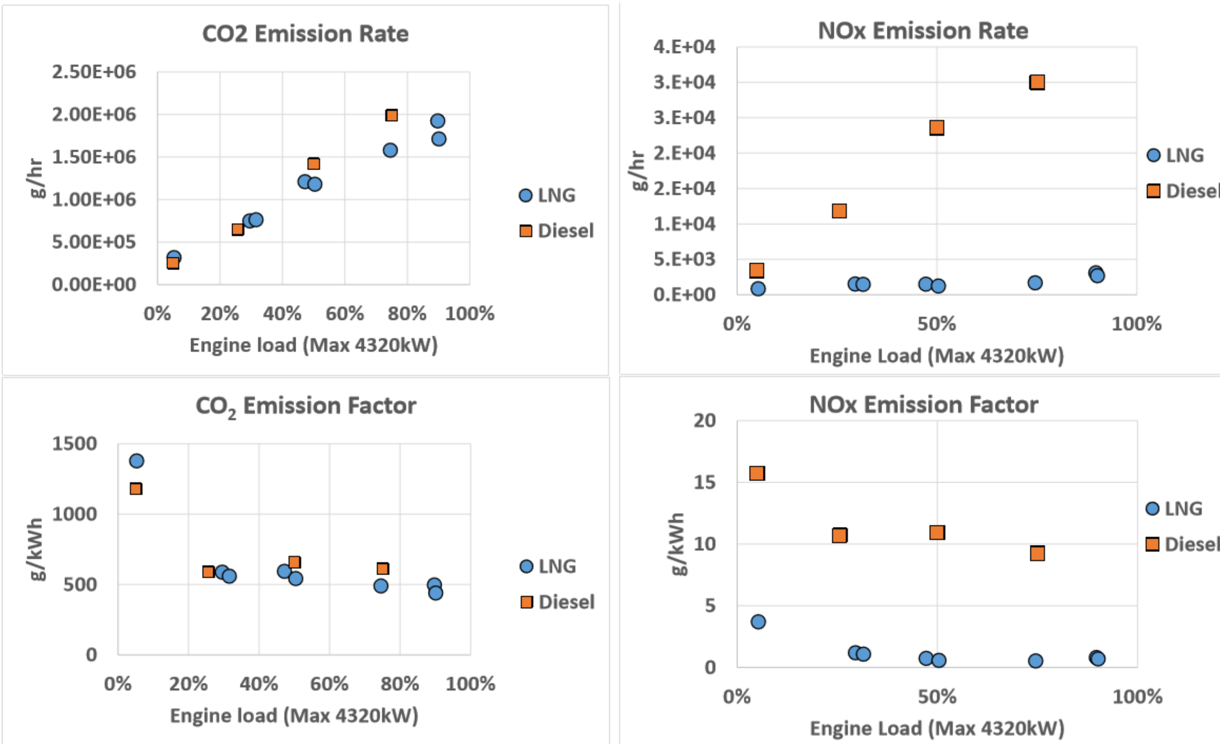


FIGURE 7 MODAL EMISSION RATES & FACTORS FOR CO_2 & NO_X

3.1.2 *THC and CH_4*

Total hydrocarbon (THC) and methane (CH_4) emissions: The THC emissions were orders of magnitude higher for the engine running on LNG due to the fact that internal combustion (IC) engines designed to run on diesel fuel have a much lower compression ratio and fuel combustion efficiency for LNG as compared with diesel fuel, Figure 8. For example, an on-road IC engine running on diesel has a fuel conversion efficiency of >40%, while the same engine using LNG at the same loads has an efficiency of ~35%. This decrease in efficiency is because most engines running on LNG are actually diesel engines adjusted or tuned to run on LNG. This approach results in more THC/CH4 emissions as observed in these data. Figure 8 shows the methane was the primary hydrocarbon compound in the THC in the exhaust when burning LNG; comprising about 80% of the THC emissions. The methane emissions measured with the JUM FID were within 10% of the values measured by the team from the UBC and who used a tunable diode laser to continuously measure emissions of methane.

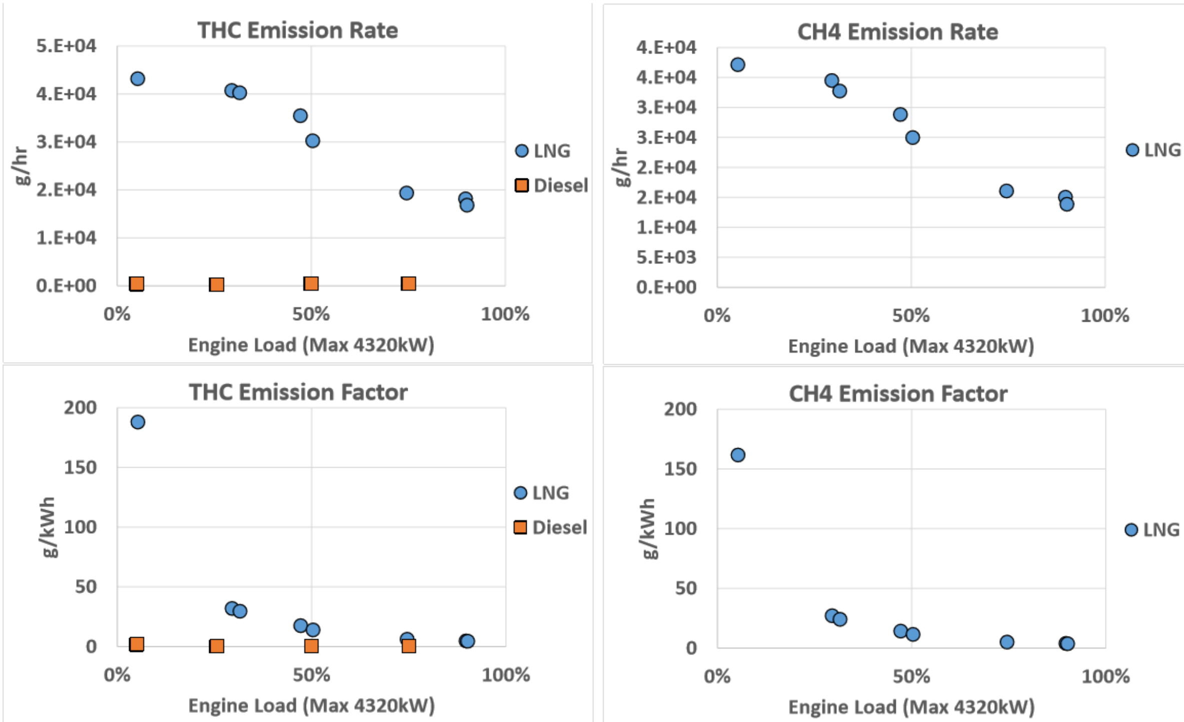


FIGURE 8 MODAL EMISSION RATES & FACTORS FOR THC & CH4

3.1.3 CO and HCHO

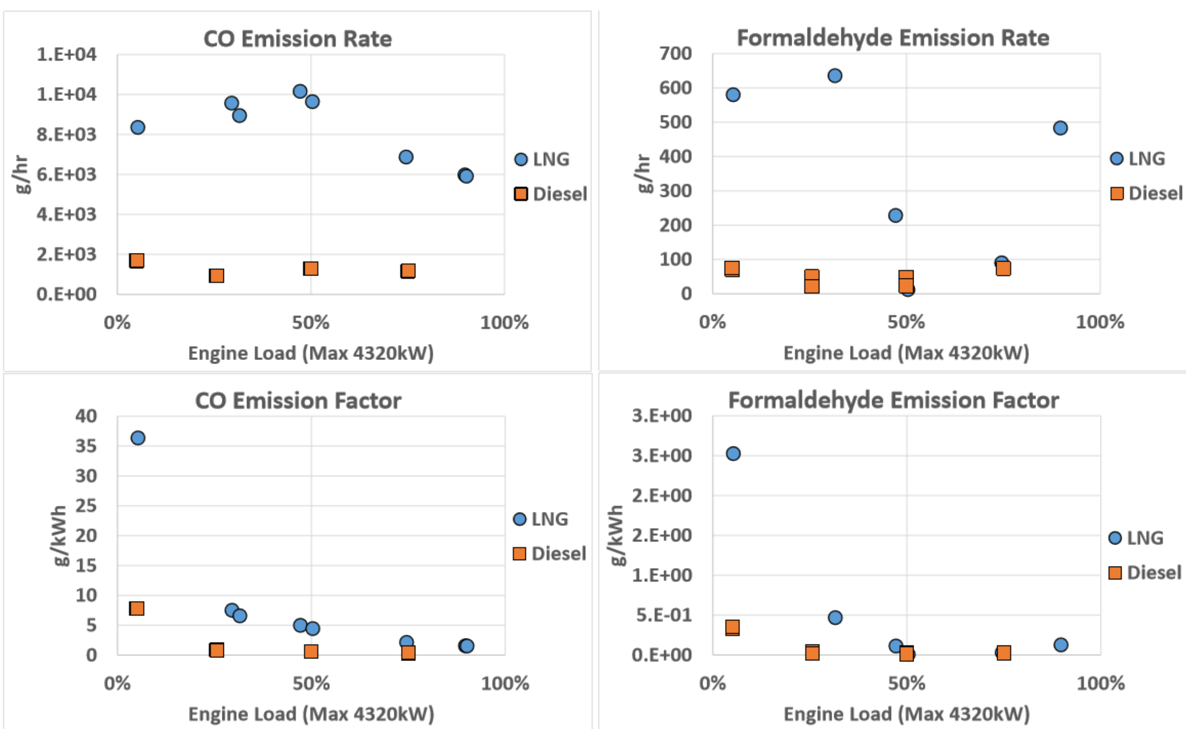


FIGURE 9 MODAL EMISSION RATES & FACTORS FOR CO & HCHO

Figure 9 shows the carbon monoxide (CO) and HCHO emissions on a g/hr and g/kWhr basis. The brake-specific emissions of CO and HCHO are highest at light loads. Additionally, these emissions are also high and similar to when the vessel is doing heavy work on per-time basis, suggesting their inventory may be important to consider given vessels spend a lot of time idling. This vessel spent 32% of its day idling (see Section 3.3). The high emissions at light load is a result of the lower fuel conversion efficiency for LNG and the result of partial oxidation combustion products occurring (CO and HCHO); a result that is amplified at idle. Observations of higher levels of CO and HCHO using LNG versus diesel in this project are consistent with earlier results for on-road applications.[5]

For all work places, Occupational Safety and Health Administration (OSHA) established the 8-hour maximum permissible exposure level (PEL) for CO as 50 ppm[6]. Maritime workers, however, must be removed from exposure if the CO concentration in the atmosphere exceeds 100 ppm. The peak CO level for employees engaged in RO/RO operations (during cargo loading and unloading) is 200 ppm. We measured CO concentrations at idle as ~1,300 ppm for LNG and 250 ppm for diesel, which are well above the PEL. Unlike buses where exhaust is at ground level and in the breathing zone of people, the high-velocity exhaust gas plume from the ferry stack can go high into the atmosphere and is expected to be greatly diluted before it reaches the ground.

Measurement of carbonyls, especially HCHO, was also of interest given that HCHO is a carcinogen and has multiple harmful effects on exposed workers[7]. To protect workers, OSHA lists 0.75ppmv as the PEL over 8 hours and 2 ppmv for 15 minutes. HCHO concentrations for LNG at idle were measured at ~100 ppmv. However, as explained for the CO, the HCHO gases are released high into the atmosphere, are short-lived, and unlikely to reach the breathing zones near the vessel surface.

As both CO and HCHO result from incomplete combustion of carbon sources, there is usually a linear correlation between the emissions of CO and HCHO. The limited data collected in this project is graphed in Figure 10 and shows a linear relationship. While not shown, the incomplete combustion of LNG results in higher levels of methane emissions and CH_4 emissions also correlates linearly with either CO or HCHO.

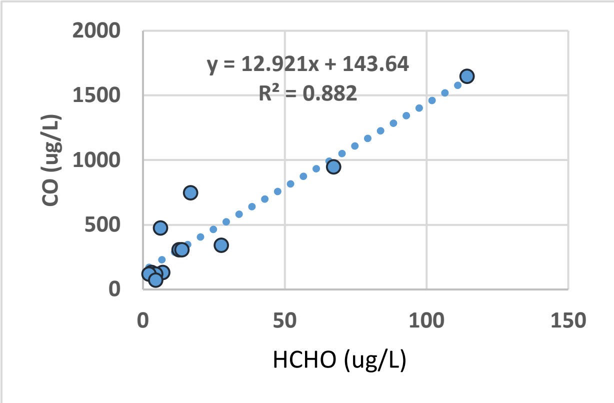


FIGURE 10 CORRELATION OF CO & HCHO

3.2 PM emissions

PM emissions were measured by collecting a portion of the diluted exhaust flowing through pre-weighted Teflon and pre-conditioned quartz filters and capturing PM on the filters. The weight on the Teflon filter determined the PM mass and the material on the quartz filter was analyzed

[5] Thomas W. Hesterberg, Charles A. Lapin, and William B. Bunn, A Comparison of Emissions from Vehicles Fueled with Diesel or Compressed Natural Gas, *Environmental Science & Technology* **2008** *42* (17), 6437-6445, DOI: 10.1021/es071718i

[6] See https://www.osha.gov/OshDoc/data_General_Facts/carbonmonoxide-factsheet.pdf

[7] See https://www.osha.gov/OshDoc/data_General_Facts/formaldehyde-factsheet.pdf

following the NIOSH 5040 Method[8] to determine the elemental and organic carbon contents. Figure 11 shows an example of the Teflon PM mass filter for LNG (left) and Diesel (right). The light color for the LNG suggests a more organic PM mass and the black for the diesel represents a higher elemental carbon PM fraction.

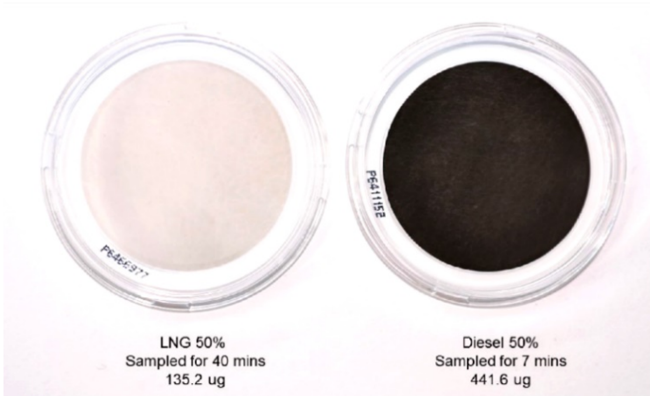


FIGURE 11 COMPARATIVE VISUAL OF FILTERS WITH LNG AND DIESEL

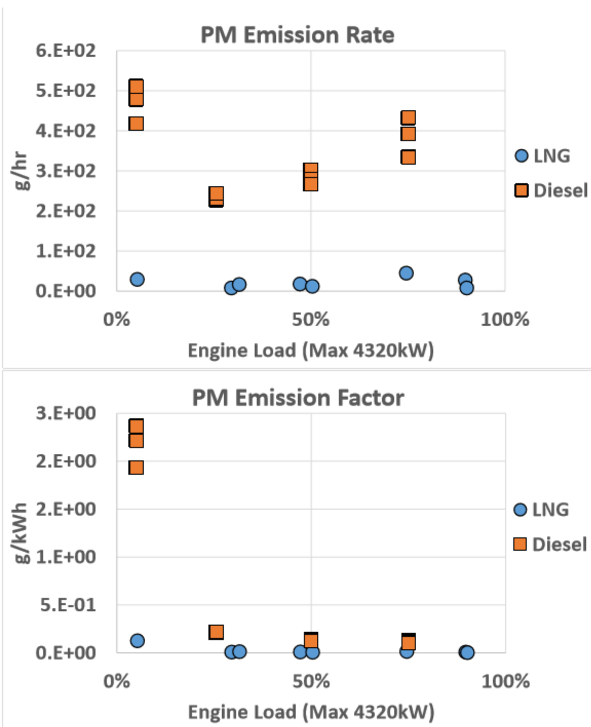


FIGURE 12 MODAL RATES AND FACTORS FOR PM MASS FOR LNG & DIESEL

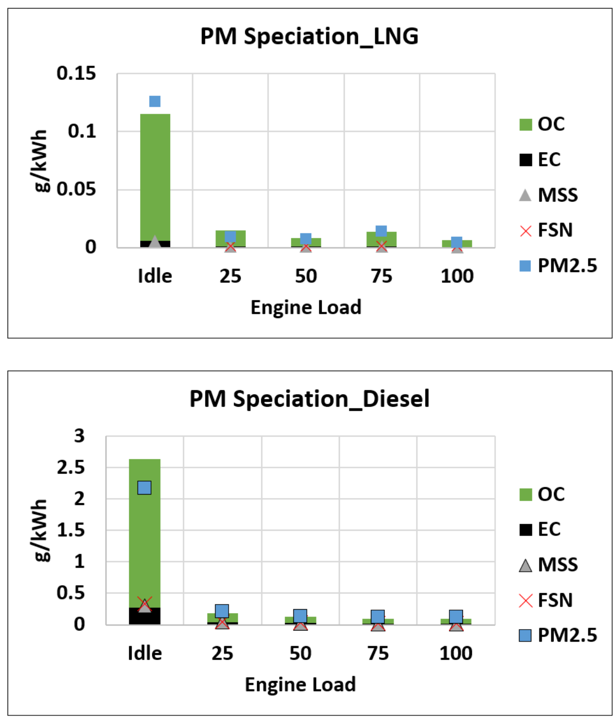


FIGURE 13 MODAL RATES AND FACTORS FOR PM FRACTIONS FOR LNG & DIESEL

The PM mass and speciated PM mass emission rates are shown in Figures 12 and 13. The highest PM emissions occurred at idle on a brake-specific and time-specific basis. PM mass emissions were ~100x lower with LNG as compared to diesel fuel. Speciation of PM mass shows that most

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[8] National Institute for Occupational Safety and Health (NIOSH), Diesel Particulate Matter as Elemental Carbon 5040 Method, http://www.cdc.gov/niosh/docs/2003-154/pdfs/5040.pdf

(>80%) of the mass is organic for both the LNG and the diesel fuels. Multiple repeats were carried out with the LNG fuel but due to time constraints, not as many repeat measurements were taken for diesel. However, the data collected was consistent with the expected values for a modern engine using diesel fuel.

3.3 Real-world activity

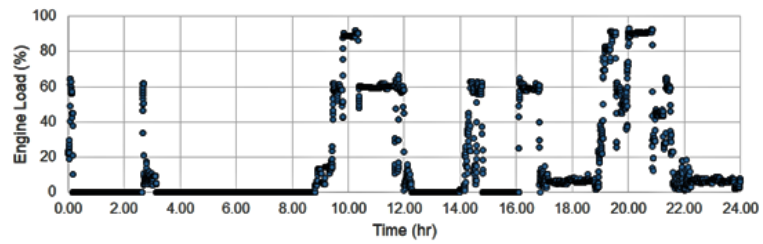


FIGURE 14 SELECTED SCADA OUTPUT FOR ONE DAY

In order to accurately find the emission contribution to an air basin, it is essential to know both the emissions at each engine load and the fraction of time that the vessel operates at that load. The weighting factors used for the certification test with the ISO 8178-E2 cycle were developed from real-world data, but real-world data for any specific vessel can vary from the certification test. Figure 14 shows a typical day of operation for the test vessel. This vessel operated in harbor service so it was unlikely to spend the same fraction of time at each load as the vessel used for E-2 cycle that operates on the open sea. Accordingly, we took two weeks of operating data from the Supervisory Control and Data Acquisition (SCADA) system to determine the fraction of time that this harbor vessel actually operates at various loads in real-world operation, and used those percentages, or weighting factors, when calculating the contribution of emissions to this air basin. Table 3-1 represents the percentage of time that the vessel spends at various loads after analyzing the data. These percentage values are significantly different from the standard E-2 weighting factors and these measured values were used for the determination of the criteria and toxic emissions released into this air basin by this vessel.

TABLE 3-1 FRACTION OF TIME AT SELECTED OPERATING MODES

Engine load (%)	Idle	25	50	75	100
E2 Standard Value	0.00	0.15	0.15	0.50	0.20
This vessel –actual	0.32	0.09	0.06	0.31	0.22

In order to compare the emissions of the engine with its certification standard, the overall weighting factors specified for ISO 8178-4 for the marine E-2 Cycle were applied to the measured modal emission values. In addition, the overall emission factors were calculated using the real-world weighting factors as shown in Table 3-1. Values of the overall emission factors for both sets of weighting factors are shown in Table 3-2 and Figure 15 below.

TABLE 3-2 CONSOLIDATED TABLE OF THE OVERALL EMISSION FACTORS (g/kWhr)

Operating Cycle	Fuel	NOx	CO	CO2	HCHO	THC	CH_4	$PM_{2.5}$	EC	OC	Soot
Standard E2 Cycle	LNG	0.63	2.51	497	0.08	7.96	6.59	0.010	0.0007	0.010	0.0007
	Diesel	9.50	0.41	617	0.02	*	*	0.125	0.0176	0.108	0.0188
Actual Ferry Cycle	LNG	0.76	3.49	521	0.18	13.64	11.52	0.013	0.0008	0.013	0.0009
	Diesel	9.63	0.67	635	0.03	*	*	0.199	0.0262	0.172	0.0281

There are two approaches to calculating the overall weighted emissions factor. One approach is to apply the equation to the data collected at the E-2 load. The other is to estimate the emission rate at exactly 25, 50, 75, and 100% loads and calcualte the overall factor. Table 3-2 shows values calcualted using the actual data. The estimated ISO load (ie corrected for differences from the actual loads to the ISO loads) emissions results for CO_2 are 405 g/kWhr and is 619 g/kWhr for LNG and diesel, respectively.

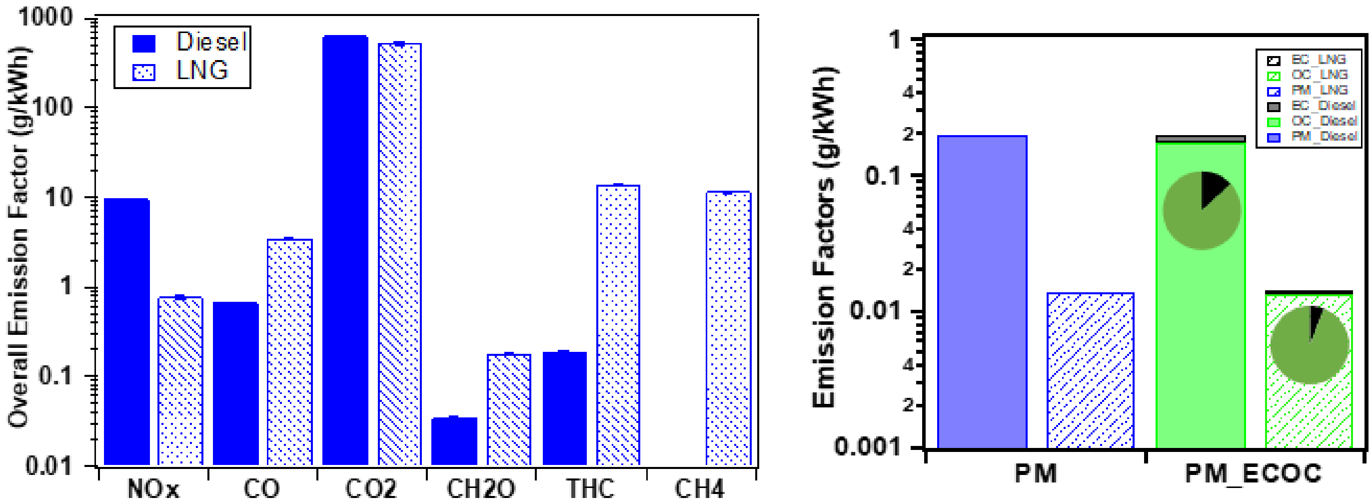


FIGURE 15 OVERALL EMISSION FACTORS FROM A DUAL-FUEL ENGINE

Using the weighting factors in the ISO E-2 standard, the overall emission factor of NOx with LNG was 0.63 g/kWh and below the Tier 3 standard of 2.4 g/kWh for this engine. Similarly, the overall emission factor for diesel fuel was 9.5 g/kWh and below the EPA Tier 2 standard of 9.7 g/kWh. When measuring emissions and calculating emission factors in the real world, the EPA measurement allowance is 20%, so the measured emission factors are well below the allowable limit.

The results and the weighting factors determined in actual or real-world service show similar reduction in emissions and benefits. These results suggest that switching to LNG from diesel is an effective option for an air basin to significantly reduce both NOx and PM.

4 Discussion

4.1 Health risk assessment

While NOx and PM are reduced, the emissions of methane, CO and HCHO increase. $PM_{2.5}$ is a suspected carcinogen by the International Agency for Research on Cancer (IARC), and both CO and HCHO are toxic gases with concentrations above the PEL levels when the engine operates at idle. A health risk assessment was conducted to consider these air contaminants. Because methane is a short-lived climate pollutant (SLCP), it is considered in a separate analysis.

A worst-case analysis of the health risk assessment was considered by evaluating the impacts of the primary toxic air pollutants at idle under the assumption that the emissions are in the breathing zone. In reality, the emissions from the exhaust stack are emitted high into the atmosphere and are greatly diluted before reaching the earth surface and breathing zone. The analysis of LNG shows a significant reduction in PM and a significant increase in HCHO compared to using diesel fuel.

Using the established models in Appendix 1, the difference between cancer and non-cancer risk as well as chronic and acute health impacts from PM and HCHO emissions from LNG and diesel were estimated. LNG provides a 92% reduction in PM, which proportionally reduces the maximum individual cancer risk (MICR), as shown in Table 4-1. This also shows that the PM risk far outweighs the HCHO risk. Non-carcinogenic health risks such as the acute hazard index (HIA), chronic hazard index (HIC) and 8-hr chronic hazard index (HIC8) were estimated considering the effects of PM and HCHO emissions on 8 major organ systems. According to the California Office of Environmental Health Hazard Assessment (OEEHA), HCHO has acute effects on eyes, and both PM and HCHO have chronic effects on respiratory systems. As shown in Table 4-1, LNG reduced HIC by 48%, indicating that longer-term health risks from LNG is far lower than that of diesel exhaust despite higher HCHO levels observed in LNG emissions. However, shorter-term hazard risks including HIA and HIC8 both increased by about 427% due to higher HCHO emission which raises concern for health risks to residents and workers who are directly exposed to these ship emissions.

As discussed previously, the hot exhaust emissions are emitted from a tall stack directly into the air, react in sunlight, and are greatly reduced before reaching the breathing zones. Furthermore, the issue of increased HCHO emissions was addressed with the large-scale introduction of LNG/CNG buses. Research and actual in-use data show that a simple oxidation catalyst removed 95% of the HCHO from the exhaust of LNG/CNG buses.[9] Assuming 95% removal of HCHO, the health risk was re-calculated with the hazard indexes shown in Table 4-1. Adding a controlling device further reduces long-term cancer risk and chronic health risks, but especially the shorter-term acute and 8-hour chronic health risks.

[9] Kado, N., Okamoto, R., Zuzmicky P., et al, 2005, Emissions of Toxic Pollutants from Compressed Natural Gas and Low Sulfur Diesel-Fueled Heavy-Duty Transit Buses Tested over Multiple Driving Cycles, Envrion. Sci. Technol. 2005, 39, 7638-7649.

TABLE 4-1 HEALTH INDEX CHANGE WHEN SWITCHING FROM DIESEL TO LNG

Health Hazards Index	Difference	Difference with control*
Long term (MICR)	-92%	-93%
Long term (HIC)	-48%	-92%
Short term (HIA)	427%	-74%
Short term (HIC8)	427%	-74%

*calculated difference if 95% of the HCHO is removed.

4.2 Global climate effects

While the impact of criteria and toxic pollutants are important local effects, an analysis of switching from diesel to LNG would be incomplete today without an assessment of the effects on global climate change. This analysis is made more complex as it involves both short-lived climate pollutants (SLCPs) and a long-term climate pollutant, carbon dioxide. The SLCPs are powerful climate forcers that remain in the atmosphere for a much shorter period of time than carbon dioxide (CO_2), yet their potential to warm the atmosphere can be many times greater. The SLCPs include: black carbon (BC), methane, tropospheric ozone, and hydrofluorocarbons, and contribute up to 45% of the current man-made global greenhouse effect after carbon dioxide. This project measured changes in two SLCPs (BC and methane) and the analysis calculated the impact over a 20-year and a 100-year time horizon. A 20-year time horizon was chosen to harmonize with air pollution reduction goals from CARB and other agencies for 2040 and for 2050. The 100-year time horizon is a typical timeline for considering long-term effects.

4.2.1 Black carbon

One goal of the project was to compare the black carbon (BC) emissions measured by multiple methods. Black carbon is known as a short-lived climate pollutant because it absorbs solar energy and warms the atmosphere. Over time (weeks) black carbon falls to earth due to gravity and loses its atmospheric effect. However, in areas where there is snow and ice, BC coats the snow and reduces the albedo or the reflecting power of the surface. Thus, warming the snow and increasing the rate of melting.

In this project, UCR measured BC using a thermo-optical method, the micro soot sensor (MSS), and a smoke meter (FSN). The measurements collected with these three methods had similar results. The National Research Council Canada also had multiple methods for measuring BC. When UCR and NRC used the same thermo-optical method, results were similar. The Modal and overall values for BC emission factors are provided in Table 4-2. The overall emissions factors were calculated using Equation 1 and the actual weighting factors. The BC emissions factor is reduced by 93% when switching from diesel to LNG. This significant reduction would have a high impact on areas with ice and snow, such as the Arctic circle.

TABLE 4-2 MEASURED BLACK CARBON VALUES BY DIFFERENT METHODS

PM	LNG						Diesel					
	Idle	**25**	**50**	**75**	**100**	**Overall**	**Idle**	**25**	**50**	**75**	**100**	**Overall**

PM2.5	0.126	0.009	0.007	0.014	0.005	**0.013**	2.171	0.212	0.131	0.119	0.119	**0.199**
EC	0.006	0.001	0.001	0.001	0.001	**0.001**	0.277	0.038	0.028	0.015	0.015	**0.026**
OC	0.110	0.014	0.008	0.013	0.006	**0.013**	2.361	0.151	0.099	0.085	0.085	**0.172**
MSS	0.006	0.001	0.001	0.001	0.001	**0.001**	0.296	0.041	0.027	0.016	0.016	**0.028**
FSN	/	0.002	0.001	0.001	0.001	**/**	0.338	0.045	0.031	0.019	0.019	**0.032**

4.2.2 Greenhouse gas effects

A true analysis of the greenhouse gas effects would consider a well-to-propeller energy usage as illustrated by the well-to-wheels energy cycle for automobiles in Figure 16. Such an analysis would include the energy used in the Fuel Cycle as well as the energy used to operate the vehicle/vessel. As expected, reports show that the energy used in the Fuel Cycle for diesel fuel would be much greater than it would be for natural gas. An indication of the Fuel Cycle differences is given in a Tiax report,[10] where it shows the well-to-tank Fuel Cycle is about 25% greater for diesel than remote natural gas (NG). However, we did not find a reference for the total comparative cycle for a vessel using LNG and one using diesel fuel, so this report only conducted the analysis for the vessel operation.

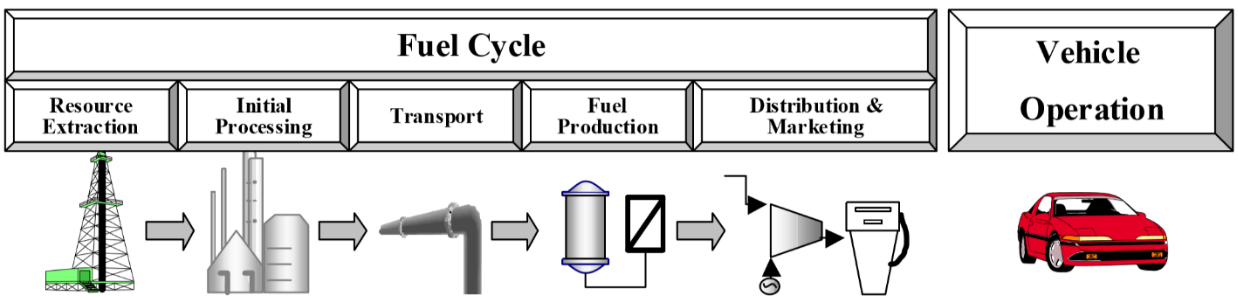


FIGURE 16 TOTAL VEHICLE WELL-TO-WHEELS ENERGY CYCLE

4.2.3 GHG fuel tank-to-propeller

Considering solely the vessel operation, the CO_2 emission factor for LNG was ~20% lower than with diesel. However, relative to CO_2, methane as a short-lived climate pollutant (SLCP) has a multiplier of ~86 using a 20-year time horizon and a multiplier of 34 using 100-year time horizon. The factor for methane decreases over time as it reacts in the atmosphere to form CO_2 and water.

[10] Tiax for the California Energy Commission, ***Full Fuel Cycle Assessment: Well-To-Wheels Energy Inputs, Emissions, And Water Impact***, CEC-600-2007-004-REV

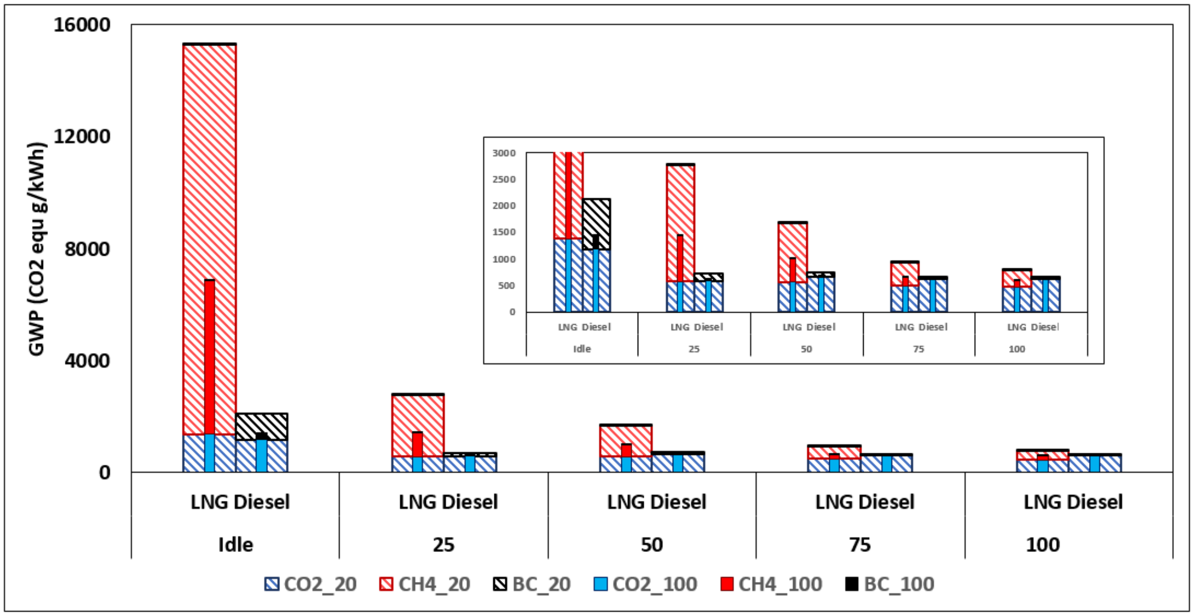


FIGURE 17 ESTIMATED GLOBAL WARMING POTENTIAL FROM LNG AND DIESEL EXHAUST

In this analysis, methane emission factors were about 10 g/kWh, a value similar to an earlier study (Li 2017). The 20-year and 100-year GWP (CO_2 equivalent g/kWh) for emissions of CO_2, CH_4 and black carbon are shown in Figure 17. In general, the major contributor of GWP from methane is at idle and GWP/kWh decreased as engine load increased. Note for >75% load, while Figure 17 shows a debt with LNG, the impact of unburned CH_4 is probably near neutral if the energy in the Fuel Cycle was considered. Black carbon effects with LNG can be ignored because of the very low BC emissions with LNG.

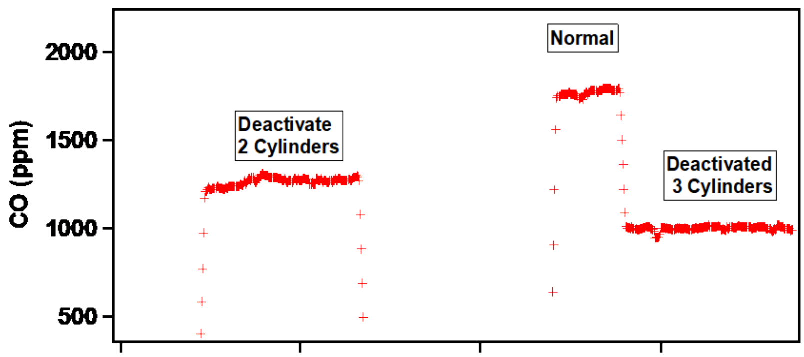
However, for diesel, black carbon accounts for ~40% of the GWP when the engine was at idle. The overall 20-year GWP (GWP20) of LNG is about 90% higher than that of diesel due to methane slip while black carbon and CO_2 emissions were reduced. This difference nearly disappears when the analysis extends to 100 years. In the end, the global climate analysis depends strongly on the time horizon.

In another analysis, Shine's (2005) methodology estimates the potential in global surface temperature change (GTP) when switching from diesel to LNG. This approach reaches the same conclusion: the increase in methane emissions overpowers the benefits of reduced CO_2 emissions.

4.2.4 Mitigation strategies

During the project, the engine manufacturer discussed approaches to reduce methane emissions, especially as the engines idle during loading/unloading containers. Wherever possible, the easiest mitigation strategy is to use shore power and shut off the engines. Using this mitigation strategy, the full benefits of the 20% CO_2 reduction can be realized and the idle portion of the methane debt is removed from the overall calculations. In addition, any health risk associated with the potential for exposure to the highest concentration of HCHO would be mitigated. The shore power mitigation strategy appears to provide a number of benefits and today is being used whenever possible.

Another approach to methane mitigation when shore power is not available is called cylinder deactivation. The engine manufacturer, Wärtsilä, used an algorithm that determined which of the nine cylinders would not fire during that cycle and reprogramed the Engine Control Module (ECM). A previous study shows deactivating engine cylinders at low engine loads (<15%) increased combustion efficiency and reduced methane emissions by 56%-60%. Similarly, the concentration of CO, another incomplete combustion product, is reduced by 30% and 44% respectively when two and three cylinders are deactivated, as shown in Figure 18. While no HCHO measurements were collected during cylinder deactivation, it is reasonable to estimate that HCHO is also reduced by a similar percentage due to the high correlation between HCHO, CH_4 and CO. By deactivating three cylinders, the overall emission factors of CH_4, CO, and HCHO from using LNG drop to 7.97, 2.91, and 0.14g /kWh respectively.



An overall perspective of the three mitigation approaches can be seen in Figure 19. Even with the use of shore power, the high methane emissions at other loads leads to an increase in GWP when figuring the impact in a 20-year time frame. Over a 100-year time frame the two fuels are about equal. However, one should expect over that time frame that the engine design and combustion processes will reduce the methane levels measured in the exhaust of the current technology.

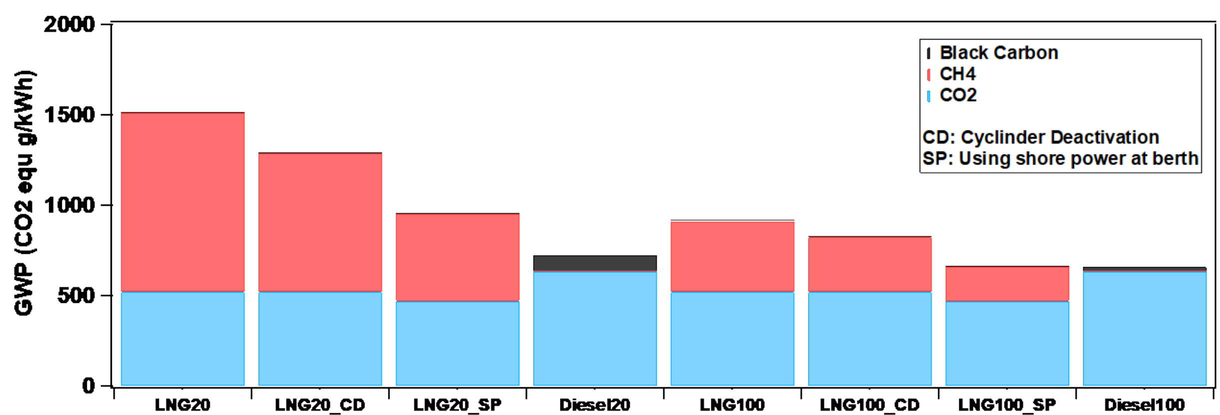


FIGURE 19 GREENHOUSE WARMING POTENTIAL FOR A NUMBER OF CASES WITH MITIGATION MEASURES

5 Summary

The project met all of its goals:

- Charaterized both the local and global effects of changing from diesel to LNG fuels on a modern marine vessel.
- Measured flow rates and the concentration of criteria pollutants (NOx, CO, THC, and $PM_{2.5}$) for LNG at multiple loads.
- Measured flow rates and the concentration of criteria pollutants (NOx, CO, THC, and $PM_{2.5}$) for diesel at multiple loads.
- Measured the toxics (carbonyls) that are emitted from the vessel for both LNG and diesel fuels and carried out a risk assessment.
- Measured the real-time/actual fraction of time that a vessel operates at each load.
- Measured and compared black carbon by three methods: Micro soot sensor, Smoke meter, and elemental carbon for both LNG and diesel.
- Carried out a partial climate analysis for only the operation of the vessel, including the impact of changes to the longer term CO_2 and the short-lived climate pollutants, black carbon and methane. The well-to-tank analysis was left for further study.

5.1 Key Findings

The overall emission factors for both LNG and diesel fuels were below the certification levels. A notable 93% reduction in PM and 92% in NOx was observed after switching from diesel to LNG. For LNG, the NOx emission factor calculated for the ISO E-2 standard cycle was 0.63 g/kWhr, which is 96.8% below the ~20g/kWhr that vessels have produced in the past decade. This provides a possible mitigation strategy for communities, like Los Angeles, where the high NOx levels drive ozone levels above the federal standards.

These results suggest that switching to LNG from diesel is an effective option for an air basin to significantly reduce both NOx and PM. However, the potential health risk and global warming impact associated with elevated CO and HCHO emissions from LNG fuel suggest there is room for improvement for LNG being used in marine applications.

Calculated emission factors based on the time a vessel actually spends at each load showed the overall emission factors for ISO E-2 cycle and the real-world were quite similar, although the fractions of time at each load were significantly different.

Having modal emissions and activity data enables the calculation of revised overall emission factors for optional mitigation methods. One mitigation method is the use of shore power while idling. This approach provides the greatest emission reduction potential since HCHO, CO, NO_x, PM and CH_4 are all reduced when engines are shut off. Calculated overall emission factors with shore power show a 40-50% reduction of CO, HCHO and CH_4, and further reduction on NOx, CO_2 and $PM_{2.5}$. While NOx and PM are reduced, the emissions of methane, CO and HCHO increase.

For areas where shore power is not an option, another mitigation method is cylinder deactivation while idling. This approach was tested during the project and it reduced CO emissions by about 40%. From our correlations, we know HCHO and methane levels were likely reduced by similar levels. Based on this limited data, we estimate a revised methane emissions factor of 8.9 g/kWh.

A third mitigation option is the installation of a diesel oxidation catalyst to remove about 95% of the CO and HCHO. The catalyst approach is widely used for city transportation busses. It does not reduce the methane levels.

5.2 Future work

Further evaluation is necessary to confirm the benefits of the mitigation methods to limit methane emissions, including the ECM-fix called skip-firing; and/or the use of shore power. Both could significantly reduce the methane emissions and the climate warming potential of methane. Given the increases seen in THC, CH_4, and partial oxidation products in this analysis, a dedicated natural gas engine configured to run on LNG could be developed, instead of a diesel engine conversion.

HCHO is a concern. It would be useful to measure the levels of HCHO that is reaching the ground or breathing zones of staff onboard the vessel. It would be useful to discuss the addition of an oxidation catalyst to remove 95% of the HCHO, as was done on buses, and decide whether a business case can be made for this option.

Appendix 1 Health Risk Calculations

A health risk assessment for the release of PM and Formaldehyde (HCHO) from using LNG and diesel fuel was conducted according to the guidelines of the state Office of Environmental Health Hazard Assessment (OEHHA) of California and South Coast Air Quality Management District (SCAQMD)[4,5]. Specifically, the differences of maximum individual cancer risk (MICR), chronic hazard index (HIC), 8-hour chronic hazard index (HIC8), and acute hazard index (HIA), when switching from diesel fuel to LNG, were calculated using the following equations.

$$MICR = Cancer\ Potency\ (CP) \times Concentration\ \times Exposure \times\ 10^{-6}$$
$$Concentration = GCL = (Q_{tpy} \times {}^{\chi}/_{Q}) \times MWAF$$
$$Exposure = CEF \times MP \times WAF$$
$$MICR = CP \times (Q_{tpy} \times {}^{\chi}/_{Q}) \times MWAF \times CEF \times MP \times WAF \times\ 10^{-6}$$

Where:

GLC: ground level concentration (ug/m^3)
Q_{tpy}: Emission rate (tons/yr)
${}^{\chi}/_{Q}$: Concentration at a receptor distance/Emission rate [(ug/m^3)/(tons/yr)]
MWAF: Molecular Weight Adjustment Factor
CEF: Combined Exposure Factor
MP: Multi-pathway Factor
WAF: Adjustment Factor

$$\begin{aligned} Total\ HIC_{target\ organ} &= \{[Q_{tpy} \times ({}^{\chi}/_{Q}) \times MP_{TAC1} \times MWAF]/Chronic\ REL_{TAC1}\}_{target\ organ} \\ &+ \{[Q_{tpy} \times ({}^{\chi}/_{Q}) \times MP_{TAC2} \times MWAF]/Chronic\ REL_{TAC2}\}_{target\ organ} + \cdots \end{aligned}$$

$$\begin{aligned} Total\ HIC8_{target\ organ} &= \{[Q_{tpy} \times ({}^{\chi}/_{Q}) \times WAF \times MWAF]/8 - Hour\ REL_{TAC1}\}_{target\ organ} \\ &+ \{[Q_{tpy} \times ({}^{\chi}/_{Q}) \times WAF \times MWAF]/8 - Hour\ REL_{TAC2}\}_{target\ organ} + \cdots \end{aligned}$$

$$\begin{aligned} Total\ HIA_{target\ organ} &= \{[Q_{tpy} \times ({}^{\chi}/_{Q}) \times MWAF]/Acute\ REL_{TAC1}\}_{target\ organ} \\ &+ \{[Q_{tpy} \times ({}^{\chi}/_{Q}) \times MWAF]/Acute\ REL_{TAC2}\}_{target\ organ} + \cdots \end{aligned}$$

Where:

REL: Reference Exposure Level (ug/m^3)

Assuming ${}^{\chi}/_{Q}$, $MWAF$, CEF and WAF are same for both diesel and LNG, these factors would be cancelled out when calculating the difference of MICR, HIC, HIC8 and HIA for these two cases.