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

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Disclaimer

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Executive Summary

Background

Environmental regulations are directing cleaner fuels and lower emissions from all maritime operations and natural gas is a fuel that enables mariners to meet all regulations. However, data with natural gas in maritime operations are quite limited. This project provided an opportunity to directly compare the emissions for a modern dual-fuel marine engine running either on natural gas as liquefied natural gas (LNG) or on 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 emissions as well as black carbon and methane as these would enhance climate change. Additionally, UCR generated the actual activity profiles for this vessel operating within the Strait of Georgia to allow the calculation of 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 the LNG and diesel fuels were below the certification levels. Especially notable was the reduction of 93% in PM and 92% in NOx by switching from diesel to LNG. For LNG, the NOx emission factor was 0.63 g/kWhr (E2 cycle), a value that offers a mitigation strategy for port communities where high NOx levels drive ozone values above the federal standards. The health hazard for particulate matter outweighed formaldehyde toxicity over the longer term and the stacking of the hot exhaust on the vessel negated short term exposure. An analysis of global warming potential (GWP) impacts is complex, especially if energy usage for both the Fuel Cycle and the Vessel Operation are analyzed. This report considered energy usage solely for vessel operation. For snow and ice areas, the reduction of 97% BC will slow ice melting. However, when considering energy in the vessel operation, the unburned methane dominates the GWP for both short and long terms.

Implications

LNG offers significant benefits within local communities by reducing criteria pollutants and improving health outlook. However, global impacts are dominated by releases of the short-lived climate pollutant, methane. Several mitigation approaches showed promise to offset some of the debit and require further investigation. Other dual-fuel engines should be tested to see if results are similar.

Emissions from the Latest LNG Engine Technology

1 Project Scope

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) was limited to 0.1 weight percent instead of the nominal 3.5 weight percent. Vessel owners are offered the alternative of installing an exhaust gas scrubber to control exhaust sulfur oxides as if the burned fuel containing 0.1 weight percent sulfur. The scope of this regulation is important considering that all the coastline of the United States and Canada was classified as an ECA area.

One approach to meeting the low sulfur fuel 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 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 project was to measure real-world criteria and toxic emissions from the same engine when burning either LNG or diesel fuels at the load points specified for certification testing. These emission measurements would provide the first independent comparison using the same fuels.

Approach

A team approach was used for the project with UCR partnering with the National Research Council of Canada (NRC), the University of British Columbia (UBC) and a vessel owner. The new LNG engine that was powering the ship 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 we 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 so 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; includes 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 focuses on the results of UCR's emission measurements.

2 Results from the testing phase (Task 2)

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

2.1 Test platform: vessel and propulsion system

The test vessel was a steel mono-hull, roll-on/roll-off (RO/RO) cargo ship built in 2017 that was designed to reduce emissions of criteria pollutants and greenhouse gases. Selected specifications for the vessel: 6,750 dwt., draft of 7m, length of 148.9m, width of 26m and capacity of 59 -53foot trailers.

The vessel was the first LNG-battery hybrid cargo ferry vessel operating in North America. It was powered by two Wärtsilä 34DF dual-fuel engines and a 1,050V, 546kWh 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 heart of the main propulsion system was twin 9L34DF LNG-diesel dual fuel engines by Wärtsilä coupled to constant-speed generators with Wärtsilä LNG Pac fuel systems. The Wärtsilä 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, engine was number PAAE-2740430, made 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

Note with displacement of >30 liters/cylinder that EPA[1] identifies this marine engine as Category 3 and 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 720RPM, the Tier 2 standard is 9.69 g/kWhr and the Tier 3 standard is 2.42 g/kWhr.

2.2 Test Conditions: Operating loads

Emissions were measured while the vessel operated as closely as possible to the four certification loads specified in the ISO 8178-E2 cycle used for Heavy-Duty, Constant-Speed Engines for Ship Propulsion. Measuring at the certification loads allowed us to calculate the modal and overall emission factors as a check on how this engine compared with published certification values.

[1] CFR Title 40 Part1042—Control of emissions from new and in-use marine compression-ignition engines and vessels; Table 1 to §1042.1

Some deviation from the E-2 cycle values was expected as the vessel was in revenue service and needed to maintain the published arrival and departure schedules. Aside from sea trials, engines rarely operate at 100% as was the case for this project where the top load was 90%. In addition to measurements at the four E2 modes, tests were carried out at idle since the vessel spent considerable time there. Repeat measurements at the same loads were carried out 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	

2.3 Test Conditions: Fuels

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

TABLE 2-3 COMPOSITION AND SELECTED PROPERTIES OF THE LNG

Component		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
	BTU	1093

2.4 Building the line to sample emissions

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

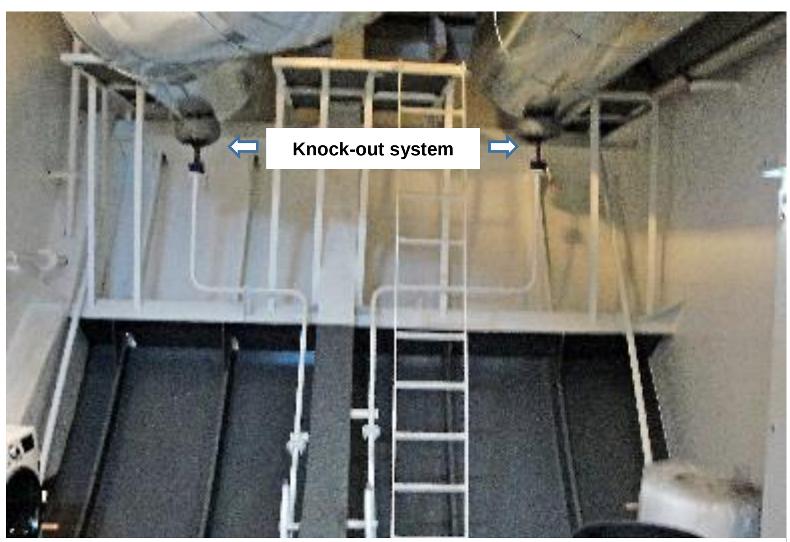

FIGURE 1 VIEW OF PROPOSED SAMPLE PORTS

Before arriving at the test site, the partner members from the University of British Columbia worked with the vessel operators to remove the valve from the knock-out system and added a blank flange with four holes drilled for connecting the planned sampling lines. Thus on the first day, we needed to build a transfer line from the exhaust to the dilution tunnel. An important part of the test design was for everyone to use the same dilution tunnel so there would not be any questions about dilution ratio when it came to comparing results.

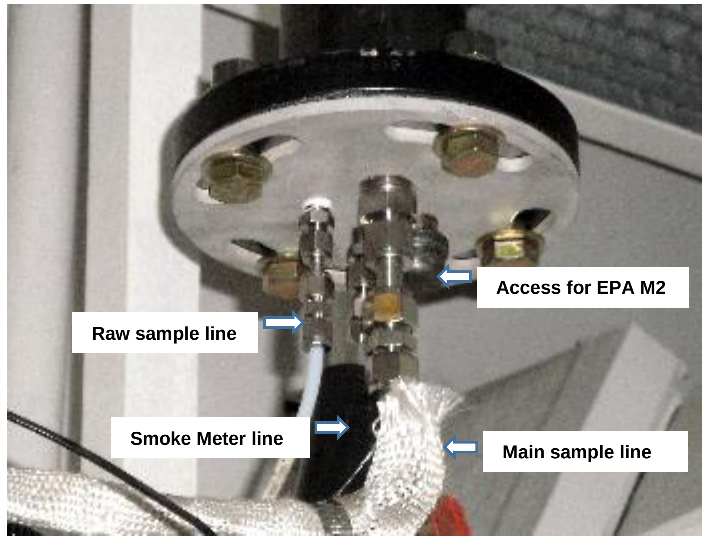

FIGURE 2 MULTIPLE SAMPLE PORT ACCESS DESIGN

One consequence of the sampling port being so far from the measurement instruments was that we needed to build a very long transfer line from the sample port to the dilution tunnel. Several features were designed into the transfer line. First a large inside diameter was selected for the transfer line to minimize pressure drop; second, the transfer line was heated to 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.

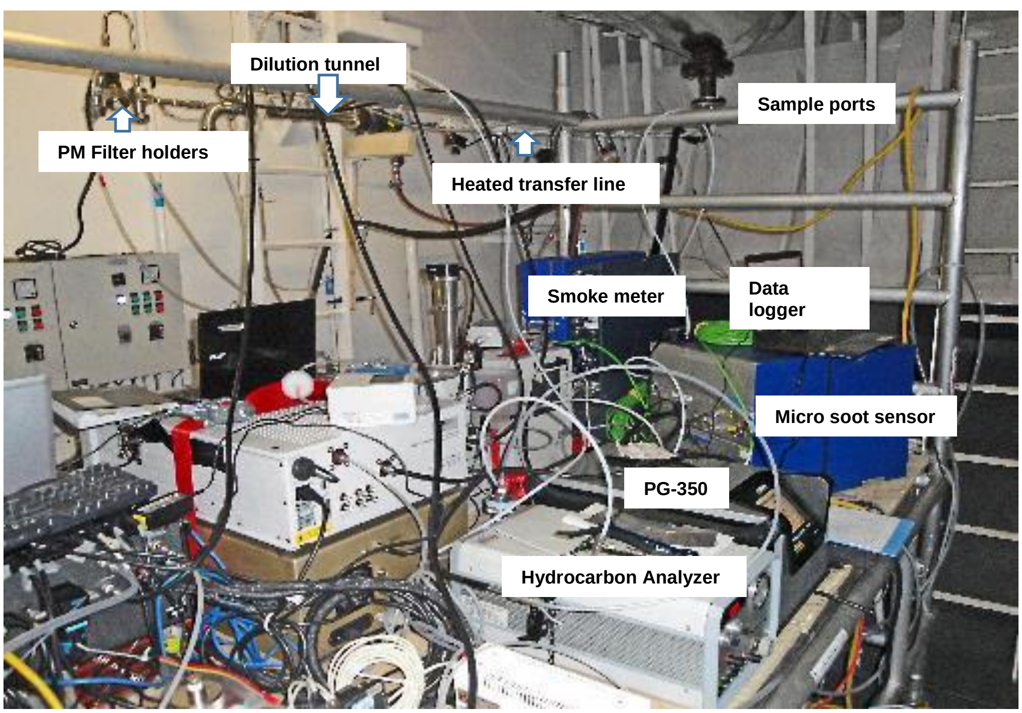

FIGURE 3 LAYOUT OF THE DILUTION TUNNEL SYSTEM AND THE ANALYTICAL INSTRUMENTS

As seen in Figure 3, we assembled staging and laid a thick plywood section across the supporting members of the staging to hold the sensitive instruments. All instruments were securely fastened to the plywood in case of rough seas. Note the platform supported specialized equipment from both UCR and NRC. With equipment installed and operating properly, the priority shifted to measurement of the real-world exhaust emissions while the vessel burned either LNG or diesel fuel.

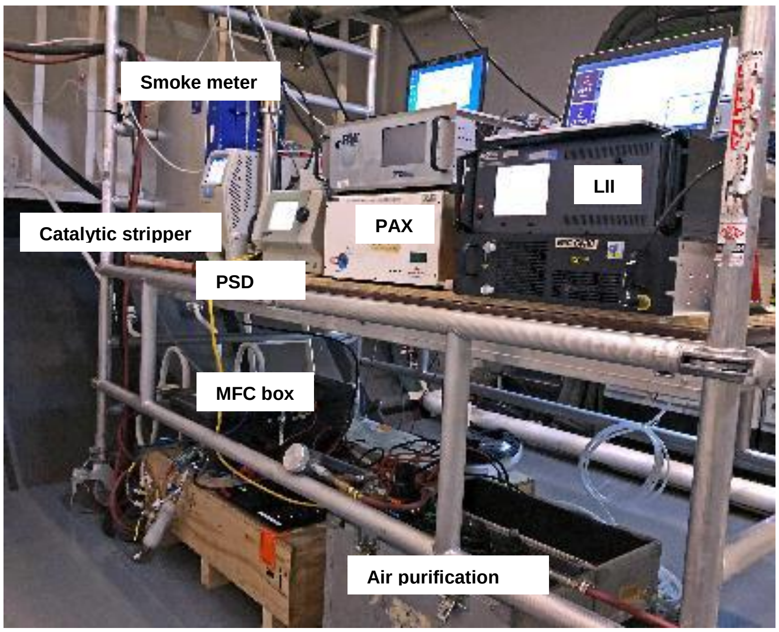

FIGURE 4 OPPOSITE VIEW OF STAGING AND INSTALLED EQUIPMENT

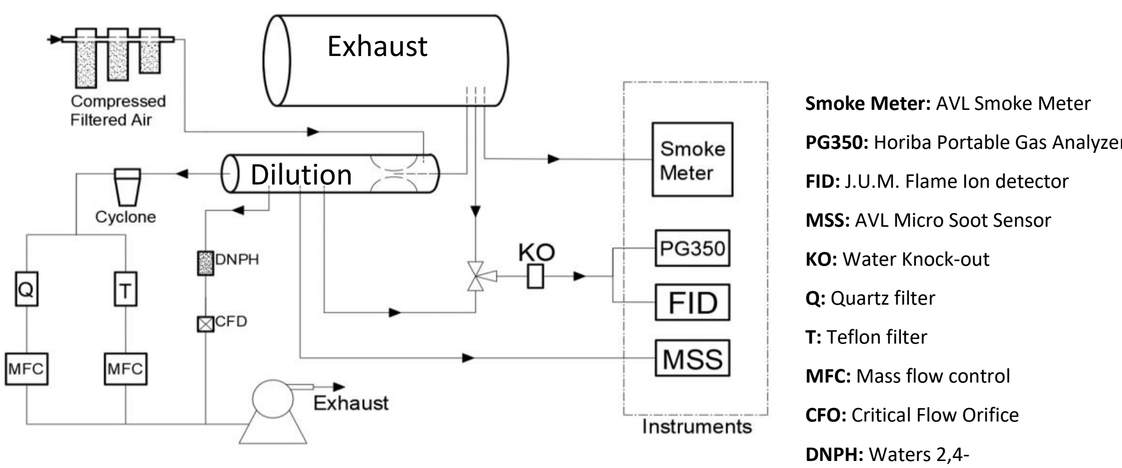

FIGURE 5 SCHEMATIC SHOWING LAYOUT OF UCR EQUIPMENT

2.5 Measuring exhaust flow rate with LNG and diesel fuels

Because concentrations are measured in the exhaust, it is essential to measure accurately the mass flow rate of the exhaust in order to calculate emissions rates and emission factors based on mass. Although there are four accepted methods for measuring flow rate only EPA Method-2 made sense 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. Results show a good agreement with the published values.

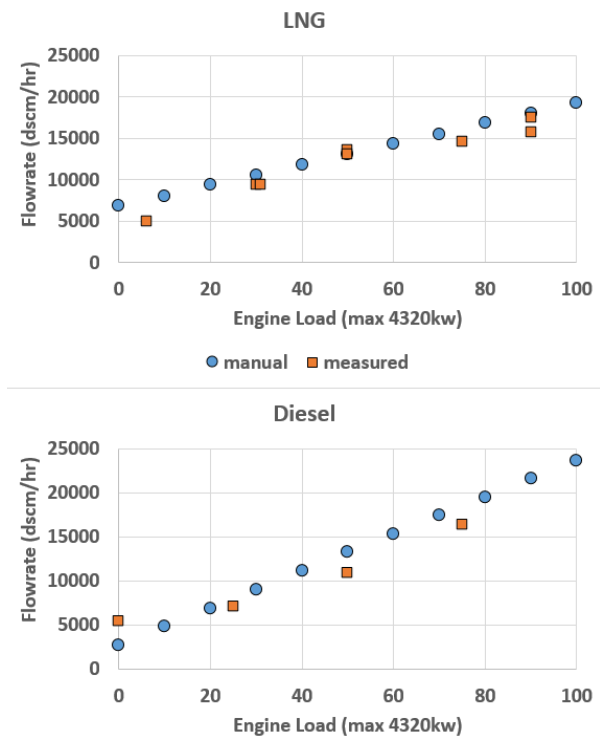

FIGURE 6 FLOW EXHAUST RATE IN DRY STANDARD CUBIC METER PER HOUR

2.6 Modal Emissions of gaseous compounds with LNG and diesel fuels

UCR measured the gaseous emissions of CO, NOx, CO_2, CH_4, total hydrocarbons and carbonyls 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, 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 carried out using an EPA protocol gas for NOx, CO_2 and CO for the span values. For the JUM FID, we used UBC's methane protocol gas to calibrate the FID data for methane so the output of the instruments could be directly compared. The carbonyl compounds, especially formaldehyde, were measured using EPA Method TO-11a. 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 formaldehyde on the DNPH coated cartridges was estimated using Dräger tubes and was minutes for LNG exhaust at idle as compared with tens of minutes for diesel exhaust.

2.6.1 Emissions data for carbon dioxide (CO_2) and nitric oxides (NOx)

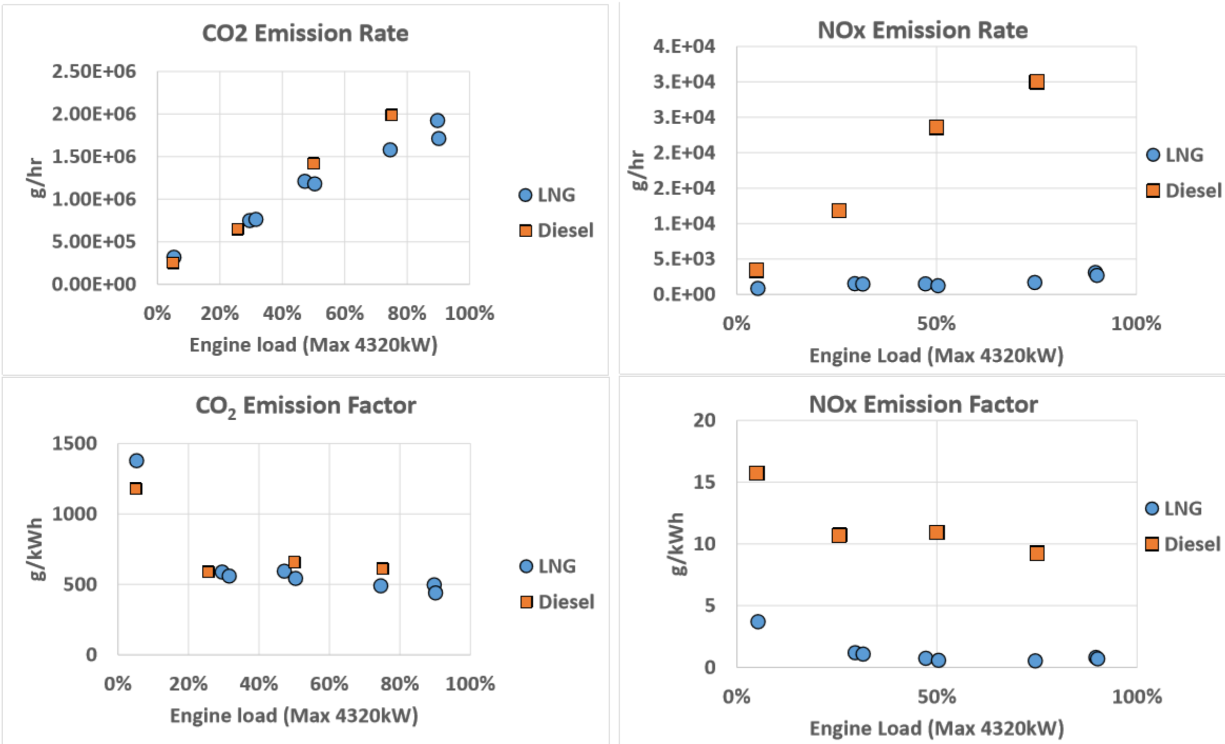

FIGURE 7 MODAL EMISSION RATES & FACTORS FOR CO_2 & NO_x

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. Note the emission factor at ~5% load was nearly 30 times higher as the engine operates with much lower efficiently at low loads. On balance, the CO_2 emission factors for LNG were lower than diesel since the hydrogen to carbon mole ratio is twice 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%. When idling, the emission factor of NOx was about 4g/kwh for LNG, ~ 80% less than with diesel fuel. These results were expected as the dual-fuel engine was certificated for NOx as Tier 3 with LNG and Tier 2 with diesel fuel. However, surprisingly NOx emission factors did not change significantly when engine load was > 25%.

2.6.2 Emissions data for total hydrocarbons (THC) and methane (CH_4)

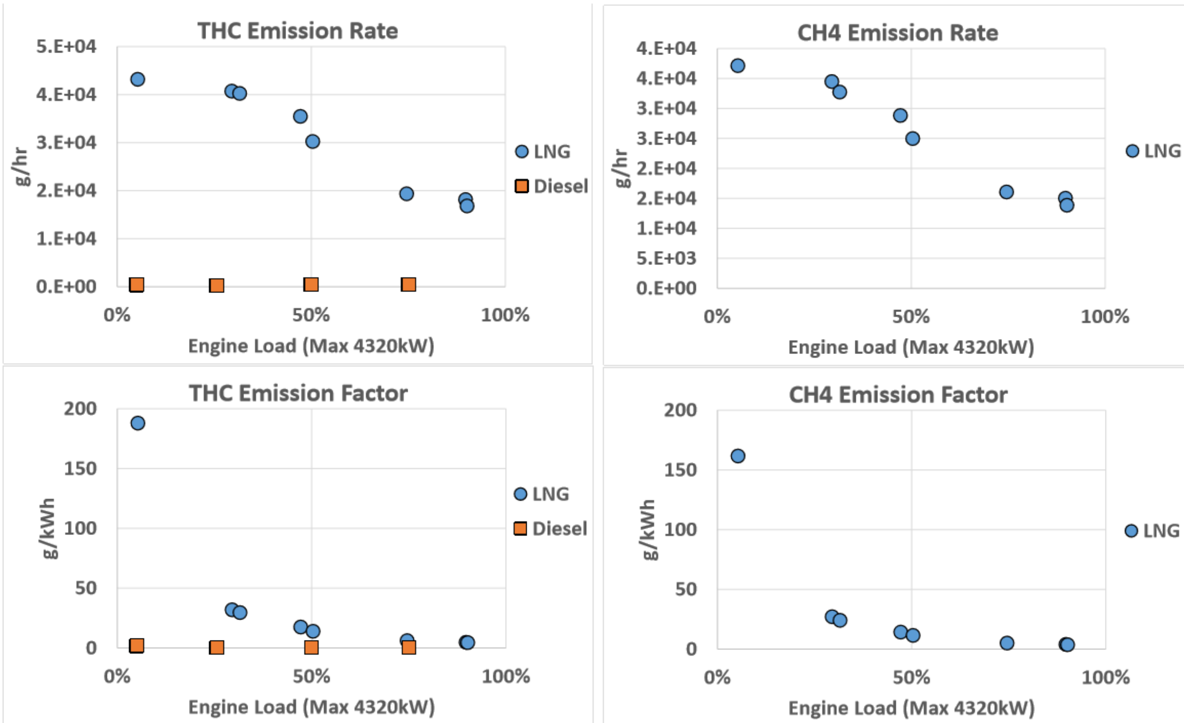

FIGURE 8 MODAL EMISSION RATES & FACTORS FOR THC & CH4

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 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. For example, an on-road IC engine running on diesel has a fuel conversion efficiency >40% while the same engine using LNG at the same loads has an efficiency of ~35%. The main reason is that most engines running 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. As is clear from the above figures, 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 this instrument were within 10% of the values measured by the team from the University of British Columbia and who used a tunable diode laser to continuously measure emissions of methane.

2.6.3 Emissions from carbon monoxide and formaldehyde

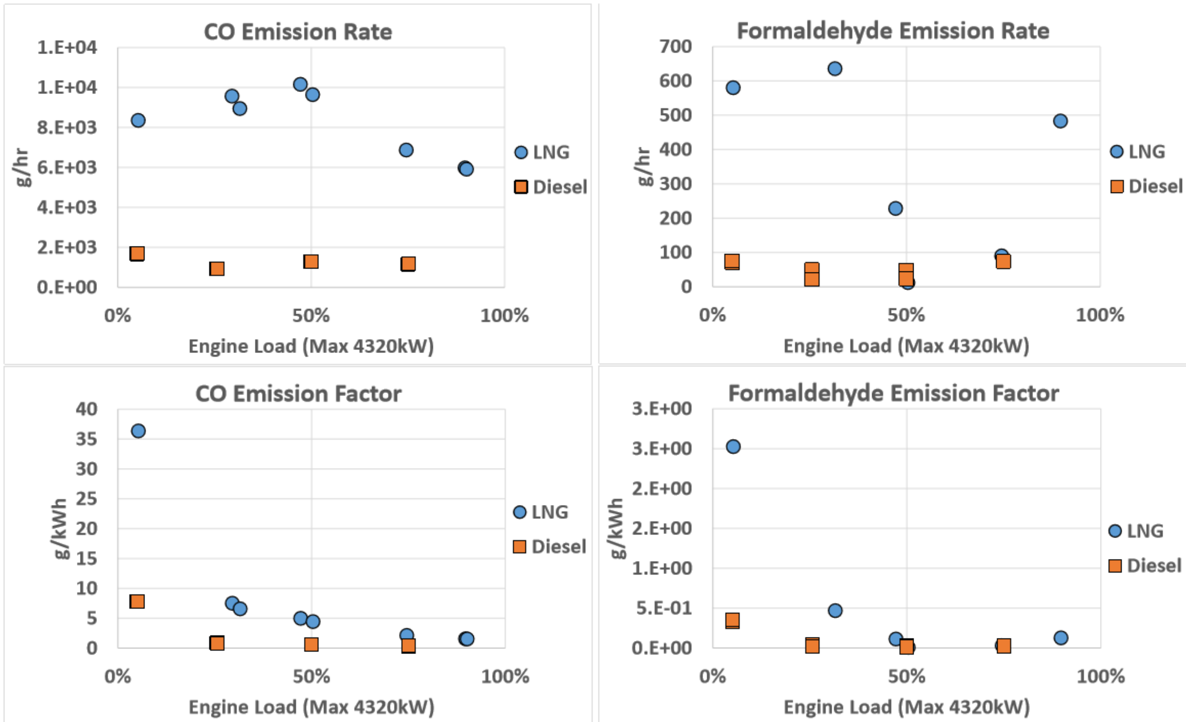

FIGURE 9 MODAL EMISSION RATES & FACTORS FOR CO & FORMALDEHYDE

Toxic gases: Carbon Monoxide and Formaldehyde…The lower fuel conversion efficiency for LNG leads to increased emissions of the partial oxidation products: carbon monoxide (CO) and formaldehyde (FA); a problem that is exacerbated at idle and where this analysis focused. Observations of higher levels of CO and FA using LNG versus diesel in this project are consistent with earlier results for on-road applications.

For all work places, OSHA established the 8-hour maximum permissible exposure level (PEL) for CO as 50 ppm[2]. 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 (roll-on; roll-off operations during cargo loading and unloading) is 200 ppm. We measured CO concentrations at idle as ~1,300ppm for LNG and 250ppm; well above the PEL. However, unlike buses where exhaust is at ground level and in the breathing zone of people, the hot, high-velocity exhaust gas plume from the ship stack go high into the atmosphere and is expected to be greatly diluted before it reaches the ground.

Measurement of carbonyls, especially formaldehyde (FA), was also of interest given that FA is a carcinogen and has multiple harmful effects on workers[3]. To protect workers, the Occupational Safety and Health Administration (OSHA) lists 0.75ppmv as the PEL over 8-hours and 2ppmv for

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

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

15-minute. In this work, formaldehyde concentrations with LNG at idle were ~100ppmv. However, as explained for the CO, the FA gases go high into the atmosphere, are short-lived and unlikely to reach the breathing zones near the vessel surface.

As both CO and formaldehyde result from incomplete combustion of carbon sources, there is usually a linear correlation between the emissions of CO and FA. The limited data collected in this campaign 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 FA.

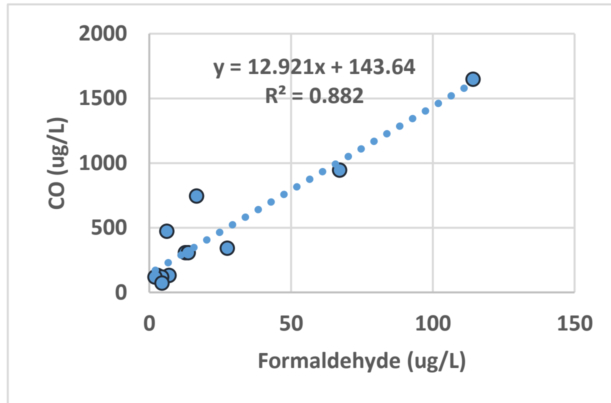

FIGURE 10 CORRELATION OF CO & FORMALDEHYDE

2.7 Emissions of PM with LNG and diesel fuels

A portion of the diluted exhaust flowed through pre-weighted Teflon and pre-conditioned quartz filters to enable particulate matter (PM) to be captured on the filers. The weight on the Teflon filter determined the PM mass and the material on the quartz filter was analyzed following the NIOSH 5040 Method to determine the elemental and organic carbon contents.

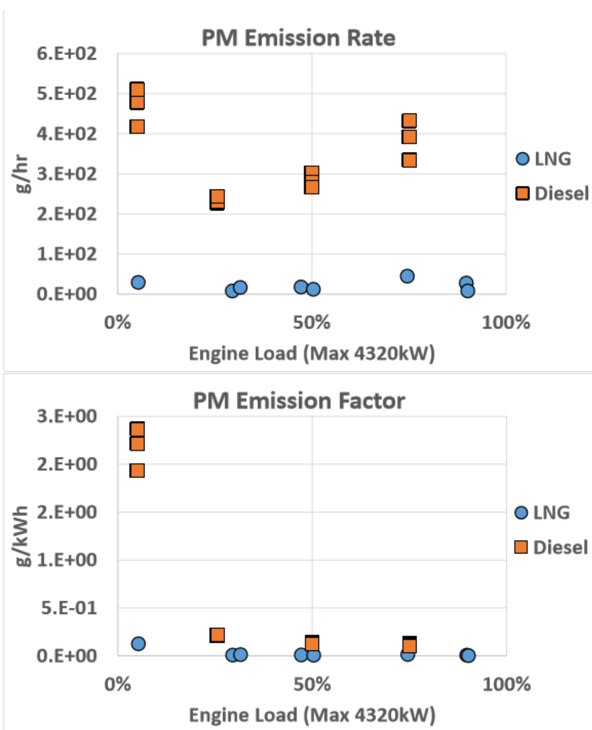

FIGURE 11 MODAL RATES AND FACTORS FOR PM MASS FOR LNG & DIESEL

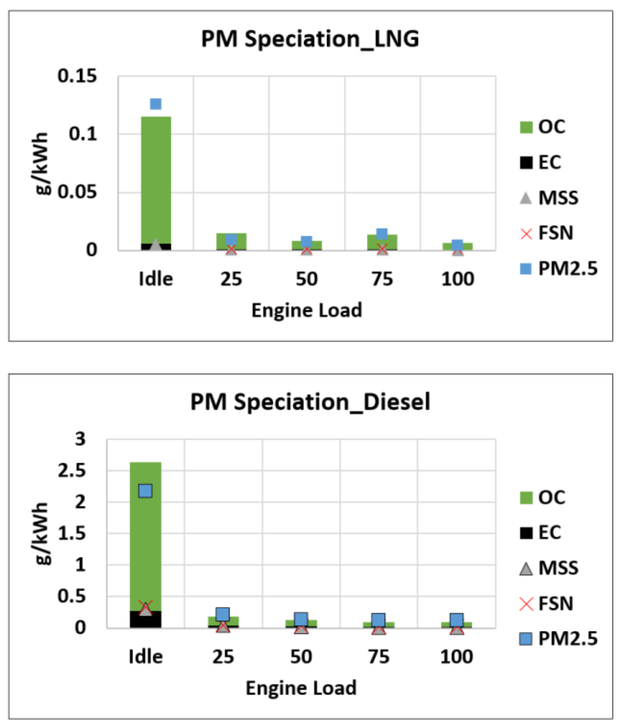

FIGURE 12 MODAL RATES AND FACTORS FOR PM FRACTIONS FOR LNG & DIESEL

As expected, PM mass emissions are ~100x lower with LNG as compared to diesel fuel. Speciation of PM mass shows that most (>80%) of the mass is organic for both the LNG and the diesel fuels, probably as the engine and its cylinder walls were designed to be "dry" in order to meet the PM standard. Multiple repeats were carried out with the LNG fuel but only a single day was available for the diesel data so data were sparse. However, the data are in good agreement with the expected values for a modern engine using diesel fuel.

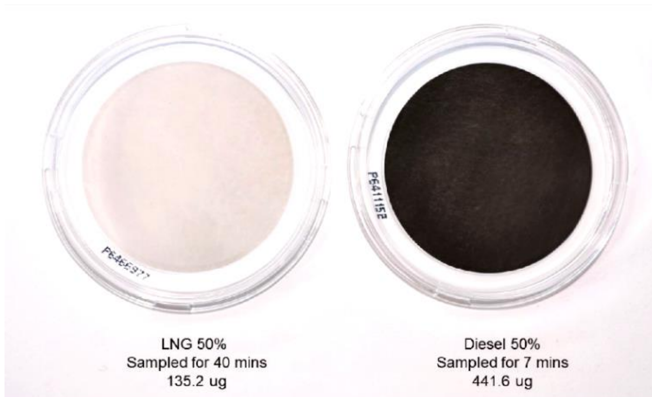

FIGURE 13 COMPARATIVE VISUAL OF FILTERS WITH LNG AND DIESEL

2.8 Analysis of real-world activity

In order to figure accurately 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. Most analyses assume the weighting factors are the same as in the standard since the standard was developed from real world data. However, a concern when applying the weighting factors in the standard ISO 8178-E2 Cycle is that 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 fraction of time that this harbor vessel actually operates at various loads in the real world operation and used those percentages or weighting factors when calculating the contribution of emissions to this air basin. Table 2-4 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 should be used in the determination of the criteria and toxic emissions released into this air basin by this vessel.

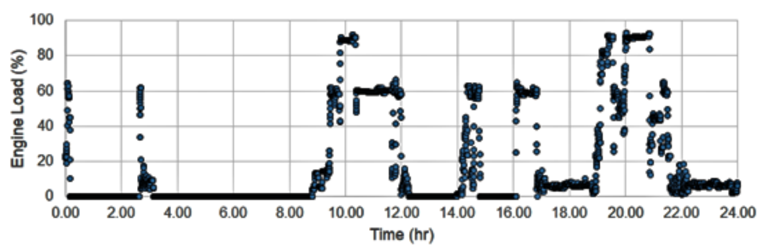

FIGURE 14 SELECTED SCADA OUTPUT FOR ONE DAY

TABLE 2-4 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

2.9 Calculation of overall emissions factors with LNG and diesel fuels

The emission factor at each mode is 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 is 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.

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 2-4. Values of the overall emission factors for both sets of weighting factors are shown in Table 2-5 and Figure 15 below.

TABLE 2-5 CONSOLIDATED TABLE OF THE OVERALL EMISSION FACTORS

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 Ship 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

Note there are two approaches to calculate the overall weighted emissions factor. One apporach is to apply the equation to the data as collected as they were 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. The table shows values calcualted using the actual data. If we had estimated the values at the exact ISO loads, the CO_2 value for LNG would be 405g/kWhr and for diesel 619g/kWhr or values within the confidence of the data.

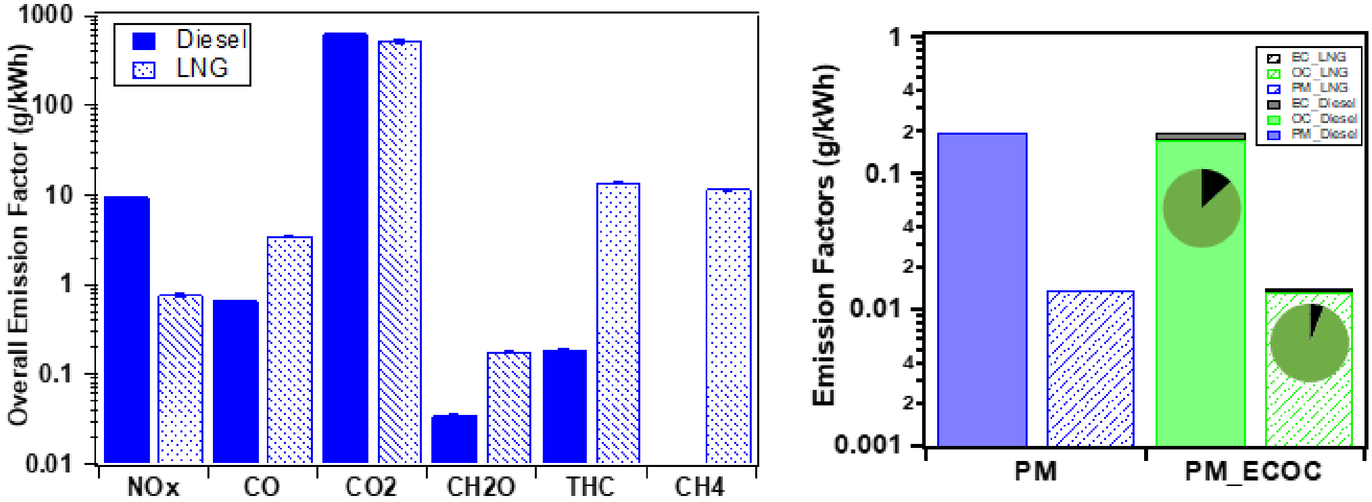

FIGURE 15 OVERALL EMISSION FACTORS FROM A DUAL-FUEL ENGINE

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

Comparing the results with the weighting factors determined in actual or real-world service, we find basically the same 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.

2.10 LNG vs. diesel; a local health risk assessment

While NOx and PM are reduced, the emissions of methane, CO and formaldehyde increase. $PM_{2.5}$ is suspected carcinogen by IRAC and both CO and formaldehyde are toxic gases with concentrations above the PEL levels when the engine idles so an analysis of the health risk assessment was carried out. Methane is a short-lived climate pollutant (SLCP) and part of a separate analysis.

A worst-case analysis of the health risk assessment was undertaken by evaluating the impacts of the primary toxic air pollutants at idle; as if the emissions were 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 carried out for LNG versus diesel is where PM is significantly reduced and formaldehyde is significantly increased.

Using the established models in Appendix 1, we estimated the difference of cancer and non-cancer as well as chronic and acute health impacts from PM and formaldehyde emissions from LNG and diesel. For LNG, the 92% reduction in PM proportionally reduces the maximum individual cancer risk (MICR) showing the PM risk far outweighs the FA 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 on PM and formaldehyde emissions on 8 major organ systems. According to the California Office of Environmental Health Hazard Assessment (OEEHA), formaldehyde has acute effects on eyes and both PM and formaldehyde have chronic effects on respiratory systems. As shown in Table 2-7, LNG reduced HIC by 48%, indicating that longer-term health risk from LNG is far less than diesel exhaust even though more formaldehyde was observed in LNG emissions.

However, shorter-term hazard risks including HIA and HIC8 both increased by about 427% due to higher formaldehyde emission which raises concern of health risks to residents and workers who are directly exposed to these ship emissions. As discussed earlier, the hot exhaust emissions are emitted from a tall stack directly into the air, reactive in sunlight and are greatly reduced before reaching the breathing zones. Further the issue of increased FA emissions was addressed with the large-scale introduction of LNG/CNG buses. Research and actual in-use data showed that a simple oxidation catalyst removed 95% of the formaldehyde from the exhaust of LNG/CNG buses (Alaya, 2003). Assuming 95% removal of formaldehyde, the health risk was re-calculated with the hazard indexes shown in Table 2-6. 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.

TABLE 2-6 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 formaldehyde is removed.

2.11 Global climate effects of switching from Diesel to LNG

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 picked since CARB and other agencies have goals for 2040 and for 2050. The 100-year time horizon is traditionally considered.

2.11.1 Emissions of black carbon

One goal of the project was to compare the black carbon (BC) emissions measured by various 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 losses 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 for a much longer time.

In this project, UCR measured BC using a thermo-optical method, the micro soot sensor (MSS) and a smoke meter (FSN). Notice the UCR measurements based on the three methods had similar values. The National Research Council Canada 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 2-7. 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. Such a significant difference would have momentous consequences on an area of ice and snow, like the Arctic circle.

TABLE 2-7 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**

2.11.2 Analysis of overall greenhouse gas effects

A true analysis of the greenhouse gas effects would consider a well-to-propeller energy usage such as commonly illustrated for automobiles in Figure 16. Such an analyses 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 reported by a Tiax report[4] wherein it shows the well-to-tank (Fuel Cycle) is about 25% greater for diesel as compared with remote NG. However, we did not find a reference for the total comparative cycle for a vessel using LNG and one using diesel fuel so in this report only carry out the analysis for the vessel operation.

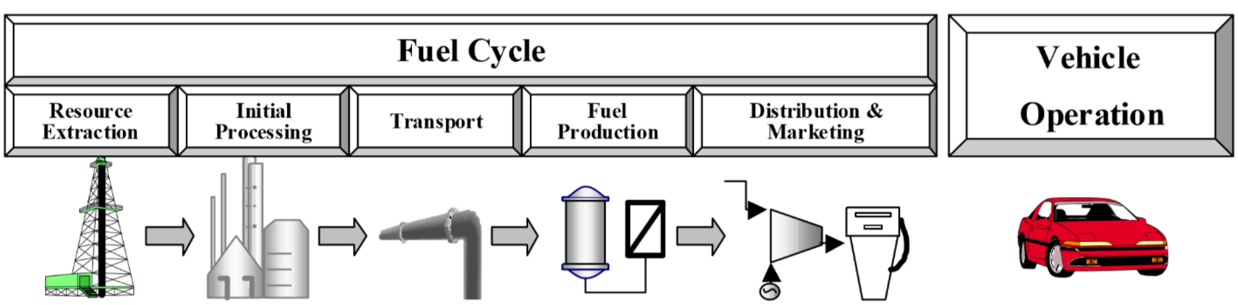

FIGURE 16 TOTAL VEHICLE WELL-TO-WHEELS ENERGY CYCLE

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

2.11.3 Analysis of greenhouse gas effects for fuel tank-to-propeller (vessel operation)

Considering solely the vessel operation, the CO_2 emission factor for LNG was ~20% lower than with diesel providing a long-term greenhouse gas benefit. However, relative to carbon dioxide, methane being 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.

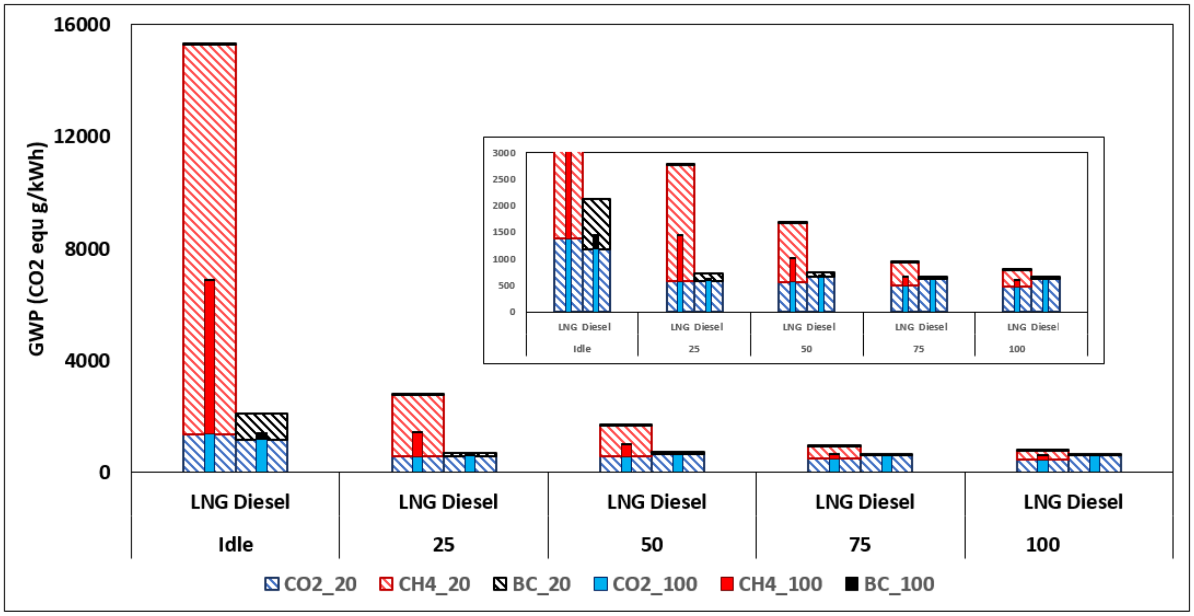

FIGURE 17 ESTIMATED GLOBAL WARMING POTENTIAL FROM LNG AND DIESEL EXHAUST

In this project, methane emission factors were about 10g/kWh, a value similar to an earlier study (Li 2017). The 20-year and 100-year GWP per CO_2 equivalent as g/kWh for emissions of CO_2, CH_4 and black carbon are shown in Figure 17. In general, the major fraction of GWP from methane is at idle and GWP 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 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 emission was 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 enables someone to estimate the potential in global surface temperature change (GTP) when switching from diesel to LNG. This approach reaches the same conclusion; namely, the increase in methane emissions overpowers the benefits of reduced CO_2 emissions.

2.11.4 Mitigation strategies for the LNG case

During the project, a number of discussions ensued with the engine manufacturer about 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. Then the full benefits of the 20% CO_2 reduction can be realized and the idle portion of the methane debit is removed from the overall calculations. In addition, any health risk associated with the potential for exposure to the highest concentration of formaldehyde would be mitigated. The simple shore power solution appears to provide a number of benefits and today is being used where possible.

Another approach to methane mitigation when shore power is not available and is called cylinder deactivation. Basically, the engine manufacturer ,Wärtsilä, used an algorithm that determined which of the nine cylinders would not fire during that cycle and reprogramed the ECM. 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 carbon monoxide, 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 measurement during cylinder deactivation, it is reasonable to estimate that HCHO is also reduced by a similar percentage because of the high correlation between HCHO and CH_4 and CO. By deactivating three cylinders, the overall emission factors of CH_4, CO, and HCHO from LNG drop to 7.97, 2.91, and 0.14g /kWh respectively.

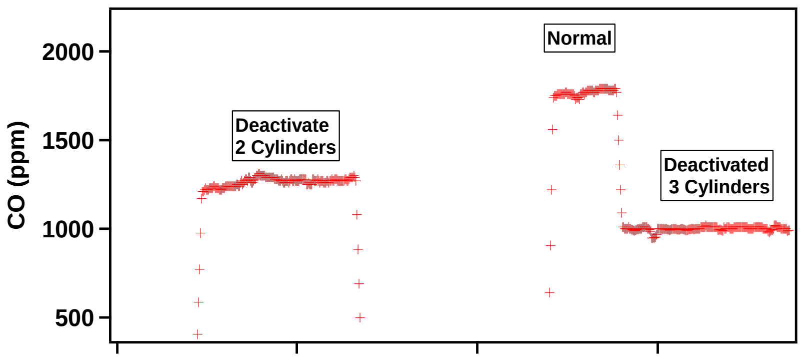

FIGURE 18 IMPACT OF CYLINDER DEACTIVATION ON CO EMISSIONS

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.

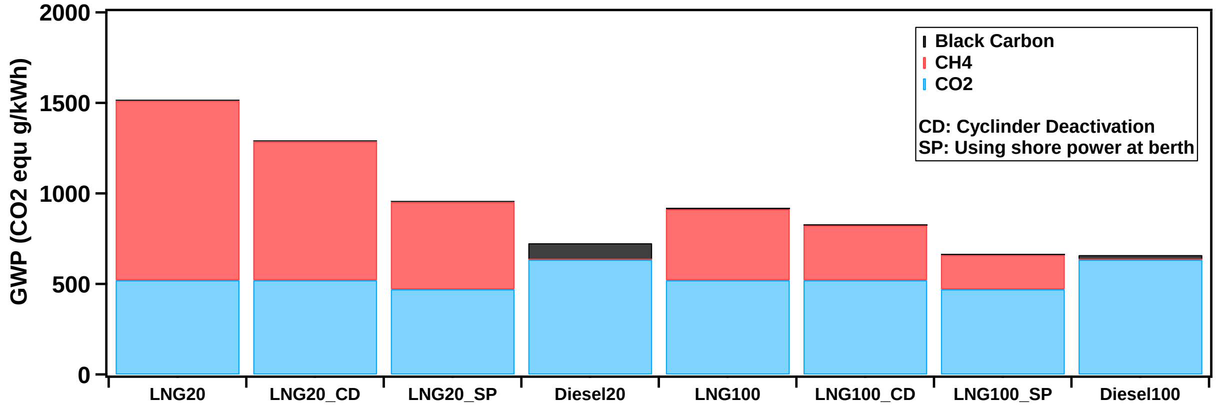

FIGURE 19 GREENHOUSE WARMING POTENTIAL FOR A NUMBER OF CASES WITH MITIGATION MEASURES

3 Summary

The project met all of its goals:

- Carried out a team effort to completely charaterize 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 important well-to-tank analysis was left for further study.

3.1 Key Findings

The overall calculated emission factors were below the certification levels for both the LNG and diesel fuels. Especially notable was the reduction of 93% in PM and 92% in NOx by switching from diesel to LNG. For LNG, the NOx emission factor calculated according to the ISO E-2 standard cycle was 0.63 g/kWhr, or 96.8% below the ~20g/kWhr where the ships have operated in the past decade. This finding offers an important opportunity and mitigation strategy for communities, like Los Angeles, where the high NOx levels drive ozone values above the federal standards.

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 emissions reduction potential since formaldehyde, carbon monoxide, nitic oxides, particulate matter and methane are all reduced. 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 $PM_{2.5}$.

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 did reduce carbon monoxide emissions by about 40%. From our correlations, we know formaldehyde and methane levels were likely reduced by similar levels. Based on these 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 carbon monoxide and formaldehyde. The catalyst approach is widely used for city transportation busses. It does not reduce the methane levels.

3.2 Recommended future work

Further work should be carried out 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.

Formaldehyde is a concern. Accordingly, it would be useful to measure and check the levels of formaldehyde that is reaching the ground or areas of the ship where people are working. It would be useful to discuss the addition of an oxidation catalyst to remove 95% of the formaldehyde as was done on the street buses and to decide whether a business case can be made for this option.

Appendix 1 Health Risk Calculations

Health risk assessment due to the emissions of PM and formaldehyde from LNG and diesel fuel was compared 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.