Ocean-Going Vessel Energy Efficiency Measurement Demonstration TAP Project: Final Report

for
San Pedro Bay Ports
Technology Advancement Program

June 2019

Prepared by:

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS & ABBREVIATIONS

CAMS	Control, Alarm, and Monitoring System
CARB	California Air Resources Board
CO_2	carbon dioxide
dB	decibel
ECHO Program	Enhancing Cetacean Habitat and Observation Program
EMS	Engine Management System
FMS	Flow Meter System
g	gram
GB	gigabytes
gHFO	grams heavy fuel oil
GHG	greenhouse gas
GPS	Global Positioning System
GVPC	Global Vessel Performance Centre
Hz	hertz
kW	kilowatt
kWh	kilowatt-hour
IFAW	International Fund for Animal Welfare
IMO	International Maritime Organization
MAREX	Marine Exchange of Southern California
ME	main engine
MSPS	Maersk Ship Performance System
MT	metric tons
NAAQS	National Ambient Air Quality Standards
NGO	non-governmental organization
nm	nautical mile
NOAA	National Oceanic and Atmospheric Administration
NO_x	nitrogen oxides
NRDC	National Resources Defense Council, Inc.
OGV	ocean-going vessel
PBCF	propeller boss cap fins
POLA	Port of Los Angeles
POLB	Port of Long Beach
PM	particulate matter
Radical Retrofit	Radical Retrofit Program
RPM	revolutions per minute
RR	radical retrofit
SFOC	specific fuel oil consumption
SO_x	sulfur oxides
SPBP	San Pedro Bay Ports
SPL	Sound Pressure Levels
TAP	Technology Advancement Program
TAP Project	Ocean-Going Vessel Energy Efficiency Measurement Demonstration Project
TCCO	turbo charger cut-out
TEU	twenty-foot equivalents
USB	universal serial bus
WMO	World Meteorological Organization

EXECUTIVE SUMMARY

The objective of the ground-breaking San Pedro Bay Ports (SPBP or Ports) Technology Advancement Program (TAP) project, "Ocean-Going Vessel (OGV) Energy Efficiency Measurement Demonstration Project" ("TAP Project"), was to evaluate and quantify the environmental benefits of energy efficiency improvements for ocean-going vessels using multiple new high-resolution data streams. The project would also evaluate the capabilities of new digital flow meters and sensors and near real-time satellite up-links being developed as part of Maersk's Connected Vessel Strategy. These new systems were to be installed and tested on ships going through the Maersk Radical Retrofit energy efficiency program (Radical Retrofit or the Program). The Radical Retrofit is part of Maersk's long-term commitment to reduce fuel consumption and related carbon dioxide (CO_2) and other air pollutants by 60% per container transported by 2020, compared to a 2007 baseline. In December 2018, Maersk announced new long-term goals with a 2008 baseline, aligned with the International Maritime Organization (IMO), including a 60% reduction by 2030, and Net Zero CO_2 shipping by 2050.

The purpose of the TAP Project was to help establish a path forward for the SPBP, the industry, and the regulatory agencies to incorporate the quantification of efficiency improvements into emissions inventories and future forecasts for air quality planning purposes. The anticipated outcomes of this Project were:

➢ Establish a methodology for quantifying the energy and emissions benefits from energy efficiency improvements on OGVs from both an emissions inventory and validation standpoint.

➢ Use the quantification methodology to demonstrate the energy efficiency improvements resulting from the Radical Retrofit, by ship operational mode

➢ Build on and enhance, where applicable, the data collection and analysis methods proposed by the California Air Resources Board's (CARB) Recommended Emissions Testing Guidelines for Ocean-Going Vessels.

The key benefit of the TAP Project for the Ports, Maersk, the maritime industry, and the regulatory community is the demonstration of the use of detailed, high-fidelity data to quantify energy efficiencies and emissions improvements. Energy efficiency improvements are critical components of CARB's Sustainable Freight Action Plan and air quality strategies to bring the South Coast Air Basin into attainment of the National Ambient Air Quality Standards (NAAQS). Currently, the regulatory community has not defined an approach to quantifying efficiency improvements specifically for ocean-going vessels, providing the TAP Project the opportunity to be the first to help develop such a quantification methodology and demonstration.

The Maersk Radical Retrofit and Connected Vessel Strategies

The Radical Retrofit budget for Maersk's twelve G-class vessels was $125 million dollars. In addition, Maersk agreed to prioritize these ships for early installation of the Connected Vessel suite, including enhanced fuel flow monitors, operational sensors, and communications capabilities (an additional estimated $3.7M), collect and process the data, and provide its in-house operational and technical expert resources to support the TAP Project. The Ports contributed a combined $1 million to support

the use of real-time data systems that represent an industry-leading application to quantify vessel operational parameters while ships are at-sea and at-berth.

The Radical Retrofit program is customized for each vessel class, including a carefully selected and integrated set of technologies to be installed on the entire class of vessels over a compressed period. The G-class efficiency improvements included redesigning the bulbous bow of each vessel, replacing existing propellers with more efficient models, adding propeller boss cap fins (PBCFs) to reduce cavitation, and "derating" the main engines to make them more efficient at lower speeds. In addition to the propulsion-related changes, the G-class retrofit program also included raising the bridge to increase each ship's capacity from about 9,500 TEUs (twenty-foot equivalent units) to 11,000 TEUs.

From the data collection side, new Flow Meter Systems (FMS) were installed before each consumer (typically only the 'day tank' was metered) and a new engineering management system was integrated with more sensors (Control, Alarm and Monitoring System (CAMS)) to allow for greater information capture of operational conditions. Another pioneering improvement came in the form of real-time data transmission from individual ships to the shore-side operating center. The program is referred to as the 'Connected Vessel,' as illustrated in Figure ES.1, which was a first for Maersk and one of the first new generation, comprehensive data collection, management, and transmittal systems in the maritime industry.

Figure ES.1: Connected Vessel
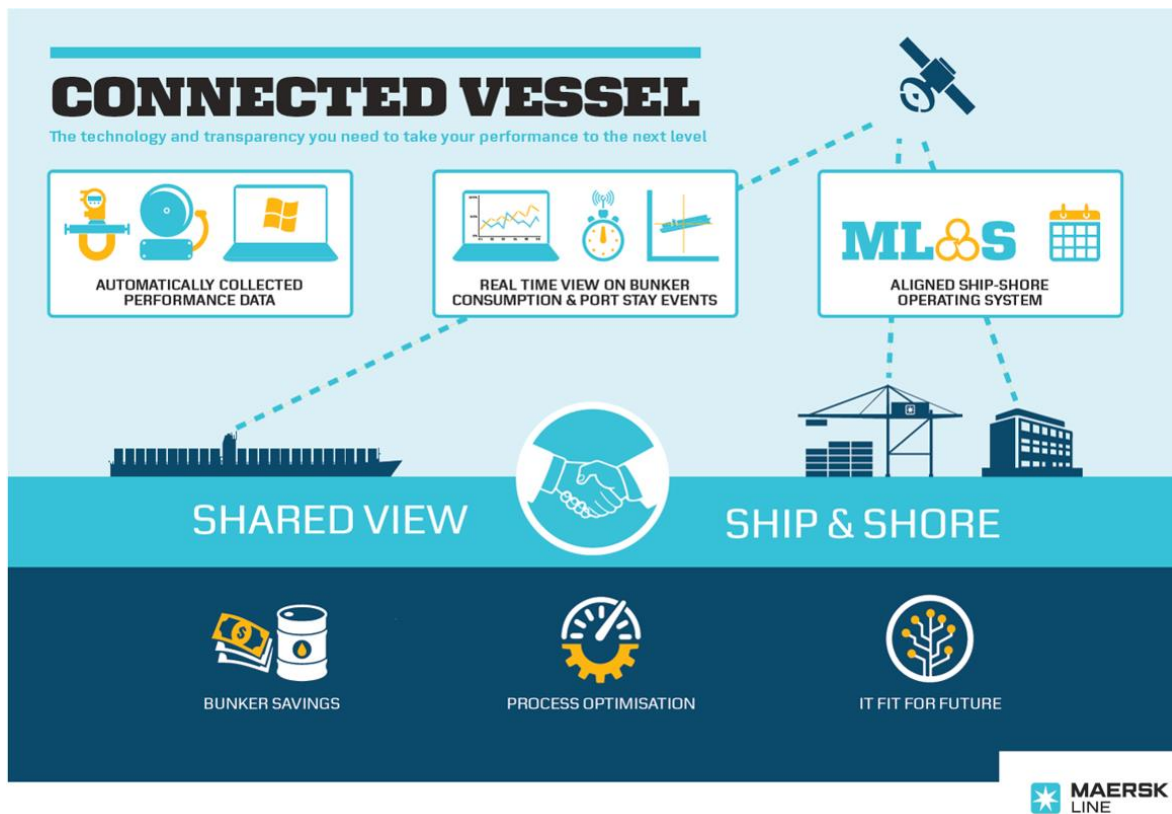
The Connected Vessel Strategy is designed to deliver three primary capabilities: automatically collected data, a real-time view on fuel consumption and port stay events and aligned ship and shore operating system. Workstreams include IT modernization, bunker optimization tools and systems, port performance, connectivity, and the operating systems to use these capabilities.

During the project, detailed high-fidelity operational energy and fuel data were collected on-board the twelve Maersk G-class ships. The G-class ships are shore power capable vessels and have called regularly at both the Port of Los Angeles (POLA) and Port of Long Beach (POLB) for the past five years. Due to a number of timing, technology development, and operational challenges, the data sets available before the retrofits were more limited than originally planned.

Analysis, Approaches and Results

In order to fulfill the Project objectives, three separate, independent analyses were incorporated into the TAP Project, conducted by Maersk's Fleet Performance Team, Duke University's Nicholas School of the Environment, and Starcrest Consulting Group. The analyses utilized available detailed energy and fuel consumption data to assess the efficiency improvements and associated emissions benefits of the Radical Retrofit on at least eleven of the twelve G-class vessels participating in the project. Data sources include the Maersk Ship Performance System (MSPS) reports (also known as Noon reports), Control, Alarm and Monitoring System (CAMS) sensors, Flow Meter System (FMS) sensors, Calculated Consumption data (Maersk-processed FMS data), Port Call Schedules, and Marine Exchange of Southern California (MAREX) data. The pre- and post-Radical Retrofit activities selected for analyses had similar operating conditions, so that differences in engine load and fuel consumption could not be attributed to confounding factors, such as vessel speed, sea state, and meteorological conditions.

Each of the three independent analyses incorporated a different technical approach.

➢ Maersk developed a technical approach where fuel economy improvements were assessed based on actual operational profiles within the context of statistical power curves and main engine specific fuel oil consumption (SFOC) being a function of vessel speed and draught. Based on the vessel's operational profile, the average transport efficiency was calculated for pre- and post-Radical Retrofit cases. The difference between the results provided an indication of the combined impact of both the improved propulsion performance and the increased capacity. Based on the methodology, Maersk's findings of the impact of the Radical Retrofit of the G-class vessels were an average reduction in fuel consumption of approximately 5% and improvement in transport efficiency (g fuel/TEU/nm) of approximately 8%.

➢ The Duke University study sought to estimate fuel consumption and emissions reductions pre- and post-Radical Retrofit using main engine load and RPM as control variables from eleven of the G-class vessels. Using a linear regression analysis approach, Duke University estimated a 19.6% fuel consumption reduction attributable to the Radical Retrofit.

> ➢ Starcrest utilized an approach in which specific periods of time were selected where the vessel operational and meteorological profiles were closely matched from eleven of the G-class vessels. This was done to isolate the energy efficiency improvements of the Radical Retrofit itself, irrespective of the vessel capacity increase. While preliminary results were along the lines of those obtained by Maersk and Duke University, Starcrest views these results as statistically inconclusive due to the inherent uncertainty associated with the MSPS Sea reports as well as the unknown impacts of hull and propeller biofouling on vessel performance. Recommendations are provided to reduce these uncertainties in future work.

It should be noted that none of the principal investigators were able to differentiate energy efficiency and fuel consumption improvements between vessel operational modes. This was a limitation of the available data. Starcrest attempted to develop matched data sets for vessel maneuvering by combining MSPS Port reports, Calculated Consumption data, and MAREX data but was unable to obtain a conclusive result.

Given the inherent uncertainty in MSPS data due to the reporting period duration and the potential for data recording inaccuracies, uncertainties in vessel power and fuel consumption due to variance in pre- and post-Radical Retrofit data matching, and the influence of biofouling, it must be recognized that the uncertainty associated with the analysis results may exceed the expected value of the energy efficiency improvements.

This is a general overarching issue with all the analyses presented and is also a primary motivation for moving towards automatic data logging of the most critical vessel performance measures, such as CAMS and FMS. It is important to recognize, however, that these higher frequency data streams require validation, filtering, and processing. These processes are still undergoing development by Maersk for the CAMS and FMS logged data.

Co-Benefits
As a direct result of the TAP Project, a study was conducted by Scripps Institution of Oceanography and Maersk to define the potential changes in underwater radiated noise resulting from the G-class Radical Retrofits. The study, conducted in 2017, found significant quantifiable reductions in underwater noise generation from the post-Radical Retrofit ships in the low and mid-range frequencies, which are believed to impact marine mammals. The estimated underwater sound pressure levels of the five selected G-class vessels were lower for post-retrofitted vessels by a median of 6 dB in the low-frequency band (8 - 100 Hz) and a median of 8 dB in the higher-frequency band (100 - 1000 Hz). This was a significant co-benefit finding; a 6 dB change translates into a 75% reduction in underwater source sound pressure levels from the post-retrofitted ships.

Challenges and Opportunities to Improve the TAP process
In addition to the technical challenges of the Project objective, significant administrative and logistical challenges were encountered over the life of the project that provided insight into how to better align future TAP OGV projects, related to TAP administrative sequences, inflexible ship drydock timelines, and a company-wide cyber-attack that refocused Maersk project resources for a significant amount of time.

Due to the phased implementation of the Radical Retrofits and the installation of the fuel and energy monitoring equipment and the Connected Vessel Program, the data produced by this equipment became available at different stages of the project duration. Maersk was able to 'pull ahead' the installation of FMS systems on two vessels prior to the Radical Retrofit during the TAP administrative process, and a third vessel after the contract was executed, in an effort to collect detailed data prior to retrofitting; however these systems were in the "Proof-of-Concept" phase. Maersk further manually collected engine management system data (pre-CAMS) from four pre-Radical Retrofit G-class vessels using universal serial bus (USB) data stick drives.

Maersk was hit by system-wide cyber-attack in June 2017, which was extremely disruptive and tied up a substantial amount of the company's resources for months. Furthermore, vessel data was not accessible for a significant amount of time as the company's Information Technology group worked to reestablish the company's systems and secure servers. This was a major unforeseen event that significantly impacted the project's resources and timeline.

Conclusions and Recommendations

The TAP Project did successfully advance the understanding of new detailed data collection systems and instrumentation being deployed on ships; identified challenges associated with data security, logistics, chain-of custody; and identified significant uncertainties that need to be address as more detailed data streams come online. The lessons learned from the project can help maximize the success of future TAP ship-related projects.

SECTION 1 INTRODUCTION

1.1 Project Description

The objective of the ground-breaking San Pedro Bay Ports (SPBP) Technology Advancement Program (TAP) project, "Ocean-Going Vessel Energy Efficiency Measurement Demonstration Project" (TAP Project), was to evaluate and quantify the benefits of energy efficiency improvements for ocean-going vessels (vessels or ships) using multiple new high-resolution data streams. During the project, detailed high-fidelity operational energy and fuel data were collected on-board twelve Maersk G-class containerships. These vessels have frequently called at both the Port of Los Angeles (POLA) and Port of Long Beach (POLB) or SPBP or the Ports for the past five years as illustrated in Figure 1.1.

Figure 1.1: G-class Calls to San Pedro Bay Ports

2014-2018 Maersk G-class SPBP Calls

By Ship

Ship Name	2014 Calls	2015 Calls	2016 Calls	2017 Calls	2018 Calls
GUDRUN MAERSK	2	3	3	4	5
GRETE MAERSK	3	2	4	2	0
GUNVOR MAERSK	4	1	4	6	8
GJERTRUD MAERSK	3	3	4	7	1
GERD MAERSK	3	2	4	3	0
GEORG MAERSK	2	1	2	4	0
GERNER MAERSK	4	4	1	4	2
GUNDE MAERSK	3	5	3	7	5
GUNHILDE MAERSK	2	3	0	0	0
GUSTAV MAERSK	4	5	2	6	5
GUTHORM MAERSK	3	2	3	6	5
GERDA MAERSK	2	4	3	2	1
Total	**35**	**35**	**33**	**51**	**32**

Classification: Public

The G-class vessels a subset of Maersk's $1 billion fleet-wide Radical Retrofit Program (Radical Retrofit or the Program), presented a unique opportunity for the Ports to partner with Maersk to study ship efficiencies before and after major retrofits. The Program is part of Maersk's long-term commitment to reduce fuel consumption and related carbon dioxide (CO_2) and other air pollutants by 60% per container transported by 2020, compared to a 2007 baseline. According to Maersk, progress against that goal as of the end of 2018 was a reduction of 47% per container per kilometer. This long-term dramatic improvement in energy efficiency is decoupling vessel emissions from growth in container transportation.

The Radical Retrofit budget for the twelve G-class vessels was $125 million dollars and Maersk agreed to incorporate enhanced fuel flow monitors, collect and process all data, and provide its in-house operational and technical expert resources to support the TAP Project. The Ports contributed a combined $1 million to support the use of real-time tracking systems that represent an industry leading application to quantify vessel operational parameters while ships are at-sea and at-berth. These systems are further detailed in subsequent sections of this report.

The Program focused on retrofitting the G-class vessels with multiple energy efficiency technologies, resulting in energy consumption efficiencies and reduced emissions. However, these technologies were being developed and adapted to the G-class vessels, and so the logistics of getting the systems on-board, calibrated, and operational prior to the ships' Radical Retrofit was challenging. The data collected from these systems were intended to support both energy-based and fuel-based evaluation approaches to be used to quantify the improvements.

Under its Radical Retrofit program, Maersk efficiency improvements included redesigning the bulbous bow of each vessel, replacing existing propellers with more efficient models, adding propeller boss cap fins to reduce cavitation, and "derating" the main engines to make them more efficient at lower speeds. In addition to the propulsion-related changes, the retrofit program also included raising the bridge to increase each ship's capacity from about 9,500 TEUs to 11,000 TEUs. The resulting increased capacity allowed the Maersk G-class ships to carry more containers per vessel sailing while decreasing their environmental impact per container moved. It should be noted that the ships calling the SPBP are already equipped with shore power capabilities, so that was not part of the program.

The primary vessel changes under the Radical Retrofit program are illustrated in Figure 1.2. For informational purposes, photographs of two new bulbous bows waiting at the shipyard for installation (Figure 1.3), bulbous bow installations in process (Figure 1.4), and installed new propellers with boss-end caps (Figure 1.5) are provided.

Figure 1.2: Maersk Radical Retrofit Illustration

Capacity utilisation
- Elevation of navigation bridge (1-3 additional tiers)
- Installation of 'ballast water' tank
- Increase scantling draught

Main engine
- Engine derating
- Dynamic cylinder cut-out (Electronic engines)

Bulbous Bow
- Modification of bulbous bow

Propulsion
- New propeller designed for 16 knots and max 22 knots
- PBCF propulsion improvement device

Figure 1.3: New Bulbous Bows Waiting for Installation at Shipyard

Figure 1.4: Installation of New Bulbous Bows

Figure 1.5: New Efficient Propeller with Boss End Caps

The TAP Project had access to continuously recorded data showing how much energy each vessel's engine used in conjunction with speed, engine power, weather, operational mode, and other operational variables through the use of the ship's upgraded engine management systems and newly installed mass flow meters to capture key performance data. Most of the data collected onboard was uploaded to Maersk servers via satellite using the company's Star Connect platform. Using this data, Maersk's Global Vessel Performance Centre (GVPC) can communicate with each vessel in real-time to increase operational efficiency, as illustrated in Figure 1.6. The goal of the TAP Project was to use the pre- and post-Radical Retrofit continuously recorded data from a minimum of four vessels to quantify energy and emissions improvements by operational mode.

Figure 1.6: Overview of the Maersk Connected Vessel Program

June 2019
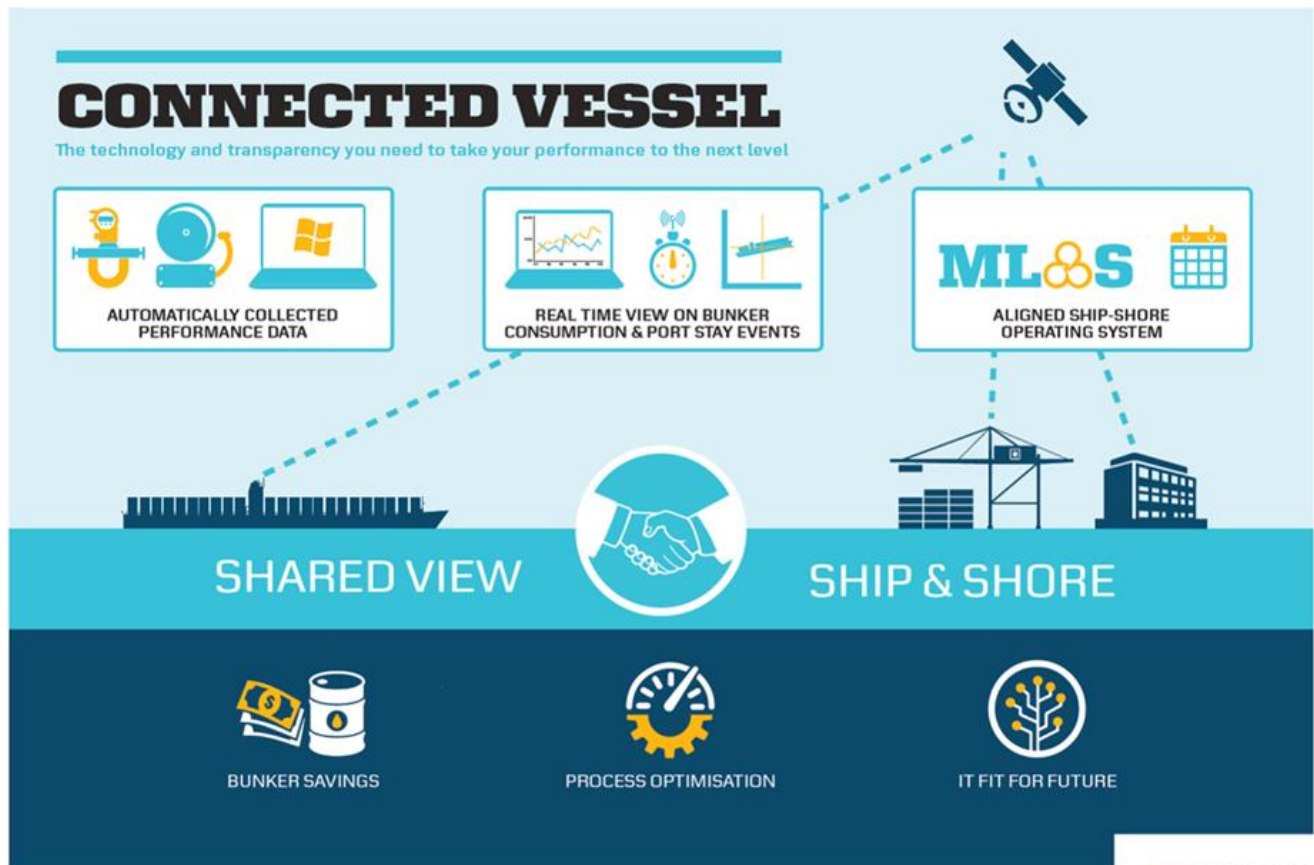
1.2 G-class Characteristics

A comparison of key G-class characteristics illustrates the changes the ships went through as part of the Radical Retrofit. A summary comparison is provided in Figure 1.7 and detailed information is provided in the TAP Project Milestone 1 & 2 report (submitted June 2017).

Figure 1.7: Summary Comparison of Key Parameters Pre- & Post-Radical Retrofit

Maersk G-Class Vessel Characteristics

Propulsion Engine: 55,598 kW **Container Capacity:** ~ 9,500 TEUs **Reefer Capacity:** 544 (Gerner class) 845 (Gudrun class)	**Radical Retrofit**	**Propulsion Engine:** 46,000 kW **Container Capacity:** ~ 11,000 TEUs **Reefer Capacity:** 544 (Gerner class) 845 (Gudrun class)

1.3 Project Benefits

The key benefits sought by the TAP Project for the San Pedro Bay Ports, Maersk, the maritime industry, and the regulatory community were the demonstration of the use of detailed data to quantify energy efficiencies and emissions improvements. Energy efficiency improvements are critical components of the California Air Resources Board's (CARB) Sustainable Freight Action Plan and air quality strategies to bring the South Coast Air Basin into attainment of the National Ambient Air Quality Standards. Currently, the regulatory community has not defined an approach to quantifying efficiency improvements specifically for ocean-going vessels, providing the TAP Project the opportunity to be the first to develop such a quantification methodology and demonstration.

From an emissions standpoint, Maersk anticipated that the Radical Retrofit was expected to reduce fuel consumption by 2,000 to 3,000 metric tons per year per ship. This will help reduce criteria pollutant and greenhouse gases (GHG) emissions. In addition, an increase in carrying capacity will reduce the carbon footprint per container transported in line with globally accepted measurement of GHG reductions from liner shipping activities. Per Maersk, the planned capacity boost on each of the 9,500+ TEU vessels will increase capacity by approximately 9%, thereby reducing fuel consumption and emissions produced per container by approximately 8% at full capacity utilization.

A significant co-benefit directly related to the Program's ship modifications was a measurable reduction in underwater noise due to higher efficiencies from the propellers and bulbous bow. These reductions were due to minimizing cavitation, which affects fuel consumption rates and is a primary source of anthropogenic underwater noise. The Marine Physical Laboratory, Scripps Institution of Oceanography, University of California San Diego conducted an analysis of five G-class ships calling at the San Pedro Bay Ports before and after the Radical Retrofit and summary of their findings are presented in this report.

1.4 Project Team

The project team members include numerous resources from Maersk, Starcrest Consulting Group (Starcrest), and Duke University. Maersk facilitated the inter-team access to data by establishing a share site, which allowed team members to access data as appropriate. The long-term TAP project core team members include:

Core Team
- Lee Kindberg, Project Manager, Head of Environment, Safety & Sustainability for North America, Maersk
- Andrew Beath, Fleet Performance and Global Project Manager for the Connected Vessel Program, Maersk
- Octavi Sado Garriga, Head, Fleet Performance Team, Maersk
- Lasse De Boer, Fleet Performance Team, Maersk
- Support from the following Maersk resource teams:
  - Connected Vessel Team
  - Fleet Performance & Efficiency Groups
  - Maersk Maritime Technologies
- Bruce Anderson, Technical Expert, Starcrest
- Paula Worley, Data Manager and Data Analysis, Starcrest
- Ray Gorski, Data Analysis Lead, Starcrest
- Archana Agrawal, Technical Expert and Quality Assurance, Starcrest
- Steve Ettinger, Data Analysis Support, Starcrest

Duke University Team
- Geoffrey Cooper, Masters Student, Nicholas School of the Environment, Duke University
- Julia Lewis, Masters Student, Nicholas School of the Environment, Duke University
- Benjamin Lozier, Masters Student, Nicholas School of the Environment, Duke University
- Jay Golden, Ph.D., Adviser, Nicholas School of the Environment, Duke University

Scripps Underwater Acoustics Team
- Martin Gassmann, Ph.D., Marine Physical Laboratory, Scripps Institution of Oceanography, University of California San Diego
- Sean Wiggins, Ph.D., Marine Physical Laboratory, Scripps Institution of Oceanography, University of California San Diego
- John Hildebrand, Ph.D., Marine Physical Laboratory, Scripps Institution of Oceanography, University of California San Diego

Maersk was the overall Project Lead. Starcrest and Maersk were responsible to perform the modal efficiency and emissions analyses based on the data that was collected during the project, the first study of its kind using actual data.

Masters students from Duke University's Nicholas School of the Environment helped to identify and consolidate the various sources of data that was to be used throughout the project. In addition, the Duke team conducted an analysis of energy efficiency improvements over a broader set of the data compared to the more modal analysis conducted by Starcrest and Maersk.

The Marine Physical Laboratory, Scripps Institution of Oceanography, University of California San Diego conducted an analysis of five G-class ships calling San Pedro Bay Ports, specifically the *Grete Maersk*, *Gudrun Maersk*, *Gunvor Maersk*, *Gerda Maersk*, and *Gerner Maersk*. The groundbreaking study's final report, "*Underwater noise comparison of pre- and post- retrofitted Maersk G-class container vessels*", MPL TM-616, October 2017, is provided as Attachment 1. The findings were presented at the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea Nineteenth Meeting, 18-22 June 2018 at the United Nations Headquarters Building in New York, New York. The findings have been presented at three other international conferences related to underwater noise from ocean-going vessels.

1.5 Project Timeline

Maersk's Radical Retrofit program was identified as a potential TAP project in 2014. The TAP administrative process was completed in May 2016 and the contract was executed in June 2016. By the time of contract execution, ten of the G-class vessels had already undergone the Radical Retrofit process and an 11th vessel was in dry dock receiving the Radical Retrofit at that time. The first eleven G-class vessels were retrofitted between February 2015 and August 2016, and the last G-class vessel completed Radical Retrofit in April 2018. Fuel flow meters were installed across the G-class vessels from December 2015 through December 2016.

The original project timeline was significantly impacted by a cyber-attack on Maersk in June 2017.[1] This resulted in a major disruption to data systems and availability of key technical resources that Maersk had committed to the project. Despite the delays, the project team completed the Energy and Fuel Parameters Report (submitted separately) and Final Project Report (this document). The TAP Project has taken three years to complete. A summary of project milestone events is presented in Table 1.1.

---

[1] Greenberg, A. (August 2018). "The Untold Story of NotPetya, The Most Devastating Cyberattack in History," *Wired.* *https://www.wired.com/story/notpetya-cyberattack-ukraine-russia-code-crashed-the-world/*

Table 1.1: Summary of Key Project Milestone

Administration	TAP Contract Milestones

- Mid 2014   Identification of a potential TAP project related to the Radical Retrofits
- May 2016   TAP Contract approved by POLA Board of Harbor Commission
- June 2016   Contract executed
- June 2017   Submittal of Fleet Characterization Report, Technical Work Plan, Data Collection Plan, & Documnetaiton for equipment installation, & Installation and Data Collection Report
- June 2019   Submittal of Energy and Fuel Parameters Report, and the Final Project Report
- June 2019   Contract term ends

Project	Key Project Milestones

- May - August 2015   *Gudrun Maersk* undergoes Radical Retrofit
- June - September 2015   *Grete Maersk* undergoes Radical Retrofit
- July - September 2015   *Gerd Maersk* undergoes Radical Retrofit
- August - October 2015   *Gunvor Maersk* undergoes Radical Retrofit
- September - November 2015   *Georg Maersk* undergoes Radical Retrofit
- November - December 2015   *Gjertrude Maersk* undergoes Radical Retrofit
- November 2015 - January 2016   *Guthorm Maersk* undergoes Radical Retrofit
- December 2015   *Gudrun Maersk* & *Grete Maersk* flow meters installed
- December 2015 - March 2016   *Gerda Maersk* undergoes Radical Retrofit
- January 2016   *Georg Maersk* flow meters installed
- January - April 2016   *Gunde Maersk* undergoes Radical Retrofit
- March 2016   *Gerd Maersk* flow meters installed
- March - May 2016   *Gustav Maersk* undergoes Radical Retrofit
- May - July 2016   *Gerner Maersk* undergoes Radical Retrofit
- October 2016   *Gjertrude Maersk* & *Gunde Maersk* flow meters installed
- November 2016   *Guvnor Maersk*, *Guthorm Maersk, Gerner Maersk, Gerda Maersk,* & *Gustav Maersk* flow meters installed
- December 2016   *Gunhilde Maersk* flow meters installed
- January - April 2018   *Gunhilde Maersk* undergoes Radical Retrofit

Timeline Impacts	Key Events that Impacted Schedule

- June 2017   Maersk is hit by a system-wide cyber attack, which significantly impacted the project's resources and timeline.

1.6 Data Availability

Due to the phased implementation of the Radical Retrofits and the installation of the fuel and energy monitoring equipment, the data produced by this equipment became available at different stages of the project. Table 1.2 shows the dry-dock stage for each G-class vessel and the dates when high-fidelity vessel and engine operation data from the Flow Meter System (FMS) and the Control, Alarm, and Monitoring System (CAMS) for each vessel came online. FMS systems were installed on three vessels prior to the Radical Retrofit (*Gerda Maersk*, *Gustav Maersk*, and *Gunhilde Maersk*). However, this limited amount of pre-Radical Retrofit FMS data was in the "Proof-of-Concept" phase. CAMS data was only available post-Radical Retrofit.

Table 1.2: G-class Vessel Radical Retrofit Timeline and Data Availability

Vessel Name	Radical Retrofit	FMS Data Availability	CAMS Data Availability
Gundrun Maersk	May - Aug 2015	Dec 2015	Apr 2017
Grete Maersk	Jun - Sep 2015	Dec 2015	Jan 2017
Gerd Maersk	Jul - Sep 2015	Mar 2016	Feb 2017
Gunvor Maersk	Aug - Oct 2015	Nov 2016	Mar 2017
Georg Maersk	Sep - Nov 2015	Jan 2016	Nov 2017
Gjertrude Maersk	Nov - Dec 2015	Oct 2016	Mar 2017
Guthorm Maersk	Nov 2015 - Jan 2016	Nov 2016	Nov 2016
Gerda Maersk	Dec 2015 - Mar 2016	Nov 2015 *	Apr 2017
Gunde Maersk	Jan - Apr 2016	Oct 2016	May 2017
Gustav Maersk	Mar - May 2016	Dec 2015 *	Jun 2017
Gerner Maersk	May - Jul 2016	Nov 2016	Nov 2016
Gunhilde Maersk	Jan - Apr 2018	Jan 2017 *	**

* High frequency data that came online prior to the Radical Retrofit.
** At the time the datasets were received by Starcrest, the *Gunhilde Maersk* had not yet gone into dry dock for the Radical Retrofit; therefore, no post-Radical Retrofit data was available for the *Gunhilde Maersk*. Additional post-retrofit data could be downloaded and analyzed if additional time is available.

1.7 Project Challenges

The original intention of the TAP Project was to utilize high-frequency pre- and post-Radical Retrofit CAMs and FMS data to analyze the impact of the Radical Retrofit on energy efficiency and fuel consumption, and ultimately, on emissions. However, there were several challenges that prevented the acquisition of pre-Radical Retrofit CAMS and FMS data needed to do a thorough analysis.

1.7.1 Administrative

As stated above, at the time of the TAP contract execution, ten of the G-class vessels had already undergone the Radical Retrofit process and an 11th vessel was in dry dock receiving the Radical Retrofit. Prior to contract execution, Maersk was able to install the FMS module on two of the vessels (*Gustav Maersk* and *Gerda Maersk*) before they received the Radical Retrofit. After contract execution, the FMS module was installed on a third vessel, the *Gunhilde Maersk*, prior to Radical Retrofit. The CAMS module, however, could not be installed on any vessel prior to Radical Retrofit because it was still in development and the schedule could not

be accelerated. Therefore, the installation and full activation of CAMS modules occurred post-Radical Retrofit on all vessels.

In lieu of pre-Radical Retrofit CAMS data, pre-Radical Retrofit data was downloaded directly from four G-class vessels' existing engine management systems (EMS) onto USB drives. The data produced by the engine management systems was not as detailed as the CAMS data; however, it did contain information about engine operations. Unfortunately, the EMS data was downloaded between 2015 and early 2016 and the analysis began in 2018 due to the delays from the cyber-attack (see 1.7.2 Cyber-Attack). During the time lapse, the association of which USB drive belonged to which vessel was lost, and some data appeared to be corrupted. After identifying this issue, the Project Core Team agreed that this data should not be included in the final Starcrest analysis.

1.7.2 Cyber-Attack
As mentioned above, Maersk was hit by system-wide cyber-attack in June 2017, which was extremely disruptive and tied up a substantial amount of the company's technical resources for months. Furthermore, vessel data was not accessible for a significant amount of time as the company's Information Technology group worked to reestablish the company's systems and secure servers. This was a major unforeseen event that significantly impacted the project's resources and timeline.

SECTION 2 ENERGY EFFICIENCY ANALYSIS

2.1 TAP Project Objectives
The TAP Project has the following objectives:

➢ Establish a methodology for quantifying the energy efficiency improvements, fuel consumption reductions, and emissions benefits resulting from the Radical Retrofit;
➢ Utilize the quantification methodology to validate energy efficiency improvements resulting from the Radical Retrofit;
➢ Quantify vessel emissions reductions resulting from the Radical Retrofit within the San Pedro Bay Ports emissions inventory geographical domain and, where feasible, in the California OGV Fuel Zone and California area of the Emissions Control Area; and
➢ Build upon and enhance the data collection methods in the CARB's ocean-going vessel (OGV) emissions reduction evaluation guidelines by utilizing unprecedented access to vessel energy consumption data by each engine type (main engines, auxiliary engines, and boilers).

The overarching objective was to establish a path forward for the San Pedro Bay Ports, industry, and the regulatory agencies to incorporate these findings into future emissions inventories and planning documents.

The following sections discuss the technical approaches used by Maersk, Duke University, and Starcrest to quantify the benefits of a vessel that has undergone a Radical Retrofit. To the extent feasible, the quantification of vessel efficiency improvements and corresponding fuel consumption and air pollutant emission reductions is based on detailed energy and fuel consumption data for the main engines, auxiliary engines, and auxiliary boilers. That said, limitations on the acquisition of pre-Radical Retrofit engine performance and fuel consumption data required a deviation from the technical approach originally outlined in the Project Scope. However, as discussed in Section 7, the consistency in independently-obtained results from Maersk and Duke University supports the overall finding that vessels that undergo the Maersk Radical Retrofit benefit from improved energy efficiency that directly results in lower fuel consumption and a reduction in both criteria air pollutants and greenhouse gas emissions for post-Radical Retrofit vessels on a "per TEU" basis. Starcrest's analysis showed that, while its findings were along the lines that the other two studies found, the results were statistically inconclusive due to the uncertainties with some of the datasets and biofouling.

2.2 Data Sources
This section describes the data sources that were used to analyze the effects of the Maersk Radical Retrofit program on engine power, fuel consumption, and ultimately, emissions.

2.2.1 Maersk Ship Performance System (MSPS) Reports
Also known as the Noon report, the MSPS reports contain information about vessel performance, sea state, and meteorological conditions. Data fields include vessel name, date/time of report, reporting period (time in hours since last report), Global Positioning System (GPS) location, draft forward and aft, average draft, average speed over ground, average speed through water, average engine power and engine run hours (main and auxiliary engines), boiler and reefer power, and fuel consumption since previous report. Beaufort Wind

Scale, wind direction and speed, wave direction and height, water depth, and sea temperature are also included.

The data is collected and aggregated manually, and the report is filed daily by the vessel's chief engineer. If the vessel changes modes of operation or if there is a change in sea or meteorological conditions, another report is filed to reflect the change in operating conditions. The report is not always filed at noon; the intent is to provide a snapshot of the vessel's performance over the previous 24-hour period. Some reporting periods may be longer than 24 hours due to time zone changes or estimated time of arrival to port, whereas others may be shorter if there is a change in operating conditions.[2]

There are two types of MSPS reports: Sea reports and Port reports. Sea reports are filed when a vessel is transiting at sea from one port to another. Port reports are filed when a vessel begins to slow as it approaches a port and encompass the time between when a vessel first slows as it approaches the port to when it increases speed as it leaves the port. Port reports do not contain information on vessel speed, sea state, or meteorological conditions, and the reporting period is generally greater than 24 hours. It is important to note that the location in the ocean where a vessel slows on approach to a port and where it increases speed as it leaves a port can vary from trip to trip; therefore, comparing two Port reports for the same vessel/port cannot be assumed to be an apples-to-apples comparison.

MSPS Sea reports contain a performance code that provides insight into the operating status of the vessel over the reporting period. See Table 2.1 for a list of performance codes and their descriptions. Maersk strives to operate at constant power (Performance Code 1) as much as possible because it increases engine efficiency and is the most fuel-efficient mode of operation.[2]

Table 2.1: MSPS Performance Codes (Sea Reports only)

Performance Code	Performance Code Description
0	Performance Test
1	Constant Main Engine (ME) load; Normal Cruising
4	Variable Speed/Power for Soot Blowing
5	Slowdown/Drifting Due to Technical Problems
6	Variable Speed/Power Due to External Factors
8	Power Test
9	Running With Incomplete Engine

The MSPS Sea reports also contain a data field for the Beaufort Wind Scale, which encapsulates both meteorological and sea state conditions. See Table 2.2 for more information. The MSPS data indicates that the G-class vessels have operated in conditions ranging from 0 (Calm) to 12 (Hurricane). The average is 4 (Moderate Breeze).

---

[2] Cooper, G. R., Lewis, J. & Lozier, B. (2017). "Demonstrating Air Emissions Reductions Through Energy Efficiency Retrofits on Maersk G-class Vessels", *Duke University, Nicholas School of the Environment.*

Table 2.2: Beaufort Wind Scale[3]

Force	Wind (Knots)	WMO Classification	Appearance of Wind Effects	
			On the Water	On Land
0	Less than 1	Calm	Sea surface smooth and mirror-like	Calm, smoke rises vertically
1	1-3	Light Air	Scaly ripples, no foam crests	Smoke drift indicates wind direction, still wind vanes
2	4-6	Light Breeze	Small wavelets, crests glassy, no breaking	Wind felt on face, leaves rustle, vanes begin to move
3	7-10	Gentle Breeze	Large wavelets, crests begin to break, scattered whitecaps	Leaves and small twigs constantly moving, light flags
4	11-16	Moderate Breeze	Small waves 1-4 ft. becoming longer, numerous whitecaps	Dust, leaves, and loose paper lifted, small tree branches move
5	17-21	Fresh Breeze	Moderate waves 4-8 ft taking longer form, many whitecaps, some spray	Small trees in leaf begin to sway
6	22-27	Strong Breeze	Larger waves 8-13 ft, whitecaps common, more spray	Larger tree branches moving, whistling in wires
7	28-33	Near Gale	Sea heaps up, waves 13-19 ft, white foam streaks off breakers	Whole trees moving, resistance felt walking against wind
8	34-40	Gale	Moderately high (18-25 ft) waves of greater length, edges of crests begin to break into spindrift, foam blown in streaks	Twigs breaking off trees, generally impedes progress
9	41-47	Strong Gale	High waves (23-32 ft), sea begins to roll, dense streaks of foam, spray may reduce visibility	Slight structural damage occurs, slate blows off roofs
10	48-55	Storm	Very high waves (29-41 ft) with overhanging crests, sea white with densely blown foam, heavy rolling, lowered visibility	Seldom experienced on land, trees broken or uprooted, "considerable structural damage"
11	56-63	Violent Storm	Exceptionally high (37-52 ft) waves, foam patches cover sea, visibility more reduced	
12	64+	Hurricane	Air filled with foam, waves over 45 ft, sea completely white with driving spray, visibility greatly reduced	

---

[3] National Oceanic and Atmospheric Administration (NOAA). *Beaufort Wind Scale.*
https://www.spc.noaa.gov/faq/tornado/beaufort.htm

The benefit of the MSPS data it that it is a long-standing report that was collected both pre- and post-Radical Retrofit. The downside of the MSPS data is that the reports are logged manually and contain averages over long periods of time (the average reporting period for Sea reports is 20.3 hours and the average reporting period for Port reports is 38.2 hours). Therefore, there was a greater degree of uncertainty with the MSPS data than with the high-fidelity data sources, which are logged automatically.

2.2.2 High-Fidelity Data Sources
As part of the Radical Retrofit, the Maersk G-class vessels were equipped with CAMS and FMS sensors to track energy efficiency and fuel consumption. These sensors output data once per second, which is then downloaded via satellite to Maersk servers and aggregated every ten minutes.

2.2.2.1 Control, Alarm and Monitoring System (CAMS) Data
The CAMS data contains many of the same data points found in the MSPS reports except for data related to fuel consumption and frequency of reporting. This includes vessel name, date/time of report, GPS location, draft forward and aft, speed over ground, speed through water, engine power and engine run hours (main and auxiliary engines, boilers, and reefers), wind direction and speed, wave direction and height, water depth, and sea temperature. It also contains additional data on air temperature and pressure, cargo hold temperature, rudder angle, vertical bow motion and velocity, fuel viscosity, and detailed information about the operation of each engine, such as air and gas inlet temperatures and exhaust outlet temperature and back pressure.

The advantage to the CAMS data was that it was a more detailed data set logged automatically and at a much higher frequency than the MSPS data. The downside was that the CAMS data was only available post-Radical Retrofit.

2.2.2.2 Flow Meter System (FMS) Data
Also known as the fuel consumption data, the FMS data contains fuel-related data points found in the MSPS reports and additional new information, such as inlet/outlet mass, flow, density, and temperature.

As with the CAMS data, the advantage to the FMS data was that it was logged automatically and at a higher frequency than the MSPS data. Additionally, there was a limited amount of pre-Radical Retrofit FMS data available; however, it was logged during the "Proof-of-Concept" phase of the project, so there was a level of uncertainty about its reliability for use in analysis.

2.2.2.3 Calculated Consumption Data
The calculated consumption dataset is populated with Maersk's calculated fuel consumption from the FMS data. It has the same level of granularity as the FMS data and contains data fields that indicate the amount and type of fuel consumed by the main engine, auxiliary engines, and boilers since the previous measurement (typically every 10 minutes). Similar to FMS data mentioned above, there was uncertainty in the reliability of this data.

2.2.3 Port Call Schedule
The G-class vessel port call schedule data was extracted from Maersk's Global Scheduling Information System. The data includes vessel arrival and departure dates to each port, as well as flags indicating whether the dates are scheduled (future dates) or whether they are actuals.

2.2.4 Marine Exchange of Southern California (MAREX) data
MAREX data for the Port of Los Angeles and the Port of Long Beach was used to determine when the G-class vessels were maneuvering in and around the ports.

2.3 Data Availability

Analysis of the effects of the Radical Retrofit on energy efficiency and fuel consumption requires that data be available both pre- and post-Radical Retrofit. Table 2.3 illustrates the availability of the pre- and post-Radical Retrofit data sources (MSPS, FMS, and CAMS) for the G-class vessels.

➢ Pre- and post-Radical Retrofit MSPS data was available for all vessels, except the *Gunhilde Maersk*.
➢ Pre- and post-Radical Retrofit FMS data was available for the *Gerda Maersk* and *Gustav Maersk* only.
➢ Only post-Radical Retrofit vessel operational CAMS data was available on eleven G-class vessels.

Pre-Radical Retrofit data was limited due to the project challenges described in Section 1.7.

Table 2.3: Pre- and Post-Radical Retrofit Data Availability

Vessel Name	Vessel Class	Pre-Radical Retrofit			Post-Radical Retrofit		
		MSPS	CAMS	FMS	MSPS	CAMS	FMS
Gudrun Maersk	Gudrun	✓			✓	✓	✓
Grete Maersk	Gudrun	✓			✓	✓	✓
Gerd Maersk	Gudrun	✓			✓	✓	✓
Gunvor Maersk	Gudrun	✓			✓	✓	✓
Georg Maersk	Gudrun	✓			✓	✓	✓
Gjertrud Maersk	Gudrun	✓			✓	✓	✓
Guthorm Maersk	Gerner	✓			✓	✓	✓
Gerda Maersk	Gerner	✓		✓*	✓	✓	✓
Gunde Maersk	Gerner	✓			✓	✓	✓
Gustav Maersk	Gerner	✓		✓*	✓	✓	✓
Gerner Maersk	Gerner	✓			✓	✓	✓
Gunhilde Maersk **	Gerner	✓		✓*	n/a	n/a	n/a

* There was a limited amount of pre-Radical Retrofit FMS data available. (*Gerda Maersk*: 4 months; no California trips. *Gustav Maersk*: 5.5 months; 1 California trip. *Gunhilde Maersk*: 13 months; no California trips.)
** At the time the datasets were received by Starcrest, the *Gunhilde Maersk* had not yet gone into dry dock for the Radical Retrofit; therefore, no post-Radical Retrofit data was available for the *Gunhilde Maersk*. Additional post-retrofit data could be downloaded and analyzed if additional time is available.

2.4 Energy Efficiency Analysis – Technical Approach

Due to the lack of availability of pre- CAMS data and limited FMS data, the original proposed technical approach to quantify the improvements of the Radical Retrofit could not be fully implemented. In an effort to fulfill the scope of work to the extent feasible, three separate, independent analyses were performed by project partners Maersk's Vessel Performance Team, Duke University Nicholas School of the Environment, and Starcrest. The following sections provide an overview of the three approaches as well as the findings from each of these teams. Additionally, a section on the findings of anthropogenic underwater noise study by The Scripps Institution of Oceanography is also included.

SECTION 3 MAERSK ANALYSIS AND FINDINGS

3.1 Approach

Maersk analysis is based on company's internal ship performance evaluation models. To evaluate time-dependent changes to a ship's performance, it was necessary to compensate for all the other (non-time-dependent) factors that might also influence the measure being investigated.

The fuel consumption is influenced by many external factors; most importantly the speed and loading condition of the ship; however, the weather situation and sea state are also important factors to consider. Maersk has developed models that account for the influences from all these factors. Using these models, the collected data can be corrected for these effects and compared on an even basis. For example, this approach allows for the tracing of decaying performance resulting from biofouling of the hull and propeller.

Maersk's Ship Performance System (MSPS) also contains models for the expected performance of the individual parts of the ship, such as hull resistance, propeller performance, and main engine performance. Collected in-service data can then be evaluated to determine the extent that the expected performance of the ship is met in reality, and calibration of the models can take place.

Two models of interest in the context of the Radical Retrofit analysis used were the Main Engine Power and Main Engine SFOC (Specific Fuel Oil Consumption) because the product of these two measures reflect the fuel consumed for propulsion of the ship.

In the Radical Retrofit scenario, several modifications were implemented at the same time. Some of these (bulbous bow, new propeller) influenced the hull resistance and required propulsion power; whereas, others influenced the efficiency of the main engine (derating, turbo charger cut-out (TCCO)). These radical modifications necessitated updating the models as well. Once enough post Radical Retrofit operational data is collected the models can be further calibrated and updated models to carry out a reasonable evaluation impact of the Radical Retrofit modifications.

Some parts of the Radical Retrofit were designed to improve efficiency over all conditions, but parts of the modification (especially the bulbous bow modification) were aimed at shifting the conditions (range of drafts and speeds) at which the vessel was optimized. In most cases this was a compromise. Hence, in order to achieve an improved performance at a given draft and speed (typically lower than initially designed) something else must be sacrificed. This is often performance at high speeds, where the vessels rarely operate given the current market and environmental considerations. Hence, the performance improvement provided by the Radical Retrofit will vary depending on operational conditions (combination of vessel speed and draft). In order to arrive at a reasonable estimate of the realized improvements, it was necessary to consider actual vessel operational conditions. The distribution of time operated on various drafts and speeds is typically referred to as the Operational Profile. This process of estimating the fuel savings (and thereby emission reduction) is summarized in Figure 3.1.

Figure 3.1: Fuel Savings as a Function of Main Engine Power and Main Engine SFOC
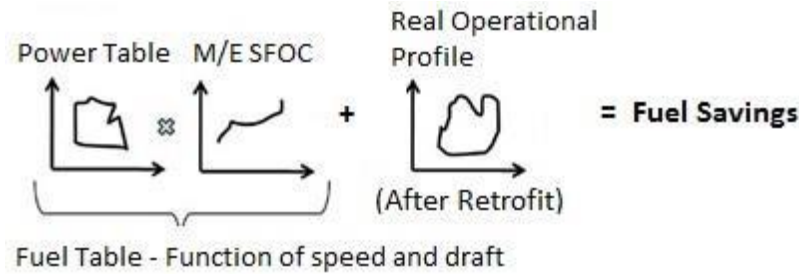
Other parts of the Radical Retrofit program were aimed at increasing the capacity of the ship (increased maximum draft, heightening of lashing bridges and super structure). These modifications will not in themselves reduce the fuel consumption at a given operational condition. However, they allow carrying an additional amount of cargo while increasing the fuel consumed carrying this additional cargo only marginally. The result is, potentially, a higher 'transport efficiency', i.e. fuel consumed per container per nautical mile (g/TEU/nm). The improvement obtained in reality, of course, depends on the extent that the increased capacity is utilized.

The number of containers a vessel can carry onboard can be restricted by different limitations; visibility from the bridge, stability, and deadweight capacity. In terms of fuel consumption, the most important metric is the total deadweight, which will be reflected by the draft. In order to determine a representative number of TEUs, an average weight per TEU can be assumed, which translates a given deadweight in tons to the number of TEUs with that average weight. In many cases regarding emissions regulation calculations, an average weight of 12 tons/TEU is applied. This value was considered for this analysis.

Based on the operational profile, respectively, before and after the Radical Retrofit, the average transport efficiency was calculated for both cases. The difference between these two values provide an indication of the combined impact of both the improved propulsion performance and the increased capacity. This method is, however, a bit more uncertain since it is influenced by any changes in the typical operational speeds before and after the retrofit.

3.2 Findings
Based on the methodology described above, Maersk findings of the impact of the Radical Retrofit of the G-class vessels are as follows:

➢ Average reduction in fuel consumption of about 5%.
➢ Improvement of transport efficiency (g/TEU/nm) about 8%.

These values are based on the actual operational profile experienced by the vessels. If they are deployed differently in the future, values will be different.

3.3 Uncertainty Analysis

The methodology outlined above reduces the uncertainty involved in comparing energy and fuel consumption at different times and conditions by applying vessel specific corrections for most, if not all, of the influencing factors, such as wind, waves, draft, trim, fuel type, etc. While this a significant improvement, there remains several sources for uncertainty. Among these are:

➢ Inaccuracies in the underlying mathematical models.

   This is being mitigated by continuously reviewing the models to identify unintended dependencies and biases.

➢ Uncertainty in the qualities measured and reported – both the direct qualities such as speed, power and fuel consumption, and also the qualities used in the correcting models, such as wave height, wave direction, wind speed, wind direction etc. Uncertainty can stem from sensor accuracy, errors when reading instruments, human error etc.

   To mitigate these uncertainties, validation and verification is performed on the reported figures, e.g. if a value is reported that is outside bounds of what is considered realistic, a warning is issued in the reporting program. Additionally, during analysis, the dataset is often filtered to exclude data that is likely to have large uncertainty, e.g. reports with significant influence from weather and sea. Introduction of auto-logged data has the potential to reduce the errors introduced by inaccurate readings etc.

➢ The rather long reporting periods in the MSPS data means averages are being made, which might make the reported quantities more uncertain and potentially biased.

   This is currently being mitigated to some extent by requesting the crews to report more frequently, such as when significant changes in environment (e.g. weather) or operating conditions have occurred. In the future, the data will be auto-logged at a higher frequency and this part of the uncertainty is expected to decrease.

Quantifying the uncertainty introduced by these sources is quite difficult. These are not controlled experiments and complete repeatability is not realistic. Also, the accuracy of different parameters can vary considerably from ship to ship and even over time for the same ship (e.g. in case of different crews being more/less aware and diligent).

On a general note it should be mentioned that the results of this analysis are based on data from twelve different ships, which all show the same trend of a better performance after the retrofit than before and the values obtained agree quite well with the theoretical expectation.

In conclusion, while it is very difficult to put an accurate value on the uncertainty involved with the values found with the data quality currently available, this is deemed the best possible estimate.

SECTION 4 DUKE UNIVERSITY ANALYSIS AND FINDINGS

4.1 Approach

Masters students from Duke University[4] conducted a study based the MSPS Sea reports between 2014 and 2016 to analyze the impact of the Radical Retrofit on fuel consumption and, subsequently, on total emissions of several key pollutants: CO_2, NO_x, SO_x, and PM. All the G-class vessels were used in the analysis, with the exception of the *Gunhilde Maersk*, which had not yet undergone the Radical Retrofit. They cross checked the MSPS data set with corresponding CAMS data. Duke University's complete report was included with the Milestone 1 & 2 report submitted in June 2017.

For each MSPS Sea report, fuel consumption in terms of tonnes of fuel consumed per km per TEU was calculated by dividing total fuel consumed by distance traveled and TEU utilization.

$$fuel\ consumption = fuel\ consumed(tonnes)/(distance\ traveled\ (km) \times TEU)$$

It was assumed that each G-class vessel's capacity before Radical Retrofit was 9,500 TEUs and after Radical Retrofit was 11,000 TEUs. It was also assumed that each vessel operated at 70% capacity both before and after Radical Retrofit per industry standard.[5]

MSPS Sea reports were included only if the vessel had been operating at constant main engine load and normal cruising conditions (Performance Code 1, as described above). From 2014 to 2016, the G-class vessels spent an average of 67% of time at constant main engine load, accounting for 68% of the total distance travelled.

The calculated fuel consumption results were highly, positively skewed, so they were logarithmically transformed to make the distribution more normal, resulting in a new variable called Log (Fuel Consumption).

Using the Log (Fuel Consumption) from each MSPS Sea report, linear regressions were performed for each vessel to measure the change in fuel consumption before and after the Radical Retrofit. A fixed effects regression was then used to calculate an average fuel consumption for all G-class vessels and control for time-independent effects that differ between the vessels.

Each regression controlled for the following variables: Radical Retrofit status (pre- and post-), duration of the MSPS Sea report, weather (measured on the Beaufort Wind Scale), average draught of the vessel, main engine load, main engine RPM, vessel speed, and reefer energy.

---

[4]Cooper, G. R., Lewis, J. & Lozier, B. (2017). "Demonstrating Air Emissions Reductions Through Energy Efficiency Retrofits on Maersk G-class Vessels", Duke University, Nicholas School of the Environment.

[5] Thibault, A. (June 2015). "Clean Cargo Working Group Carbon Emissions Accounting Methodology".
https://www.bsr.org/s/BSR_CCWG_Carbon_Emissions_Methodology_2015.pdf

4.2 Findings

Table 4.1 contains the regression results for each G-class vessel. The Retrofit coefficients for each vessel range from -0.058 to -0.333 with a class average of -0.196. The coefficients represent the percent change in fuel consumption. This means the G-class vessel average of -0.196 translates to a 19.6% reduction in fuel consumption as a result of the Radical Retrofit.

Table 4.1: Regression Results with Retrofit Coefficients for G-class Vessels

	Number of Observations	Retrofit Coefficient	Robust Standard Error	P-Value	95% Confidence Interval	
					Low	High
Georg	502	-0.224	0.051	0.000	-0.325	-0.123
Gerd	626	-0.100	0.045	0.027	-0.190	-0.012
Gerda	660	-0.247	0.047	0.000	-0.339	-0.155
Gerner	446	-0.202	0.084	0.016	-0.366	-0.037
Gjertrud*	583	-0.058	0.055	0.291	-0.167	0.050
Grete	598	-0.159	0.042	0.000	-0.241	-0.076
Gudrun	538	-0.333	0.045	0.000	-0.421	-0.246
Gunde	570	-0.201	0.053	0.000	-0.306	-0.097
Gunvor	452	-0.162	0.059	0.007	-0.279	-0.045
Gustav	584	-0.301	0.066	0.000	-0.431	-0.172
Guthorm	539	-0.226	0.069	0.001	-0.362	-0.091
Class	6,098	-0.196	0.020	0.000	-0.241	-0.152

*Gjertrud not statistically significant

Figure 4.1 visually displays the decrease in fuel consumption for each G-class vessel as well as the vessel class average.

Figure 4.1: % Decrease in Fuel Consumption
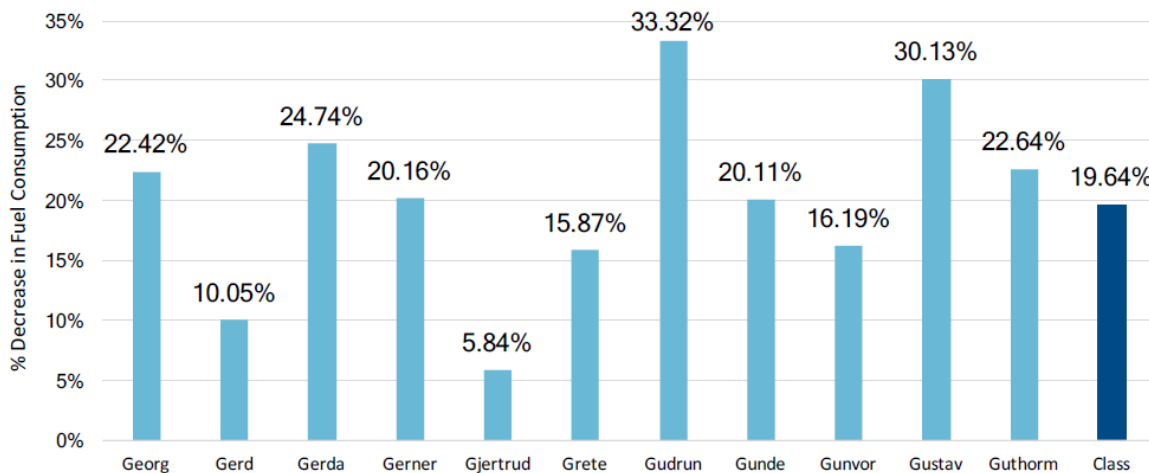
To calculate emissions reductions, reduction in fuel consumption was calculated by first establishing a pre-Radical Retrofit fuel consumption baseline for each vessel using the MSPS Sea reports (prior to Radical Retrofit) and the average distance traveled per year for all G-class vessels (115,744 km). Once the fuel consumption baseline was established for each vessel, the Retrofit coefficient was applied to estimate post-Radical Retrofit fuel consumption. The difference between the pre- and post-Radical Retrofit fuel consumption was assumed to be the fuel savings due to the Radical Retrofit.

To translate fuel savings into emissions reductions, fuel-based emission factors from the IMO's Third IMO GHG Study[6] were utilized. The emission factors used from the study were based on 2.7% sulfur content fuel for Tier I slow-speed diesel engine. These emissions factors were modified to account for a 2.1% sulfur content fuel, which was the average sulfur content for the fuel used by the G-class vessels in 2016. The emission factors used were:

- CO_2 = 3,114 kg/tonne of fuel
- NO_x = 87.18 kg/tonne of fuel
- SO_x = 41.55 kg/tonne of fuel
- PM = 6.36 kg/tonne of fuel

Using the estimated fuel savings and emissions factors, average G-class vessel emission reductions were estimated to be:

- CO_2: 1.278 tonnes per TEU, annually
- NO_x: 0.036 tonnes per TEU, annually
- SO_x: 0.017 tonnes per TEU, annually
- PM: 0.003 tonnes per TEU, annually

Fuel savings and emissions reductions were calculated on a per-TEU basis because of the increase in vessel capacity during the Radical Retrofit.

4.3 Uncertainty Analysis

In order to verify the accuracy of the MSPS Sea reports, the MSPS Sea report data was compared to the higher-frequency CAMS data. Three variables were selected for the comparison that are present in both datasets: main engine RPM, main engine power, and vessel speed. Figures 4.2 through 4.4 compare these three variables during a trip where the *Guthorm Maersk* transited from Singapore to the Suez Canal on February 18 – March 1, 2017. The graphs don't represent the entire trip; only a period of time where 10 consecutive MSPS Sea reports indicated a constant main engine load and normal cruising (Performance Code 1).

The MSPS Sea report data is depicted in red and the higher-frequency CAMS data is depicted in blue. The MSPS data can be observed to follow a similar pattern as the CAMS data and, in most cases, there does not appear to be a large discrepancy between the two data sources. However, on February 22, there was a spike in the CAMS data for all three variables. It is unclear what caused the spike, but the MSPS data does not reflect this pattern. This situation illustrates that the CAMS data can capture sudden changes in the operating parameters of the vessel, whereas the MSPS data cannot.

---

[6] International Maritime Organization (IMO). "Third IMO Greenhouse Gas Study 2014: Executive Summary and Final Report."

As mentioned above, these comparisons were made when the vessel was operating under constant main engine load and normal cruising. It is expected that greater differences between the MSPS Sea reports and the CAMS data will be observed when the vessel is operating under variable conditions (Performance Code <> 1).

Figure 4.2: *Guthorm Maersk* MSPS and CAMS main engine RPM from consecutive constant ME load/normal cruising reports (Feb 19 to Feb 24, 2017). Vessel departed Singapore on Feb 18, 2017 and arrived at Suez Canal on Mar 1, 2017.

Figure 4.3: *Guthorm Maersk* MSPS and CAMS main engine power from consecutive constant ME load/normal cruising reports (Feb 19 to Feb 24, 2017). Vessel departed Singapore on Feb 18, 2017 and arrived at Suez Canal on Mar 1, 2017.
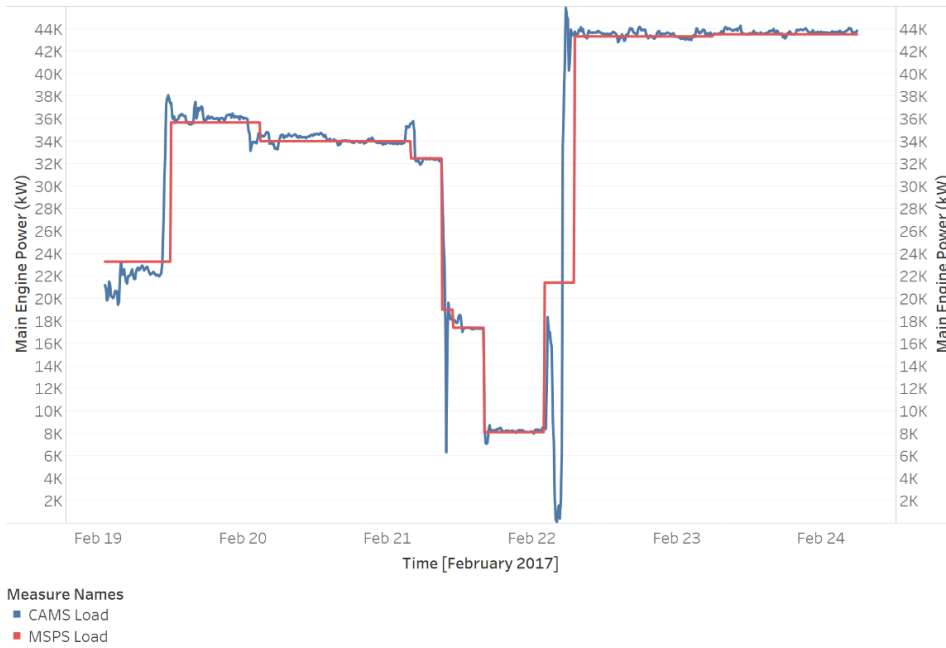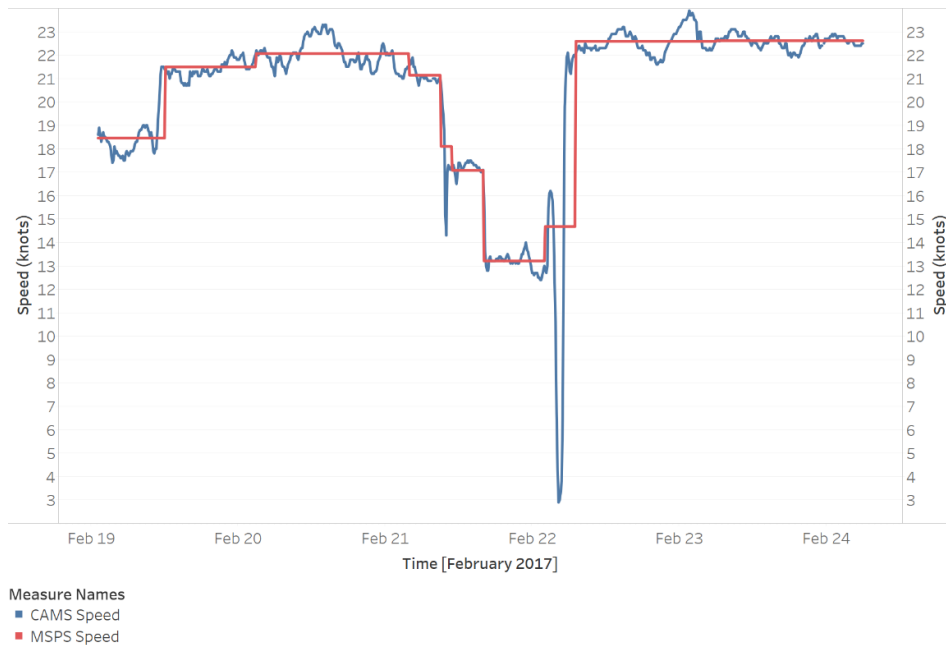

Figure 4.4: *Guthorm Maersk* MSPS and CAMS vessel speed from consecutive constant ME load/normal cruising reports (Feb 19 to Feb 24, 2017). Vessel departed Singapore on Feb 18, 2017 and arrived at Suez Canal on Mar 1, 2017.

In order to quantify the differences between the MSPS and CAMS datasets, two paired t-tests were run on the data for the *Guthorm Maersk*. First, on the data graphed above from the Singapore to Suez Canal trip (10 MSPS reports and corresponding CAMS data). Next, on all the MSPS reports for the *Guthorm Maersk* with constant ME load/normal cruising (39 MSPS reports and corresponding CAMS data). For the CAMS data, main engine RPM, main engine power, and vessel speed were averaged over the time period of each MSPS report.

Table 4.2 shows the results of the paired t-test from the Singapore to Suez Canal trip and Table 4.3 shows the results of the paired t-test for all *Guthorm Maersk* data while the vessel was operating at constant ME load and normal cruising.

Table 4.2: Paired t-test Comparison of MSPS and CAMS Data for the *Guthorm Maersk* from Feb 19 to Feb 24, 2017. Vessel departed Singapore on Feb 18, 2017 and arrived at Suez Canal on Mar 1, 2017

	Sample Size	MSPS Mean	CAMS Mean	Difference	Standard Error	P-Value
ME Power (kW)	10	27,808.50	26,866.70	941.80	1,098.39	0.41
ME RPM	10	72.70	72.60	3.90	1.27	0.01
Speed (knots)	10	19.14	19.08	0.06	0.05	0.27

Table 4.3: Paired t-test Comparison of MSPS and CAMS Data for the *Guthorm Maersk* from Dec 7, 2016 to Feb 24, 2017

	Sample Size	MSPS Mean	CAMS Mean	Difference	Standard Error	P-Value
ME Power (kW)	39	25,248.92	25,149.15	99.77	284.15	0.73
ME RPM	39	73.67	74.86	1.19	0.41	0.01
Speed (knots)	39	18.96	18.93	0.03	0.01	0.02

The results for the Singapore to Suez Canal trip indicated that only the difference in main engine RPM was statistically significant (p-value = 0.01). Whereas, results for all *Guthorm Maersk* data indicated that the differences in main engine RPM and vessel speed were statistically significant (p-values 0.01 and 0.02 respectively).

Figures 4.5 through 4.7 compare main engine RPM, main engine power, and vessel speed between the MSPS and CAMS datasets as the *Gerner Maersk* transited from the Port of Long Beach to the Port of Oakland on Jan 11 - Jan 12, 2017. For this trip, there was only one MSPS Sea report to use for comparison, so there is only one averaged MSPS value in each figure (the single red line). The variability in CAMS data before the red line begins indicates vessel operations as the vessel left the Port of Long Beach, and the variability in CAMS data after the red line ends indicates vessel operations as the vessel arrives at the Port of Oakland. Figures 4.5 to 4.7 clearly shows that variability in main engine rpm, engine kW and speed, which will impact fuel consumption, as measured by CAMS were not captured by MSPS reports.

Figure 4.5: *Gerner Maersk* MSPS and CAMS main engine RPM from Port of Long Beach to Port of Oakland (Jan 11, 2017 to Jan 12, 2017)
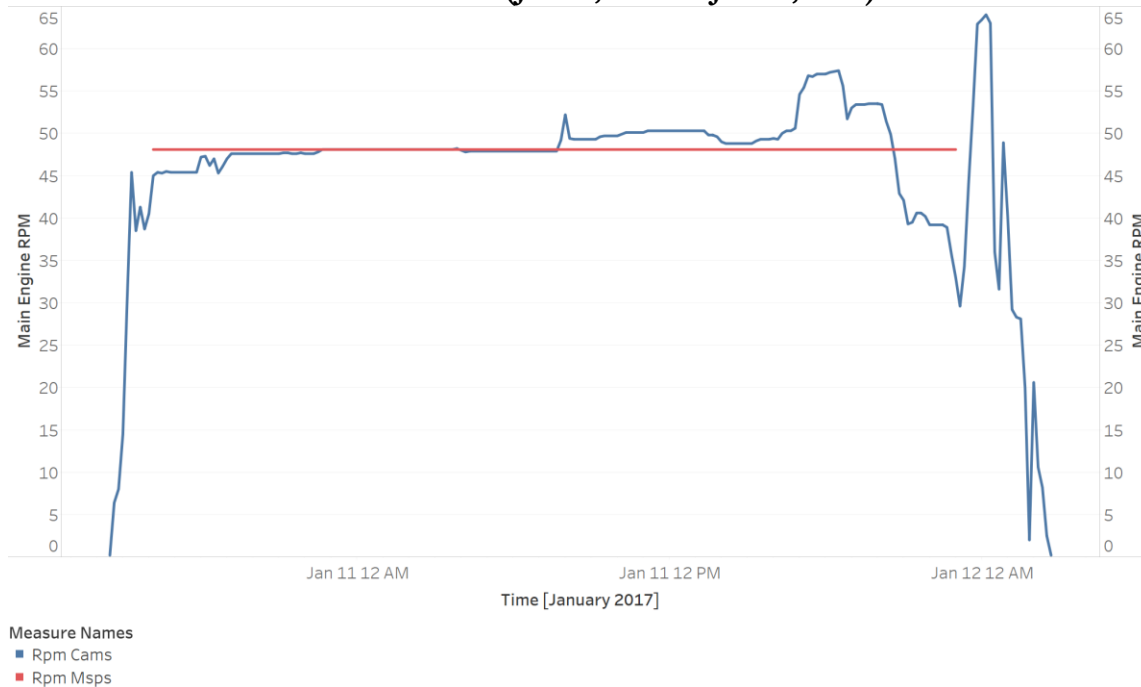
Figure 4.6: *Gerner Maersk* MSPS and CAMS main engine power from Port of Long Beach to Port of Oakland (Jan 11, 2017 to Jan 12, 2017).
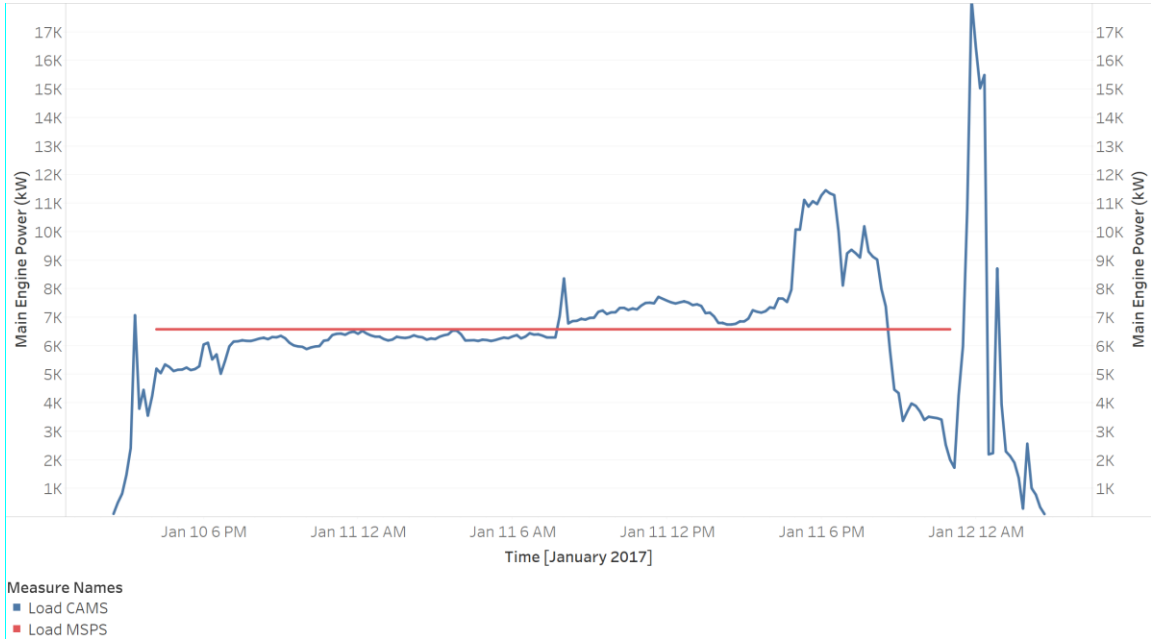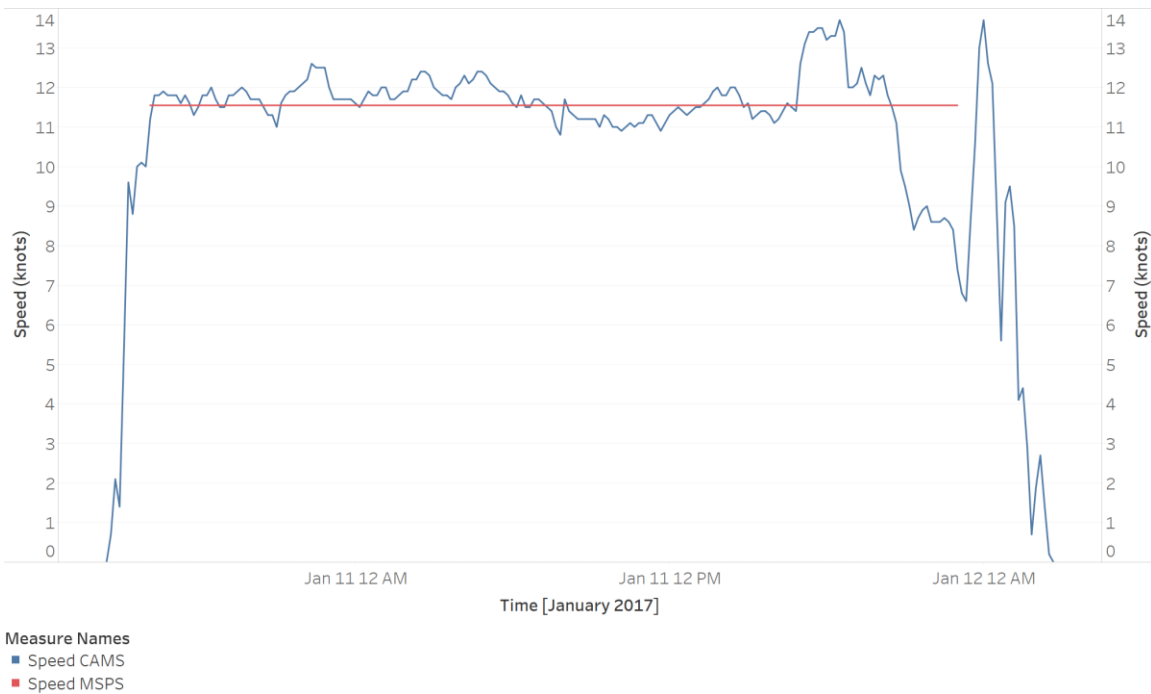

Figure 4.7: *Gerner Maersk* MSPS and CAMS vessel speed from Port of Long Beach to Port of Oakland (Jan 11, 2017 to Jan 12, 2017)

SECTION 5 STARCREST ANALYSIS AND FINDINGS

5.1 Approach

The approach taken by Starcrest in its analysis of the energy efficiency from the Radical Retrofit Program is discussed in the following subsections.

5.1.1 Analysis of Vessel Transit Energy Efficiency

Starcrest evaluated the available pre-and post-Radical Retrofit datasets and, due to reasons that impacted the timeline of acquisition of detailed Radical Retrofit data, as mentioned in Section 1.7 "Project Challenges", and lack of pre-retrofit CAMS data, the MSPS dataset was the only data source for G-class vessels collected both pre- and post-Radical Retrofit that could be used to analyze the effects of the Radical Retrofit on average daily vessel performance in transit. As a result, a modified technical approach was developed whose primary objective was to meet, to the extent feasible, the intent of the original project scope. This was accomplished with the understanding that the uncertainty in the results due to the use of lower fidelity MSPS data is greater than would have been achieved had the pre-Radical Retrofit CAMS data been available.

The analysis had the following objectives:

- ➢ Validate that the Radical Retrofit under normal vessel cruise conditions (Performance Code 1) increases vessel efficiency with an associated reduction in fuel consumption and air pollutant emissions;
- ➢ Quantify the energy efficiency improvements, fuel consumption reduction, and air pollutant emission reductions resulting from the Radical Retrofit during vessel transit and maneuvering operational modes;
- ➢ Quantify on a per-TEU basis the energy efficiency improvement, fuel consumption reduction, and air pollutant emissions reductions attributable to the Radical Retrofit during vessel transit and maneuvering;
- ➢ Compare the Starcrest methodology results with those obtained by Maersk and Duke University.

The technical approach used to validate the benefits of the Radical Retrofit under normal cruise conditions can be described as follows: for a specific G-class vessel, query the available pre- and post-Radical Retrofit MSPS Sea report dataset and identify those reports for which the relevant and essential vessel operating, sea state, and meteorological conditions are matched within a specified tolerance. In matching these pre- and post-Radical Retrofit environmental and operational parameters, one can essentially eliminate them from the analysis, as they are, within an appropriately defined tolerance, equal values. The remaining vessel operational parameters can then be analyzed to determine pre- and post-Radical retrofit changes in energy and fuel consumption under otherwise similar conditions.

It is important to note that the dataset matching described above was performed for the purpose of validating the energy efficiency benefits of the Radical Retrofit under nominal transit conditions itself, without taking into account the potential benefits of increased TEU capacity or fuel consumption reduction benefits potentially attributable to slow steaming.

When matching the MSPS pre- and post-Radical Retrofit Sea reports, the vessel speed and deadweight were matched to within the determined tolerance. In this case, deadweight was matched using the vessel performance parameters of draught and trim.

The following parameters were used to determine a pre- and post-Radical Retrofit data match during vessel transit operations:

Table 5.1: MSPS Parameters Used for Pre- and Post-Radical Retrofit Match

Data Field Name	Match Criteria
Vessel name	Equal
Report date/time	Pre-Radical Retrofit/Post-Radical Retrofit
Report type	= 1 (Sea report)
Performance code	= 1 (Constant ME load; Normal cruising)
Vessel speed	+/- 0.125 knots
Average Draught	+/- 0.25 meters
Trim	+/- 0.1 meters
Beaufort	Equal
Wind direction	+/- 10 degrees
Wave height	+/- 0.5 meters
Sea temperature	+/- 5 °C
Water depth	> 50 meters

➢ **Vessel Name**: The G-class vessels are similar, but not identical; therefore, only pre- and post-Radical Retrofit MSPS Sea reports for the same vessel were matched to each other.

➢ **Performance Code**: Only MSPS Sea reports with Performance Code 1 were considered. A Performance Code of 1 indicates the vessel was cruising normally and maintaining a constant main engine load during the reporting period. Other Performance Codes indicate that conditions were variable during the reporting period or that the vessel was in test mode or that engines were not fully functioning. Refer to Table 2.1 for a description of the MSPS Performance Codes.

➢ **Vessel Speed**: Main engine power and fuel consumption is directly impacted by vessel speed.

➢ **Draught Average and Trim:** Vessel draught impacts ship resistance and is directly related to the total deadweight of a vessel. The trim of a ship describes its floating position in length direction, namely if the bow or the aft of the ship is deeper submerged into the water. The trim can have a significant impact on a vessel's energy demand for propulsion while underway. The most efficient trim for a vessel depends on its design, operational draft, and speed.

➢ **Beaufort Wind Scale, Wind Direction, Wave Height, and Sea Temperature**: To ensure similar sea state and meteorological conditions, the MSPS Sea reports were matched on the Beaufort Wind Scale, wind direction, wave height, and sea temperature. These parameters are known to affect ship resistance, and therefore, main engine power and fuel consumption. Wind and waves will increase ship resistance if they move towards the ship's bow and sides. Wind direction is especially influential for ships with large windage areas, such as the G-class vessels, which are containerships.[7]

➢ **Water Depth**: Operating in shallow water negatively impacts a vessel's maneuverability and results in a reduction in speed over water while increasing the bow wave and engine load. The effects of operating in shallow water are typically encountered only in cases where the water depth is less than or equal to 1.5 times the maximum draught of the vessel. To ensure that water depth wouldn't have an impact on engine performance, only MSPS Sea reports with water depth greater than 50 meters were considered.

In establishing the allowable tolerances shown above in Table 5.1, the objective was to make the pre-and post-Radical Retrofit match as precise as practical. Discussions with Maersk Vessel Performance staff as well as information obtained by researching published, peer-reviewed technical papers[7,8] were used to set the initial match parameter tolerance thresholds. That said, there was also a practical consideration, in that too tight a tolerance limited the number of matches available for analysis. Any relaxation of the match criterion tolerance strictly for the purpose of increasing the number of matched MSPS Sea reports was done with extreme caution, as it would have further contributed to the uncertainty associated with a result. For this analysis, it was the opinion of Starcrest that the match criterion tolerances shown above in Table 5.1 did not introduce an unacceptable additional uncertainty in the results and yielded a number of matches sufficient to conduct the energy efficiency analysis.

The technical approach described above was also used to assess the benefits of the Radical Retrofit on a "per TEU" basis. To conduct this analysis, Maersk Vessel Performance staff provided a correlation between vessel draft and the number of TEUs at a given specific weight (12 tons/TEU). This relationship remained (almost) unchanged by the retrofit. Therefore, increased TEU capacity should be reflected by a deeper draft, if utilized. In this case, a set of matched data for pre- and post-Radical Retrofit MSPS Sea reports was obtained for cases where the vessel was operating at approximately 70% of maximum capacity in both the pre- and post-Radical Retrofit configuration.

---

[7] Adland, R., Cariou, P., Jia, H. & Wolff, F-C. (2018). "The energy efficiency effects of periodic ship hull cleaning". *Journal of Cleaner Production*. 178. DOI: 10.1016/j.jclepro.2017.12.247.

[8] Demirel, Y. K., Uzun, D., Zhang, Y., Fang, H.-C., Day, A. H. & Turan, O. (2017) "Effect of Barnacle Fouling on Ship Resistance and Powering", *The Journal of Bioadhesion and Biofilm Research*, Biofouling, 33:10, 819-834, DOI: 10.1080/08927014.2017.1373279

5.1.1.1 Study Energy & Fuel Consumption Parameters

In consultation with Maersk, the MSPS Sea report data fields appropriate for the assessment of pre- and post-Radical Retrofit energy efficiency benefits were identified. The data fields most relevant to the analysis are listed in Table 5.2.

Table 5.2: MSPS Parameters Used to Analyze Pre- and Post-Radical Retrofit Matches

Data Field Name	Units
Report Period	Hours
Distance Observed/Logged	NM
Main Engine Running Hours	Hours
Main Engine Load	kW
Main Engine Fuel Total	MT
Reefer Energy	kWh
Shaft Generator Energy	kWh
Main Engine Specific Fuel Oil Consumption (SFOC)	gHFO/kWh
Total Energy SFOC	gHFO/kWh
TEU Estimate	TEU

Thus, the parameters shown in Table 5.2 were variables in the energy and fuel consumption analyses; the parameters shown in Table 5.1 were constant values.

5.1.1.2 Validation of Energy Efficiency Improvements of the Radical Retrofit

A primary objective of this study was to validate that the Radical Retrofit does improve vessel energy efficiency, and to quantify these benefits in terms of fuel consumption and air pollutant reductions as a function of vessel operational mode.

To validate vessel efficiency improvements, Starcrest analyzed pre- and post-Radical Retrofit MSPS Sea reports in which the environmental and vessel operational parameters were as closely aligned as the data allowed but within the parameter tolerances shown in Table 5.1. Sensitivity analyses were also conducted on specific parameters to determine their relative influence, such as wave direction.

Acceptable MSPS Sea report matches had, within the tolerances shown above, equal speed through water, equal temperature, equal deadweight as represented by equal draught and equal vessel trim. Note that water temperature influences vessel hull resistance so for this reason water temperature was normalized to 20 degrees C.

By fixing vessel speed, deadweight (draught, trim), sea state, and meteorological parameters as constant values pre- and post-Radical Retrofit, Starcrest was able to scrutinize the parameters specific to vessel performance.

To accomplish this, pre- and post-Radical Retrofit vessel propulsive power requirements were analyzed. The MSPS Sea Report parameters evaluated are shown above in Table 5.2. Reefer Energy and Shaft Generator Energy are essentially power takeoff from the Main Engines; thus, these values must be accounted for when assessing propulsion energy efficiency. Also, variability of MSPS Sea reporting periods must be taken into account. While an MSPS Sea report typically covers a period of 24 hours, there is variability and the vessel performance data must be normalized to account for differences in reporting frequency.

5.1.2 Analysis of Vessel Maneuvering Energy Efficiency

Given the availability of the pre- and post-Radical Retrofit data, the MSPS Port reports, MAREX, and the Calculated Consumption datasets were used to analyze the benefits of the Radical Retrofit while the G-class vessels were maneuvering near port.

The MSPS Port reports don't have the granularity needed to accommodate analysis of vessel movements in and around a port, specifically vessel maneuvering. Therefore, MAREX data was used to supplement the information in the MSPS Port reports by identifying when the G-class vessels arrived and departed from the San Pedro Bay Ports. From the MAREX data, vessel speed is known and the time when each vessel was maneuvering can be calculated.

The MAREX data was then combined with the Calculated Consumption data, which identified main engine fuel consumption during vessel maneuvering. By comparing pre- and post-Radical Retrofit trips, the intent was to evaluate effects of the Radical Retrofit on fuel consumption while maneuvering.

It should be noted that the energy efficiency improvements cannot be determined from the Calculated Consumption dataset because the main engine power needed to calculate energy usage was not available.

Table 5.3 contains the trips selected for analysis of maneuvering benefits. The *Gustav Maersk* was the only vessel in the list because it was the only vessel that had both pre- and post-Radical Retrofit FMS and Calculated Consumption data and visited the San Pedro Bay Ports during both pre- and post-Radical Retrofit periods.

Operating conditions were assumed to be similar for each pre- and post-Radical Retrofit trip because the vessel visited the same port, Port of Long Beach (POLB), and terminal each time.

Table 5.3: Pre- and Post-Radical Retrofit G-Class Vessel Visits for Maneuvering Analysis

Radical Retrofit Status	Port	Vessel Name	Arrival Date/Time	Departure Date/Time	Berth
Pre-RR	POLB	*Gustav Maersk*	2015-12-10 13:20	2015-12-14 20:50	T140
Post-RR	POLB	*Gustav Maersk*	2016-07-28 03:15	2016-08-01 06:05	T140
Post-RR	POLB	*Gustav Maersk*	2016-11-12 05:15	2016-11-15 06:30	T138
Post-RR	POLB	*Gustav Maersk*	2017-05-29 00:25	2017-06-01 05:30	T140
Post-RR	POLB	*Gustav Maersk*	2017-07-10 03:10	2017-07-14 04:20	T140
Post-RR	POLB	*Gustav Maersk*	2017-08-21 03:00	2017-08-25 04:35	T140
Post-RR	POLB	*Gustav Maersk*	2017-10-04 03:00	2017-10-08 20:10	T140
Post-RR	POLB	*Gustav Maersk*	2017-11-13 04:35	2017-11-17 18:40	T140
Post-RR	POLB	*Gustav Maersk*	2017-12-26 03:00	2017-12-31 06:25	T140

5.2 Findings
Similar to the Maersk analyses, the Starcrest analysis sought to quantify the benefits of the Radical Retrofit based on actual vessel operations. This was to be done for multiple vessel operational modes. The primary analytical objectives were to:

➢ Validate that the Radical Retrofit, under normal vessel cruise conditions (Performance Code 1), improves vessel energy efficiency;
➢ Quantify the energy efficiency improvements, fuel consumption reduction, and air pollutant emission reductions resulting from the Radical Retrofit for multiple operational modes (e.g., vessel transit, maneuvering);
➢ Factor in the impacts of the capacity increase and engine de-rating (i.e., lower power/fuel consumption) elements of the Radical Retrofit;
➢ Compare the Starcrest methodology results with those obtained by Maersk and Duke University.

5.2.1 Transit Operational Mode
As discussed above, Starcrest was successful in developing a dataset of MSPS Sea report matches for G-class vessels pre- and post-Radical Retrofit. This dataset was analyzed to understand how vessel performance varies pre- and post-Radical Retrofit under similar environmental and meteorological conditions. For the purpose of validating the performance impacts of the Radical Retrofit in a steady state transit mode, this analysis considered vessel speed through water, deadweight, and trim held to within the tolerances noted in Table 5.1.

It should be reiterated that the use of MSPS Sea reports as opposed to CAMS data increased the uncertainty in the findings. Although Starcrest attempted to mitigate this uncertainty by limiting the analysis to those data matches corresponding to sustained nominal vessel operations (Performance Code 1), the long duration of the reporting period – typically 24 hours - potentially obscured short-term deviations in vessel operational status or changes in environmental or meteorological conditions. This was noted during the analysis, as some data points appeared as "outliers" – substantially deviating from the norm and thus implicating that data point's validity. For that reason, these results should be considered inconclusive. A complete pre- and post-Radical Retrofit CAMS dataset is available for the Maersk Emma Class vessels. It is recommended that this high-fidelity data be used to conduct a follow-on Phase 2 analysis, as the CAMS data has the potential to substantially reduce the uncertainty associated with the results presented herein.

Table 5.4 illustrates a sample of a pre- and post-Radical Retrofit Sea report match and the degree of precision obtained in matching the vessel pre- and post-Radical Retrofit operational and meteorological conditions. It should be noted that the vessel speed is not the typical service speed for the G-class, it is closer to the design speed, which indicates the vessels were recovering from a delay.

Table 5.4: Sample Match Using MSPS Sea Report Data

Pre-/ Post-RR	Vessel Name	Report Period (hrs)	Draught Fore (m)	Draught Aft (m)	Draught Avg (m)	Sea Temp (C)	Vessel Speed (knots)	Wind Speed (knots)	Wind Direction (deg.)	Beaufort Number
Pre-RR	*Gudrun Maersk*	24	14.96	15	14.98	33	20.87	14.08	8°	3
Post-RR	*Gudrun Maersk*	24	15.2	15.2	15.2	34	20.83	15.39	9°	3

To reduce uncertainty in the analysis results, Starcrest attempted to match the MSPS pre- and post-Radical Retrofit vessel operational and meteorological parameters as closely as possible, developing a dataset of matched MSPS Sea Reports to within +/- 0.125 knot speed through water and +/- 0.25 meter average draught.

5.2.1.1 Radical Retrofit Efficiency Improvement Validation & Quantification
The matched MSPS Sea reports were further segregated into a transit operational mode with vessel speed through water between 18 and 22 knots. The efficiency improvement, represented by a reduction in required power, was found to be approximately 3%. This is the reduction in vessel power required to maintain a specified speed between 18-22 knots under similar conditions.

Energy Efficiency Analysis: Performance Code 1, Vessel Speed 18-22 knots

➤ Average Power Required in Transit Mode (kW): Approximately 3% lower post-Radical Retrofit

For vessel speed through water representative of Slow Steaming, i.e., vessel speed 18 knots +/- 1 knot, the energy efficiency improvement was greater and much closer to the values obtained by Maersk, with an average reduction in propulsion power on the order of 11% lower.

Energy Efficiency Analysis: Performance Code 1, Vessel Speed 18 +/- 1 knot

➢ Average Power Required in Transit Mode (kW): Approximately 11% lower post-Radical Retrofit

The above findings take into account power diverted from the main engine propulsion system to accommodate reefer loads, etc. It should be noted that the number of data points in the 18-knot vessel speed range was very limited, and due to the inherent uncertainty, this value requires further validation during a potential Phase 2 analysis. The data suggests that the engine de-rating element of the Radical Retrofit is effective under slow steaming transit operations. However, as noted above, the uncertainty in the analysis requires this data to be viewed as preliminary only. Because the uncertainty most likely is equal to or greater than the net benefit derived, the results cannot be considered conclusive proof of the effectiveness of the Radical Retrofit in improving vessel energy efficiency. The availability of CAMS data and more refined data analysis techniques will allow this aspect of the Radical Retrofit to be more thoroughly and precisely analyzed.

5.2.1.2 Fuel Consumption Benefits
Not all MSPS Sea reports provided adequate specific fuel oil (SFOC) consumption data. As such, the analysis of fuel consumption reductions attributable to the Radical Retrofit is incomplete. The limited data available yielded a net reduction in propulsion fuel consumption of approximately 3.1%. However, this was primarily assessed at higher vessel operating speeds greater than 20 knots. Further analysis is needed at lower vessel speeds to quantify the reduction in fuel consumption potentially attributable to the Radical Retrofit. As noted, this result also must be viewed as preliminary and non-conclusive, as the uncertainty in the data is potentially equal or greater than the analysis result.

5.2.2 Maneuvering Operational Mode
Analysis to determine energy efficiency and fuel consumption impacts of the Radical Retrofit for vessels operating in a maneuvering mode was conducted using MAREX data as a supplement to MSPS Port report data, and Calculated Consumption data.

The results of this analysis were inconclusive. This was due primarily to the difficulty in correctly matching temporally the Calculated Consumption data with MAREX data – Starcrest encountered cases where the timestamps associated with the Calculated Consumption data and MAREX data did not appear to be synchronized. Effort was expended to match the available data correctly; however, the results of the maneuvering analysis were inconclusive. Starcrest was unable to demonstrate any energy efficiency or fuel consumption benefit of the Radical Retrofit during vessel maneuvering.

5.3 Uncertainty Analysis

There was a relatively high degree of uncertainty in the results due primarily to three factors:

➢ **Reliance on MSPS data as opposed to CAMS data**. The CAMS data has a frequency of ten (10) minutes, whereas the MSPS Sea reports are filed on an approximately 24-hour frequency. Errors in parameter measurement as well as the potential for human error also introduce an uncertainty in the MSPS data values;

To mitigate the uncertainty associated with the use of MSPS data as opposed to CAMS data, only MSPS Sea reports filed under Performance Code 1 – Normal Cruise – were used for the transit data matching analysis. The primary uncertainties are in the areas of parameter measurement accuracy and human reporting accuracy. The magnitudes of these uncertainties are difficult to characterize analytically.

➢ **Precision in Matched MSPS Sea Report Data**. Starcrest endeavored to match pre- and post-Radical Retrofit data as closely as possible, within the tolerances shown above in Table 5.1. That said, from a power and fuel consumption standpoint, any variance between the pre- and post-Radical Retrofit data values introduces additional uncertainty into the analysis.

Starcrest also recognizes the uncertainty in the matched MSPS Sea reports used in the transit analysis. Starcrest applied the matching criteria shown in Table 5.1 to obtain a workable number of data matches. It would have been preferable to further tighten the match tolerance to obtain a more precise pre- and post-Radical Retrofit operating match; however, these attempts resulted in too few data points.

Vessel energy requirements and fuel consumption are strongly correlated with vessel speed through water and draught; for this reason, Starcrest established initial MSPS match criteria of +/- 0.25 knot and 0.5 meter, respectively. Vessel trim was matched to within +/- 0.1 meter.

Discussions with Maersk technical staff concluded that these variances could introduce an uncertainty in vessel fuel consumption on the order of 5% and as high as 12%. To mitigate this uncertainty, Starcrest identified MSPS Sea report data matches with vessel speed within +/- 0.125 knot and average draught +/- 0.25 meter. This reduction in the allowable variance between pre- and post-Radical Retrofit speed through water and draught reduces the uncertainty but does result in fewer matched MSPS Sea reports for subsequent analysis.

➢ **Effect of Biofouling on Engine Load**. The increased roughness of a vessel's hull caused by the accumulation of marine life (biofouling) increases hull frictional resistance can substantially increase fuel consumption. The rate of biofouling accumulation after a hull cleaning or repaint varies with vessel hull design, the geographical location and water temperature in which the vessel is sailing, the specific antifouling paint applied, etc. Biofouling has the potential to introduce a high level of uncertainty in an energy efficiency analysis. Lack of robust data to analyze the effect of biofouling over time created uncertainty in Starcrest analysis.

Studies have attempted to analytically derive methods to correlate the degree of biofouling as a function of time between hull cleanings, and subsequently develop friction factors that can be used to predict engine load increase and fuel consumption as a function of the increasing hull resistance.[9] Other studies have sought to collect empirical data on a per vessel basis to statistically derive curves that equate biofouling rate, hull resistance, engine load increase, and fuel consumption increase as a function of time.[10]

The Maersk Vessel Performance team completed an analysis of the impact of hull cleaning and painting during the Radical Retrofit on fuel consumption. Their findings for all twelve G-class vessels combined indicated that the cleaning and painting during the Radical Retrofit resulted in about a 3% reduction in fuel consumption. In other words, on average, the fuel consumption decreased by about 3% when comparing the four months prior to the retrofit with the four months immediately following the retrofit. Findings for the Gerda Maersk and Gustav Maersk, the two vessels with pre-Radical Retrofit FMS data, indicated that the cleaning and painting during the Radical Retrofit resulted in about a 1% reduction in fuel consumption.

These findings are lower than what is seen in published studies because Maersk strives to keep the impact of biofouling at a minimum. The cleaning and painting during the Radical Retrofit had an especially small impact on the Gerda Maersk and Gustav Maersk because these two vessels were only about half-way into their dry-docking cycle of five years when the retrofit was carried out; therefore, the paint was still likely in good condition. Since the last dry-docking, they also had their propellers polished several times, which would have kept the impact of fouling at bay.

The difference between the 3% decrease in fuel consumption for all twelve G-class vessels versus the 1% decrease in fuel consumption for the Gerda Maersk and Gustav Maersk is reflected by where the vessels were in their dry dock cycles at the time of the Radical Retrofit. The 3% decrease for all twelve G-class vessels is an average that includes vessels that were quite clean and with paint in good condition when they were retrofitted (like the Gerda Maersk and Gustav Maersk) and also vessels that were due for their 5-year dry-dock and likely had paint in worse condition.

It should be noted that the degradation of performance due to fouling is not necessarily linear, so these findings are not average numbers for a certain period. They are indicative of the impact of cleaning and repainting at the stage of paint degradation of the twelve G-class vessels before they received the Radical Retrofit.

---

[9] Demirel, Y. K., Uzun, D., Zhang, Y., Fang, H.-C., Day, A. H. & Turan, O. (2017) "Effect of Barnacle Fouling on Ship Resistance and Powering", *The Journal of Bioadhesion and Biofilm Research*, Biofouling, 33:10, 819-834, DOI: 10.1080/08927014.2017.1373279

[10] Adland, R., Cariou, P., Jia, H. & Wolff, F-C. (2018). "The energy efficiency effects of periodic ship hull cleaning". *Journal of Cleaner Production*. 178. DOI: 10.1016/j.jclepro.2017.12.247.

An alternative biofouling analysis approach attempted by Starcrest was to include an additional parameter in the pre- and post-Radical Retrofit MSPS Sea report matching criteria. The additional criterion would limit pre- and post-Radical Retrofit MSPS Sea report matches to those that took place within a specified time from the last hull cleaning. The dates associated with hull cleanings for the G-class vessels are known. This approach would effectively eliminate biofouling as an influencing parameter in energy efficiency and fuel consumption analysis, as the only MSPS data to be used was associated with vessel trips that occurred within a specified timeframe since the most recent hull cleaning.

Starcrest attempted to implement this approach to mitigate the influence of biofouling and associated uncertainty in the energy efficiency analyses. However, it was determined that there was no pre-Radical Retrofit data available immediately following a hull cleaning.

Given the inherent uncertainty in MSPS data due to the reporting period duration and the potential for data recording inaccuracies, uncertainties in vessel power and fuel consumption due to variance in pre- and post-Radical Retrofit data matching, and the influence of biofouling, it must be recognized that the uncertainty associated with the analysis results may exceed the expected value of the energy efficiency improvements.

However, this is a general overarching issue with all of the analyses presented, and this is also a primary motivation for moving towards automatic data logging of the most critical vessel performance measures, such as CAMS and FMS. It is important to recognize, however, that, the higher fidelity CAMS data require validation, filtering, and processing. These processes are still undergoing development by Maersk for the CAMS and FMS logged data.
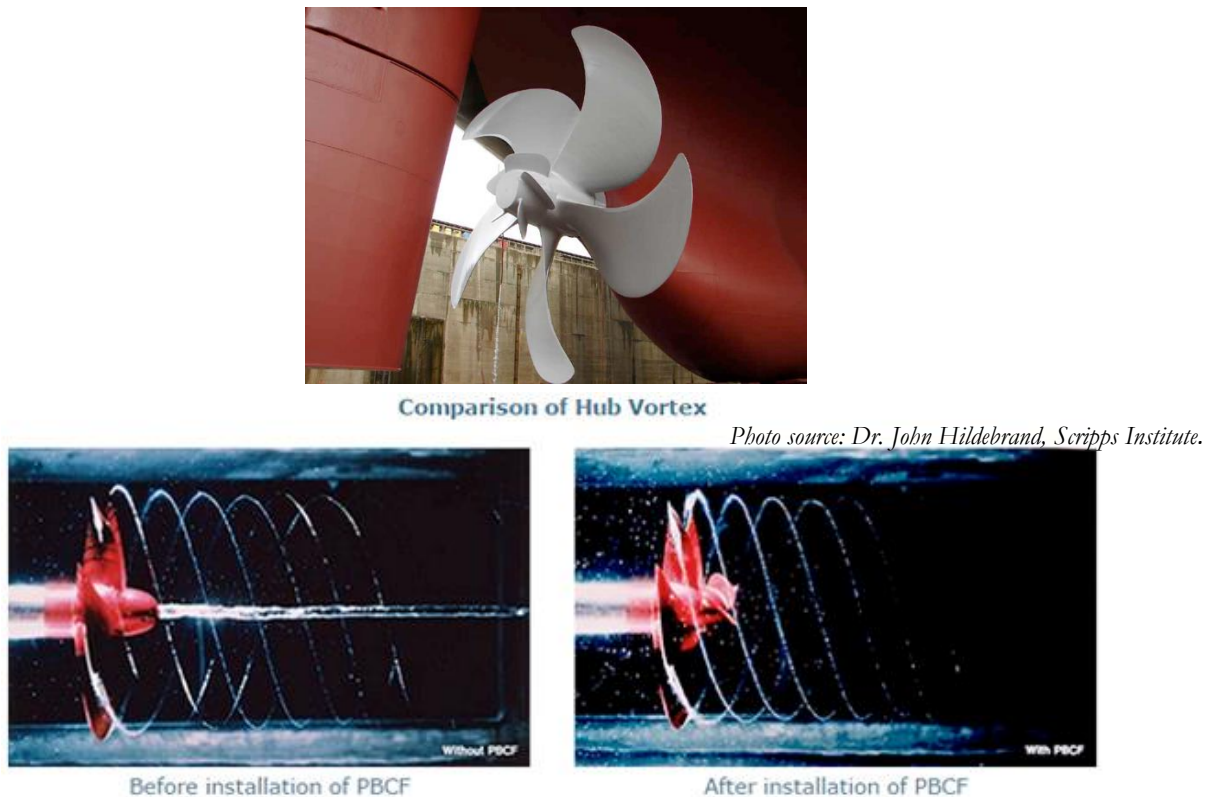
SECTION 6 THE SCRIPPS INSTITUTION OF OCEANOGRAPHY UNDERWATER NOISE STUDY

Over the last decade, marine biology researchers, governmental agencies and non-governmental organizations (NGOs) have increasingly recognized that underwater sound can negatively impact life functions of marine mammals and other species. Such negative impacts include interfering with communications between animals, hunting/feeding behaviors, mating, and interactions of mothers and calves. Particular concerns have been raised about the impacts of underwater noise on endangered species such as the Southern Resident Killer Whales and North Atlantic Right Whales. Activity in this area has been increasing by National Oceanic and Atmospheric Administration (NOAA), National Resources Defense Council, Inc. (NRDC), the Enhancing Cetacean Habitat and Observation (ECHO) program in Vancouver BC, Transport Canada's work to activate IMO to act on this emerging issue, and work by the Vancouver Aquarium and the New England Aquarium.

Commercial vessels have been identified as sources of underwater sound, with cavitation related to propulsion systems making the primary contribution.

Maersk's intent in the overall Radical Retrofit program was clearly energy efficiency. The Radical Retrofit technology selection process included a goal of reducing cavitation around the propulsion system to improve energy efficiency and reduce maintenance needs. Specifically, the G-class retrofits and many of the other classes in the program included installations of cavitation reduction technologies such as propeller boss caps fins (PBCF), as presented in Figure 6.1 below.

Figure 6.1: Propeller Boss Caps Fins and Comparison of Hub Vortex Effects

Comparison of Hub Vortex

Photo source: Dr. John Hildebrand, Scripps Institute.

Before installation of PBCF

After installation of PBCF

This TAP brought focus to the G-class vessel retrofits while these other programs were also raising awareness and initiating actions. These simultaneous activities led to the recognition that the cavitation reduction aspects of the Radical Retrofits could potentially provide co-benefits such as reducing the generation of underwater noise.

Maersk was fortunate to learn about a unique database of underwater sound measurements. Professor John Hildebrand of Scripps Institution of Oceanography has been making in-water vessel sound measurements for over 10 years in the Santa Barbara Channel. The Maersk G-class vessels were among the many vessels measured in this study, since they pass through this area traveling between Asia and the Ports of LA and Long Beach.

In 2017 Maersk worked with Drs. Gassmann, Wiggins, and Hildebrand of Scripps Institution of Oceanography to define the impact of the retrofits on underwater radiated noise. [11] Scripps' data was sufficient on 5 of the Maersk G vessels to allow evaluation before and after the retrofits.

This study showed a clear co-benefit to the retrofit: reduction in underwater noise generation (Sound Pressure Levels (SPL)). The estimated underwater sound pressure levels of the five selected vessels were lower for post-retrofitted vessels by a median of 6 dB in the low-frequency band (8 - 100 Hz) and a median of 8 dB in the higher-frequency band (100 - 1000 Hz). These are the low and mid-range frequencies which are believed to impact marine mammals. This is a significant finding: a 6-decibel change is a 75% reduction in source sound pressure levels. Pre- and Post-Radical Retrofit underwater sound pressures levels are illustrated in Figures 6.2 and 6.3.

Figure 6.2: Pre- and Post-Radical Retrofit Underwater Sound Pressure Levels (Low Frequency)
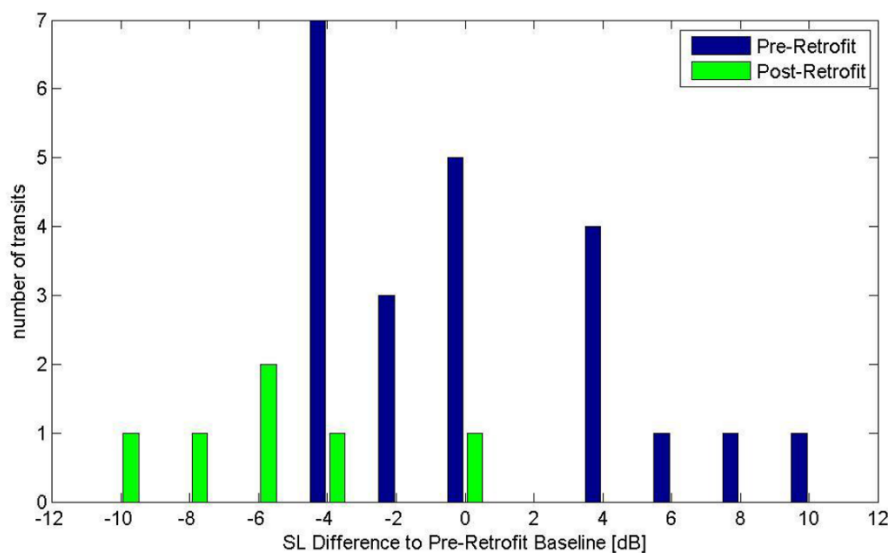
Sound Pressure Levels in the Low Frequency range 8-100 Hz SPL

---

[11] Gassmann, M., Kindberg, L. B., Wiggins, S. M. & Hildebrand, J. A. (2017). Underwater Noise Comparison of Pre- and Post-Retrofitted MAERSK G-Class Container Vessels. *Marine Physical Laboratory, Scripps Institution of Oceanography, University of California San Diego.* Retrieved from *http://cetus.ucsd.edu/Publications/Reports/GassmannMPLTM616-2017.pdf*
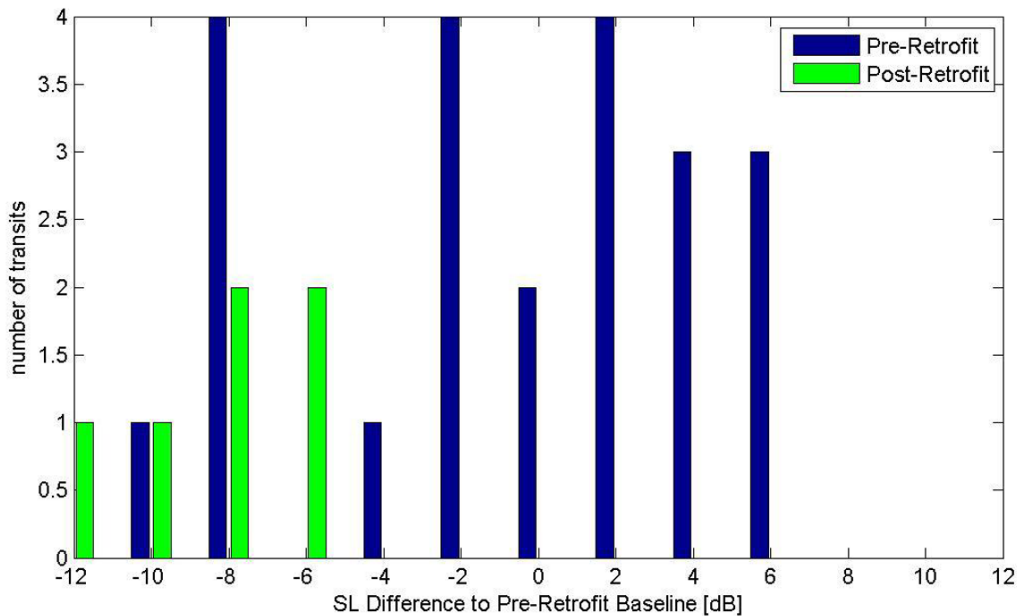
Figure 6.3: Pre- and Post-Radical Retrofit Underwater Sound Pressure Levels (High Frequency)

Sound Pressure Levels in the Mid-range Frequencies 100-1000 Hz SPL

The Scripps' scientists concluded that **"Reductions of ship source sound pressure level due to changes such as those employed by the radical retrofits may result in ocean-basin-wide noise reductions."**

These reductions are believed to result from less cavitation due to both the retrofitted propellers with boss cap fins, and from propeller operation at greater depth where ambient pressure is higher. The greater propeller depth is a result of the deeper draft that the G-class vessels experience post-retrofit due to increased TEU capacity.

Disclaimer – It should be noted that the global fleet cannot be extrapolated from the results of the Maersk fleet. Each segment is different and even inside the same sector retrofits are often on ship by ship basis projects with some variation in the results.

In addition to the Scripps' researchers, support to this study was also provided by:

➢ Data on ship specifications and operations was provided by the Master and Chief Engineers of the G-class vessels, as well as Maersk Naval Architects in Copenhagen and the Maersk Global Vessel Performance Center in Singapore.
➢ Financial support to the Scripps' study was provided by NRDC (Michael Jasny), International Fund for Animal Welfare (IFAW) (Patrick Ramage) and the Ocean Foundation (Mark Spaulding and Caroline Coogan).

SECTION 7 CONCLUSIONS & RECOMMENDATIONS

7.1 Conclusions
The conclusions from the TAP Project are as follows:

7.1.1 Maersk, Duke University, and Starcrest Studies
Each of the three independent analyses conducted by the Project Core Team incorporated a different technical approach. Maersk developed a technical approach where fuel economy improvements were assessed based on actual operational profiles within the context of statistical power curves and main engine SFOC being a function of vessel speed and draught. Based on the vessel's operational profile, the average transport efficiency was calculated for pre- and post-Radical Retrofit cases. The difference between the results provides an indication of the combined impact of both the improved propulsion performance and the increased capacity. Based on the methodology, Maersk's findings of the impact of the Radical Retrofit of the G-class vessels were an average reduction in fuel consumption of approximately 5% and improvement in transport efficiency (g fuel/TEU/nm) of approximately 8%.

The Duke University study sought to estimate fuel consumption and emissions reductions pre- and post-Radical Retrofit using main engine load and RPM as control variables. Using a linear regression analysis approach, Duke University estimated a 19.6% fuel consumption reduction attributable to the Radical Retrofit.

Starcrest applied an approach in which the vessel operational and meteorological profiles were closely matched. This was done to isolate the energy efficiency improvements of the Radical Retrofit itself, irrespective of the vessel capacity increase. While preliminary results were along the lines of those obtained by Maersk and Duke University, Starcrest views these results as statistically inconclusive due to the inherent uncertainty associated with the MSPS Sea reports as well as the unknown impacts of hull and propeller biofouling on vessel performance.

None of the principal investigators were able to differentiate energy efficiency and fuel consumption improvements between vessel operational modes. This was a limitation of the available data. As noted, Starcrest attempted to analyze the benefits of the Radical Retrofit on vessel maneuvering by combining MSPS Port reports, Calculated Consumption data, and MAREX data, but was unable to obtain a conclusive result.

7.1.2 Scripps Institution of Oceanography Underwater Noise Study
Over the last decade marine biology researchers, governmental agencies and NGOs have increasingly recognized that underwater sound could negatively impact life functions of marine mammals and other species. Such negative impacts include interfering with communications between animals, hunting/feeding behaviors, mating, and interactions of mothers and calves. Particular concerns have been raised about the impacts of underwater noise on endangered species such as the Southern Resident Killer Whales and North Atlantic Right Whales.

The Scripps-Maersk study successfully demonstrated a quantifiable and significant reduction in the low and mid frequency ranges that are believed to impact marine mammals and other species. The measured reductions from five of the G-class ships was 75% lower in source sound pressure levels compared to the ship's pre-Radical Retrofit configuration. This is believed to a result of the new propellers with PBCFs and propeller operation at greater depths where ambient pressure is higher.

Efficient propellers and PBCFs are good for energy consumption, associated air emissions, and reducing underwater noise.

7.1.3 Ocean-Going Vessel TAP Projects Experience
In addition to the technical challenges of the Project objective, significant administrative and logistical challenges were encountered over the life of the project that provided insight into how to better align future TAP OGV projects, related to TAP administrative sequences, inflexible ship drydock timelines, and a company-wide cyber-attack that refocused Maersk project resources for a significant amount of time.

Due to the phased implementation of the Radical Retrofits, the installation of fuel and energy monitoring equipment, and the Connected Vessel Program, the data produced by this equipment became available at different stages of the project duration. Maersk was able to 'pull ahead' the installation of FMS systems on two vessels prior to the Radical Retrofit during the TAP administrative process, and a third vessel after the contract was executed, in an effort to collect detailed data prior to retrofitting; however these systems were in the "Proof-of-Concept" phase. Maersk further manually collected engine management system data (pre-CAMS) from four pre-Radical Retrofit G-class vessels using USB data stick drives. In the end data on USB could not be used because the association of which USB drive belonged to which vessel was lost, and some data appeared to be corrupted. .

Maersk was hit by system-wide cyber-attack in June 2017, which was extremely disruptive and tied up a substantial amount of the company's resources for months. Furthermore, vessel data was not accessible for a significant amount of time as the company's Information Technology group worked to reestablish the company's systems and secure servers. This was a major unforeseen event that significantly impacted the project's resources and timeline.

7.2 Recommendations
The following recommendations are made by the TAP Project Core Team:

1. Maersk has conducted an internal review of the Radical Retrofit program and has determined that the *Emma Maersk* class ships, which just started calling the San Pedro Bay Ports, has significant pre- and post-Radical Retrofit FMS and CAMS data. Biofouling data should be available for these ships as well. It is recommended that the Emma Class be evaluated as to their potential for furthering the progress made on the G-class vessels.

2. Maersk recommends conducting a second analysis of the energy efficiency improvements of the Maersk Radical Retrofit program using pre- and post-Radical Retrofit CAMS and FMS data from the Emma Class vessels. These datasets are logged at ten (10) minute measurement durations as opposed to ~24-hour periods and include high-fidelity energy efficiency and fuel consumption data. These datasets are also available for all vessel operational modes and would provide the high-fidelity data needed to more accurately quantify Radical Retrofit benefits.

    In conducting this follow-on analysis, Maersk would collaborate with the Project Core Team to 1) ensure data and data fields that were sought in this study are available pre- and post-Radical Retrofit, 2) more fully develop a technical approach to reduce the uncertainty associated with the results, and 3) the methodology developed to assess the benefit of Radical Retrofit is compatible such that it can be included in SPBP annual ocean going vessel emissions inventories. Maersk expects the energy efficiency and fuel consumption benefits attributable to the Radical Retrofit to be on the order of 5%-10%; as such, the uncertainty associated with the data must be either absolutely or statistically, significantly less than 5%.

    Additionally, Maersk and Starcrest recommends continued effort to quantify and incorporate the effects of hull and propeller biofouling on vessel performance.

3. If the project proceeds further based on high-fidelity data from *Emma Maersk* class and quantification the energy efficiency improvements, fuel consumption reduction, and air pollutant emission reductions resulting from the Radical Retrofit during vessel transit and maneuvering operational modes are completed, the next step would be to incorporate these reductions into SPBP annual ocean-going vessel emissions inventory for those vessels that have undergone Radical Retrofit improvements. For this step, the high-fidelity data should be analyzed and managed such that it can reflect a similar resolution of the operational and emissions data used to estimate ship emissions during transit and maneuvering mode for the emission inventories. As an example, ship speed and time data needed for emissions calculations during transit is obtained as averages in 5 nautical miles intervals. The emissions factors used are based on marine engine duty cycle and very limited data is available to assess the difference in emissions by engine load.

4. High-fidelity CAMS, FMS, and Calculated Consumption datasets were provided to Starcrest Consulting Group in the form of SQL Server database backups, along with database schemas, and SQL code examples that demonstrated how to access the data. This was an efficient way to share data, which was on the order of approximately 20 gigabytes (GB). Additionally, a data dictionary was provided with data field names and units for the CAMS and FMS datasets. However, the data dictionary didn't contain detailed descriptions for each data field because the CAMS and FMS systems were still under development. As a recommendation for future projects, it would be helpful to have a complete data dictionary with a detailed description each data field – what it encompasses, how it was measured or calculated, and the level of uncertainty in the measurement or calculation. In turn, this information could then be used to assist in analyzing the impact of the Radical Retrofit on energy efficiency and fuel consumption.

5. Given the inherent uncertainty in traditional MSPS data due to the reporting period duration and the potential for data recording inaccuracies, uncertainties in vessel power and fuel consumption due to variance in pre- and post-Radical Retrofit data matching, and the influence of biofouling, it must be recognized that the uncertainty associated with the analysis results may exceed the expected value of the energy efficiency improvements. This is a general overarching issue with all of the analyses presented, and this is also a primary motivation for moving towards automatic data logging of the most critical vessel performance measures such as CAMS. It is important to recognize and recommend, however, that, the higher frequency CAMS data will still require validation, filtering, processing, and analysis by knowledgeable reviewers to ensure data is usable to demonstrate results and minimize uncertainties.

6. The TAP Project Core Team debrief with both Port's TAP Teams to discuss lesson learned, potential future integration with emissions inventories, and the unique challenges of conducting TAP projects on ocean-going vessels to maximize the effectiveness of future TAP ocean-going vessel projects. This is crucially important as ships are the dominant source of air pollutants within the emission inventories' geographical domain and with the developments of IMO's carbon reduction strategies at the international level.

ATTACHMENT 1

Scripps Institution of Oceanography, University of California San Diego Report "Underwater noise comparison of pre- and post- retrofitted Maersk G-class container vessels", MPL TM-616, October 2017

Underwater noise comparison
of pre- and post-retrofitted
MAERSK G-class container vessels

(c) Jan Svendsen

Martin Gassmann, Lee B. Kindberg, Sean M. Wiggins
and John A. Hildebrand

Marine Physical Laboratory
Scripps Institution of Oceanography
University of California San Diego
La Jolla, California 92093-0205
martin.gassmann044@gmail.com

Contents

Executive Summary

As part of a radical retrofit program, MAERSK LINE, the world's largest container shipping company, has modified eleven G-class container vessels in the years of 2015 and 2016 under an investigative and energy-efficiency improvement effort. As the radical retrofit includes replacing the bulbous bow to reduce drag, derating the main engines for slow steaming and installing more efficient propellers with propeller boss cap fins to reduce cavitation, another benefit of the retrofit may be reduction in underwater radiated noise.

The Marine Physical Laboratory at the Scripps Institution of Oceanography has opportunistically recorded underwater noise radiated by commercial vessels, including MAERSK G-class vessels before and after their retrofits, as they transit from the ports of Los Angeles (POLA) and Long Beach (POLB) in the northbound shipping lane through the Santa Barbara Channel off the coast of California. Five MAERSK G-class vessels, GRETE, GUDRUN, GUNVOR, GERDA and GERNER, were selected to compare the underwater radiated noise before and after the vessels' radical retrofits, utilizing a total of 36 transits at speeds between 4 m/s and 11 m/s.

The estimated underwater source sound pressure levels of the five selected MAERSK G-class vessels were found to be lower for post-retrofitted vessels by a median of 6 dB in the low-frequency band (8 - 100 Hz) and a median of 8 dB in the high-frequency band (100 - 1000 Hz), when compared to pre-retrofitted vessel estimated source sound pressure levels. The reduction in source sound pressure levels, in particular in the low-frequency band, may result from less cavitation due to both the retrofitted propellers with boss cap fins, and to propeller operation at greater depth where ambient pressure is higher.

Reductions of ship source sound pressure level due to changes such as those employed by the radical retrofits may result in ocean-basin-wide noise reductions.

Background

Underwater noise from shipping is a significant contributor to low-frequency ambient noise (<100 Hz) in the ocean (Wenz, 1962; Hildebrand, 2009). It is unintentionally generated by the ships' movement through the water and by the ships' auxiliary and propulsion machineries, in particular propellers (Urick, 1975; Ross, 1976). The cavitation processes occurring near the tip of rotating propellers generate underwater noise over a broad frequency range and at a series of distinct frequencies that is related to the propeller blade rate and therefore to a ship's speed (Gray and Greeley, 1980). Ships that operate at higher speeds have been observed to radiate underwater noise at a higher intensity into the marine environment (Jansen and de Jong, 2015; Simard *et al.*, 2016).

Various animals in marine environments, such as whales and dolphins, rely on underwater sound to navigate, feed and communicate. Given the high intensity of ship underwater radiated noise and its low-frequency, long-range propagation, environmental concerns about noise contributions from commercial shipping have been raised at both, the regional and the global level, e.g. (Erbe *et al.*, 2012; Redfern *et al.*, 2017).

As the global seaborne trade has doubled over the last couple of decades with a volume of over 10 billion tons in the year of 2015 alone, the world commercial shipping fleet has grown dramatically (UNCTAD, 2016) . As of January 1st, 2016, the world commercial fleet consisted of 90,917 vessels in total with a combined capacity of 1.8 billion deadweight tonnage (DWT). Vessels for containerized cargo, referred to as container vessels, have concurrently not only increased in number, but also in their cargo capacity and as a result have become significantly larger. While a larger container vessel may require for the same amount of cargo less transits than a smaller container vessel, larger container vessels, however, have been observed to radiate underwater noise during their transits at a higher intensity into the marine environment, as more energy is needed for their operation (McKenna *et al.*, 2013).

The world's largest container shipping company, MAERSK LINE, has been investing significantly to investigate and improve the energy efficiency and greenhouse gas emissions performance of its fleet (MAERSK LINE, 2017). As part of this work, eleven out of twelve MAERSK G-class container vessels underwent a $100+ million Radical Retrofit Program. This includes replacing the bulbous bow to reduce drag, derating the main engines for slow steaming and installing more efficient, four-bladed propellers with propeller boss cap fins to reduce cavitation, which may also reduce the underwater noise radiated by retrofitted MAERSK G-class vessels during their operation (Figure 1).
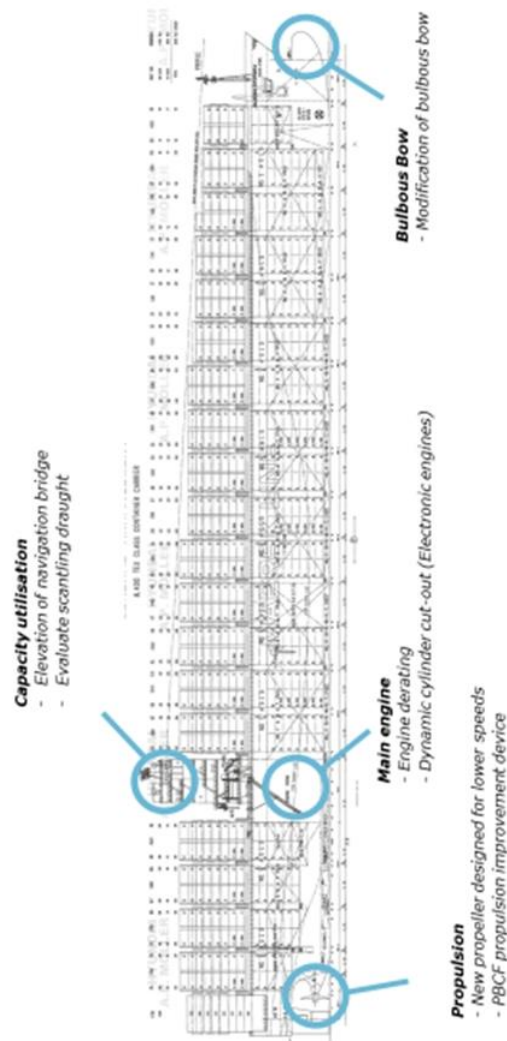

Figure 1 Components of Radical Retrofit applied to MAERSK G-class vessels

The goal of the Radical Retrofit Program is to reduce fuel consumption through increased efficiency and to increase cargo capacity by over 1,000 twenty-foot-equivalent units (TEU). These vessels are also now part of a Technology Advancement Project funded by the Ports of Los Angeles and Long Beach which will relate these efficiency improvements to air emissions and greenhouse gases.

The Marine Physical Laboratory at the Scripps Institution of Oceanography has made opportunistic recordings of underwater noise radiated by commercial vessels, including MAERSK G-class vessels before and after their retrofits, as they transit from the ports of Los Angeles (POLA) and Long Beach (POLB) in a shipping lane through the Santa Barbara Channel off the coast of California. To compare the underwater radiated noise before and after the vessels' radical retrofits, five MAERSK G-class vessels that were retrofitted in 2015 and 2016 were selected: GRETE MAERSK, GUDRUN MAERSK, GUNVOR MAERSK, GERDA MAERSK and GERNER MAERSK (Table 1).

Table 1 MAERSK G-class vessels selected for analysis.

Vessel IMO	2015 VSL Vessel Name	Vessel Class	Keel Laid Date	Radical Retrofit Completion Date
9359052	GERDA MAERSK	L-211	02-Sep-2008	06-Mar-2016
9359002	GERNER MAERSK	L-211	20-Oct-2007	02-Jul-2016
9302889	GRETE MAERSK	L-197	05-Nov-2004	05-Sep-2015
9302877	GUDRUN MAERSK	L-197	10-Dec-2004	14-Aug-2015
9302891	GUNVOR MAERSK	L-197	01-Jan-2005	08-Oct-2015

Methods

Experimental Setup

Long-term recordings of underwater sound pressure levels were made near shipping lanes off the coast of California in the Santa Barbara Channel by the Marine Physical Laboratory at the Scripps Institution of Oceanography since 2008 (McKenna *et al.*, 2012a; McKenna *et al.*, 2012b) (Figure 2). For the last nine years, underwater sound was recorded by a High-frequency

Acoustic Recording Package (HARP) at a sampling frequency of 200 kHz with a single hydrophone approximately 20 m above the seafloor at 565 m water depth (Wiggins and Hildebrand, 2007). The HARP was deployed (34° 16.53 N 120° 1.11 W) 3 - 4 km north from the center of the 1 nm (1.852 km) wide northbound shipping lane for merchant ships that transit from the POLA and POLB through the Santa Barbara Channel (Figure 2).
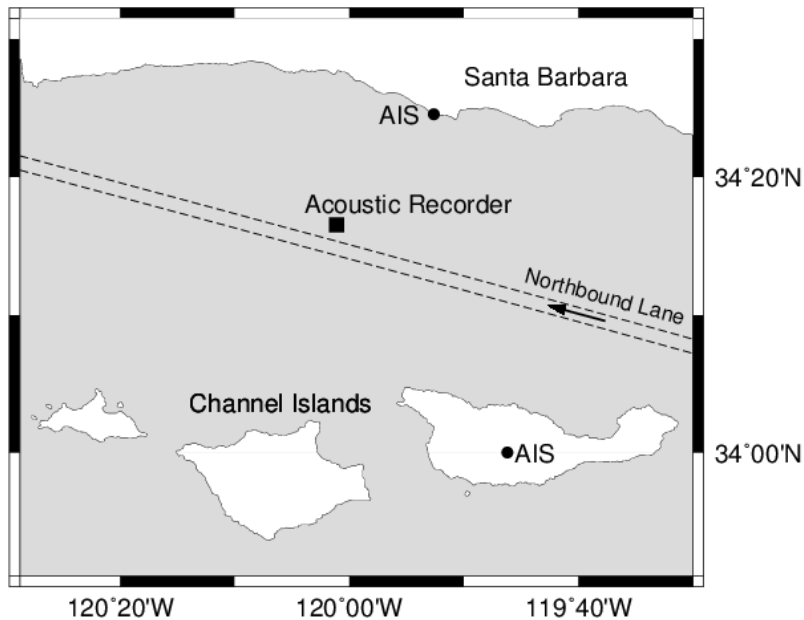

Figure 2 Map of the Santa Barbara Channel showing the locations of the underwater acoustic recorder (square) and the AIS receivers (circles). Dashed lines represent shipping lane with arrow indicating the direction of travel.

Vessel Identification and Tracking

To identify and track MAERSK G-class vessels that transit by the HARP in the northbound shipping lane, position, speed, and vessel data from the Automatic Identification System (AIS) were collected. AIS receivers were located on Santa Cruz Island (33° 59.6670 N and 119° 37.9410 W) and Coal Oil Point (34° 2 4.5320 N 119° 52.68216 W) to provide coverage for the northbound shipping lane and its vicinity (Figure 2). The received AIS messages were time-stamped and continuously logged on-site by a computer. AIS messages were decoded with the Shipplotter program (ver. 12.4.6.5 COAA) and software developed by Robin T. Bye (Project: Virtual More) to search for messages from MAERSK G-class vessels that contain position

(latitude and longitude), ship's reference point for the reported position and Speed Over Ground (SOG). These messages were then filtered to retain only messages with positions that were less than 30 km away from the HARP. As the AIS messages were received typically every 10 – 20 s during which the ship speed was presumed to be linearly changing, the positions and SOGs of the filtered AIS messages were linearly interpolated to yield an AIS-derived track with a time resolution of 3 s for any of the transits of the five MAERSK G-class vessels.

Acoustic Data Processing

The timing information of the AIS-derived tracks was used to identify transits of the selected MAERSK G-class vessels in the HARP acoustic recordings. Each identified acoustic record containing the underwater radiated noise from a transiting MAERSK G-class vessel was then downsampled by factor of 20 to yield a Nyquist frequency of 5 kHz. This provides computational savings as the underwater radiated ship noise is mostly absent at frequencies greater than 5 kHz. The downsampled record was then manually examined for corruption from electronic noise and interference from other ships or marine mammals to exclude corrupted records from further processing. To minimize the number of excluded records, the lower and upper limit of the frequency range of interest was set to 8 Hz and 1 kHz, respectively. Start time and length of each record were determined from the time of the closest point of approach (CPA) of the ship's bow and the duration for the ship to travel its own length (35 - 90 sec for SOGs between 11 and 4 m/s), respectively.

Received Sound Pressure Levels

Each of the selected, downsampled acoustic records was divided into consecutive, non-overlapping segments with a length of 1 s (10,000 samples). A two-sided Fast Fourier Transform (FFT) with 10,000 points (NFFT) was applied to each segment to provide a frequency bin spacing of 1 Hz. The magnitude squared values of the complex FFT coefficients for the positive frequencies were multiplied by $2/NFFT^2$ to account for the processing gain of the FFT. Their mean was computed for each frequency bin, $|\overline{FFT}|^2$, and then converted onto a relative logarithmic scale in decibels (dB) with a reference pressure of 1 µPa². This quantity is the received sound pressure level (RL):

$$RL = 10log_{10}\left(\frac{|\overline{FFT}|^2}{(1\mu Pa)^2}\right)$$

The frequency distribution of RL will be referred to as RL spectrum and will be shown for 1 Hz bands and for one-third-octave (OTO) bands.

Source Sound Pressure Levels

The source sound pressure level (SL) of underwater radiated noise of each of the five MAERSK G-class vessels was estimated at a reference distance of 1 m using the RL at the HARP and by accounting for the loss in sound transmission (TL) during each transit:

$$SL = RL + TL$$

The TL between the radiating ship and the receiving hydrophone of the HARP was computed with a Lloyd's mirror model to account for the losses caused by interference from surface reflections that are significant for sources at near-surface depths (Gassmann *et al.*, 2017). For this model, the complex horizontal and vertical source distribution of a ship is reduced to a single point source with an effective source depth. The effective source depth of the ship during each transit was computed from her draft measured at her aft minus 85% of her propeller diameter (Gray and Greeley, 1980). Pre- and post-retrofit propeller diameters for all MAERSK G-class vessels were 9 m and 9.3 m, respectively. Propeller offset from the keel line was assumed to be negligible. In addition, slant ranges from the locations of the ship's propeller to the hydrophone of the HARP were computed for the Lloyd's mirror model.

Drafts and slant ranges for the transits of the selected MAERSK G-class vessels that were used in the Lloyd's mirror model are shown for the years 2011-2017 in Figure 3. All drafts of the post-retrofitted MAERSK G-class vessels were greater than 12 m while drafts of the pre-retrofitted vessels were shallower between 9 – 12 m, except for one pre-retrofit transit of GRETE and GERNER (upper panel in Figure 3). This is presumably due to the increased cargo capacity of the retrofitted MAERSK G-class vessel by over 1,000 twenty-foot equivalent units (TEU), which causes the retrofitted vessels to travel with a greater draft. Slant ranges varied between 3.4 and

5 km (center panel in Figure 3), presumably due to the course chosen by the MAERSK G-class vessels in the 1.852 km wide shipping lane. No significant difference in slant range between pre- and post-retrofit transits was found. Furthermore, SOGs varied by transit between 4 – 11 m/s with all post-retrofit SOGs below 8 m/s (lower panel in Figure 3).

The frequency distribution of SL will be referred to as SL spectrum and will be shown for 1 Hz bands and for one-third-octave (OTO) bands.

Determination of Differences in Received Sound Pressure Levels and in Source Sound Pressure Levels due to Retrofitting

To distinguish between noise radiated by the propeller and by other ship machinery such as generators, the frequency range of interest (8 - 1000 Hz) was divided into low (8 - 100 Hz) and high (100- 1000 Hz) frequency bands. For each band and transit, a one RL and one SL value was computed by integrating over the magnitude-squared pressure values of the respective band. The lower limit of 8 Hz was selected to minimize the impact of pressure fluctuations due to ocean waves on the recorded signal (Webb, 1998).

The SOG-dependent RL and SL distributions for the low- and high-frequency band were divided further into pre- and post-retrofit sub-distributions resulting into four RL and four SL sub-distributions. First-order polynomials were fitted to each of the eight SOG-dependent sub-distributions by using a Theil-Sen robust linear regression algorithm (Gilbert, 1987) as a means for predicting the contribution of ship speed to the radiated noise.

The first-order polynomials fitted to the pre-retrofit distributions establish the pre-retrofit base lines for RL and SL in the low- and high-frequency band. Differences between these pre-retrofit base lines and the post-retrofit distributions were computed and charted as histograms with a bin size of 2 dB to evaluate changes in received and source sound pressure levels due to retrofitting. To characterize the goodness of fit of the first-order polynomials for the pre-retrofit base lines, differences between the pre-retrofit base lines and the pre-retrofit distributions were computed and charted also as histograms with a bin size of 2 dB.
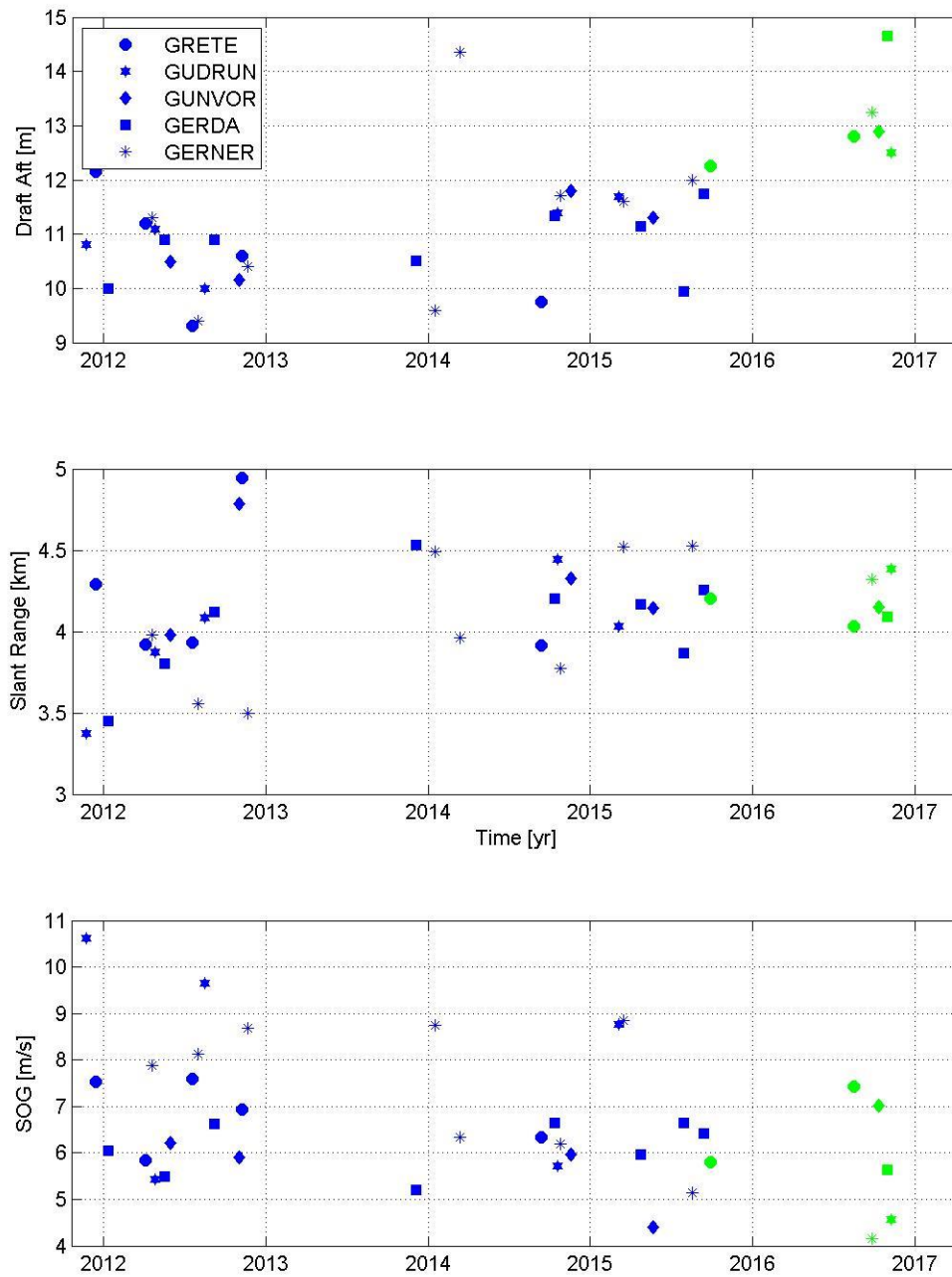
Figure 3 Draft, speed (SOG,) and slant range at the closest point of approach to the acoustic recorder for transits of GRETE (circles), GUDRUN (hexagrans), GUNVOR (diamonds), GERDA (squares) and GERNER (stars) between December 2011 and November 2016. Pre- and post-retrofit values are represented by blue and green symbols, respectively.

Results

A total of 36 transits of the five selected MAERSK G-class vessels were used to compute RL and SL spectra. To exemplify the dependence on speed and differences due to retrofitting, RL and SL spectra of three transits from the GUDRUN MAERSK are shown in Figure 4. For the transit at low speed (5.7 m/s), the values of the RL spectrum are generally lowest (red line, upper panel in Figure 4). Values of the RL spectrum for the high-speed, post-retrofit transit (9.3 m/s) are similar for frequencies smaller than 100 Hz or lower for frequencies greater than 100 Hz than for the high-speed, pre-retrofit transit (9.7 m/s) (upper panel in Figure 4). In contrast, the values of the SL spectrum for the high-speed, post-retrofit transit are generally lower than for the high-speed, pre-retrofit transit while being greater or similar than for the low-speed transit (lower panel in Figure 4). A complete presentation of the RL and SL spectra from all transits in 1 Hz and one-third octave (OTO) bands can be found in Appendix A.

Pre- and post-retrofit RL and SL distributions along with the fitted, speed-dependent baselines are shown for the low-frequency (8 - 100 Hz) and high-frequency (100 - 1000 Hz) band in Figure 5 and Figure 6, respectively. For the dominant low-frequency band, there are no significant differences between the pre- and post-retrofit RL distribution yielding a maximum difference between the pre- and post-retrofit baselines of less than 1 dB (upper panel in Figure 5). In contrast, the baseline for the post-retrofit SL distribution is significantly lower than for the pre-retrofit SL distribution by 3 – 8 dB, depending on vessel speed (lower panel in Figure 5). SLs for the post-retrofitted vessels range from 188 dB re 1μPa m (8-100Hz) at a SOG of 4.4 m/s to 205 dB re 1μPa m (8-100Hz) at a SOG of 9.3 m/s while SLs for pre-retrofitted vessels ranged from 190 dB re 1μPa m (8-100Hz) at 4.5 m/s to 214 dB re 1μPa m (8-100Hz) at 10.6 m/s. For the high-frequency band, the baselines for the post-retrofit RL and SL distribution are both lower by 1-3 dB and 6 – 9 dB than their respective pre-retrofit baselines (Figure 6).
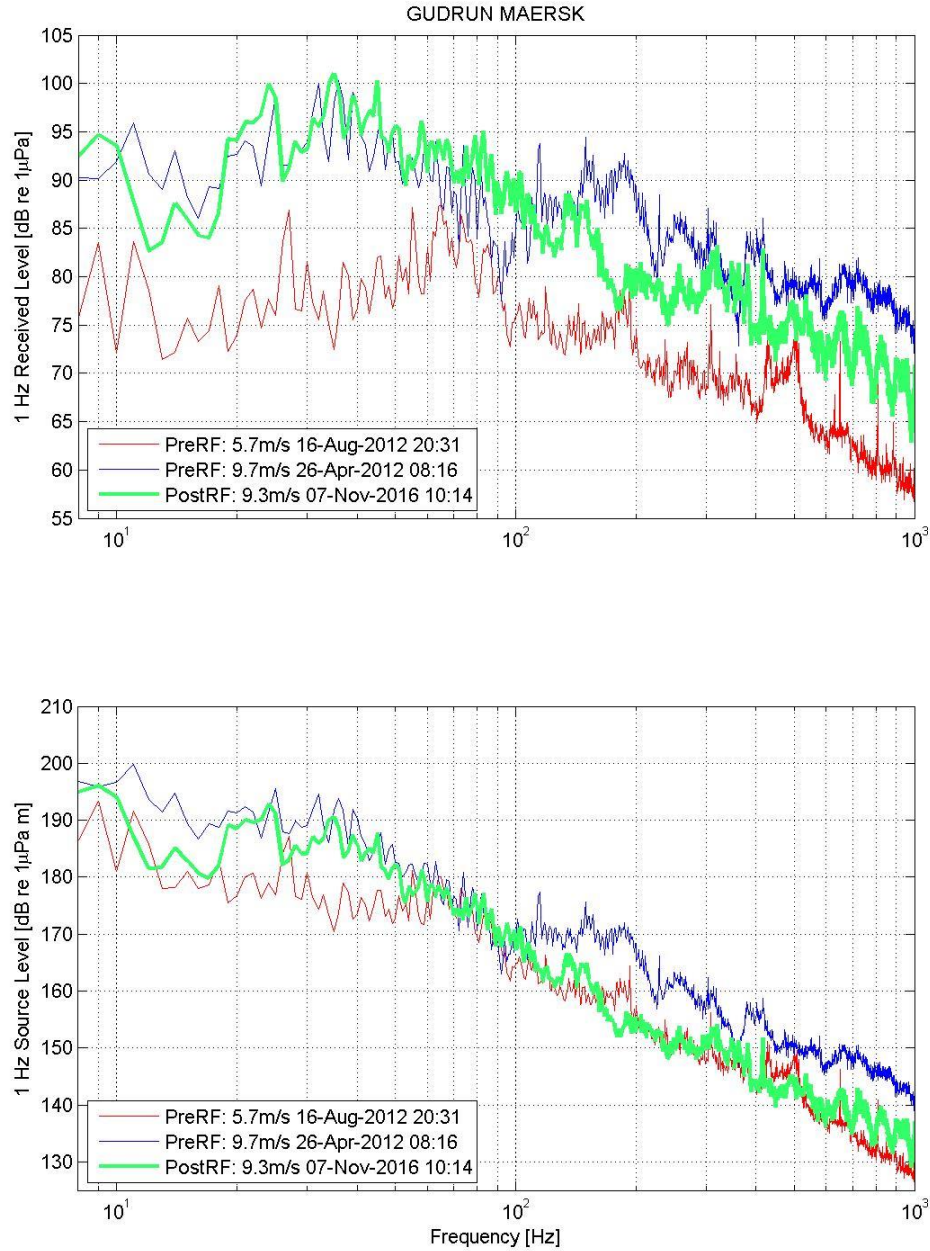
Figure 4 Measured received sound pressure levels at the HARP (upper panel) and estimated source sound pressure levels (lower panel) as a function of frequency for three transits of GUDRUN. Two transits were pre-retrofit at low (5.7 m/s) and high speed (9.7 m/s) (red and blue line respectively). Third transit was post-retrofit at high speed (9.3 m/s) (green line).

Figure 5 Low-frequency band (8 - 100 Hz) integrated received sound pressure level at HARP (upper panel) and source sound pressure level (lower panel) as a function of speed over ground (SOG) for GRETE (circles), GUDRUN (hexagrans), GUNVOR (diamonds), GERDA (squares) and GERNER (stars). Lines represent polynomials of first order fitted with a Theil-Sen linear regression to the pre- and post-retrofit level distributions. Blue and green color indicates pre- and post-retrofit, respectively.
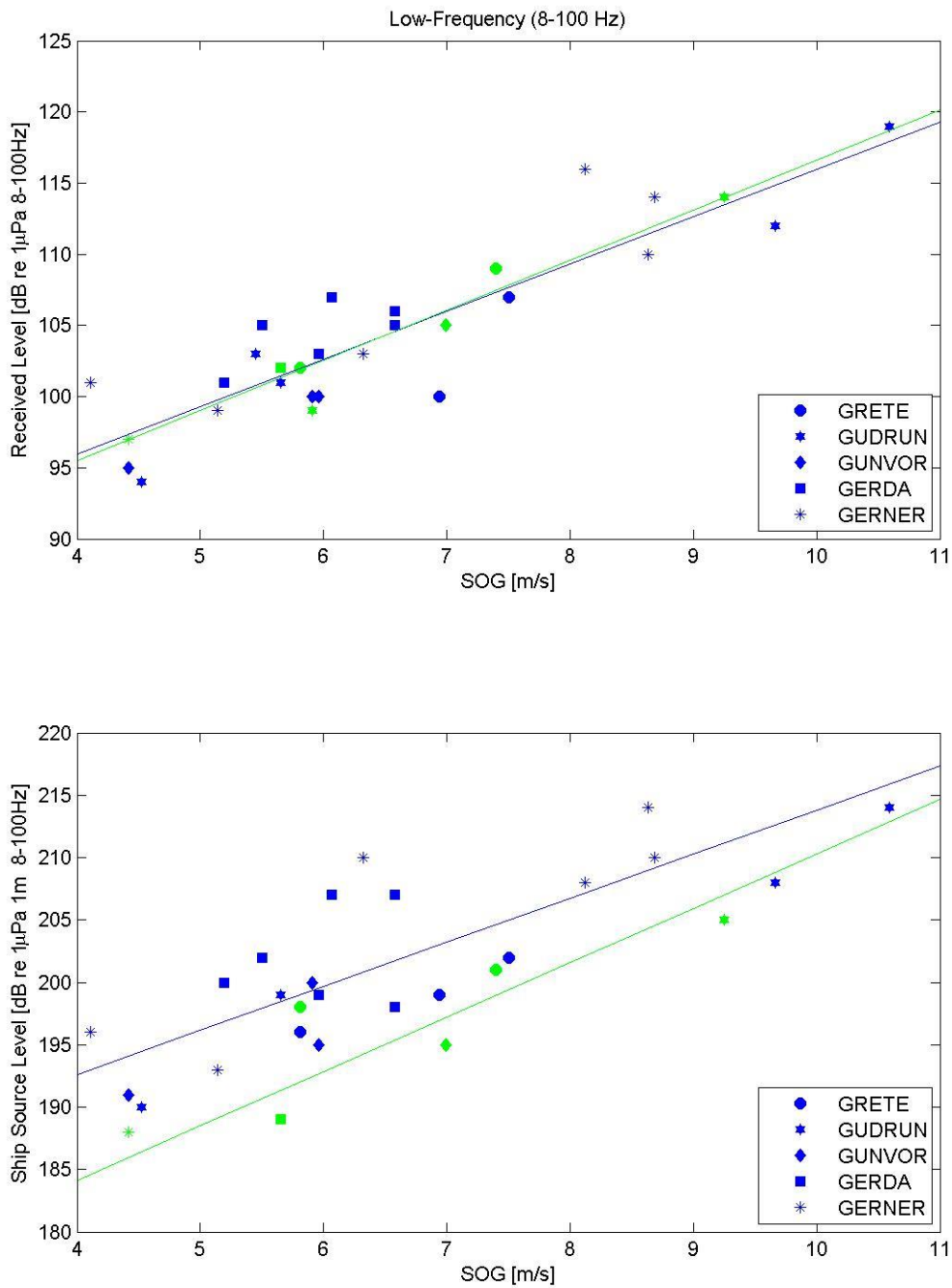
Figure 6 High-frequency band (100 - 1000 Hz) integrated received sound pressure level at HARP (upper panel) and source sound pressure level (lower panel) as a function of speed over ground (SOG) for GRETE (circles), GUDRUN (hexagrans), GUNVOR (diamonds), GERDA (squares) and GERNER (stars) . Lines represent polynomials of first order fitted with a Theil-Sen linear regression to the pre- and post-retrofit level distributions. Blue and green color indicates pre- and post-retrofit, respectively.
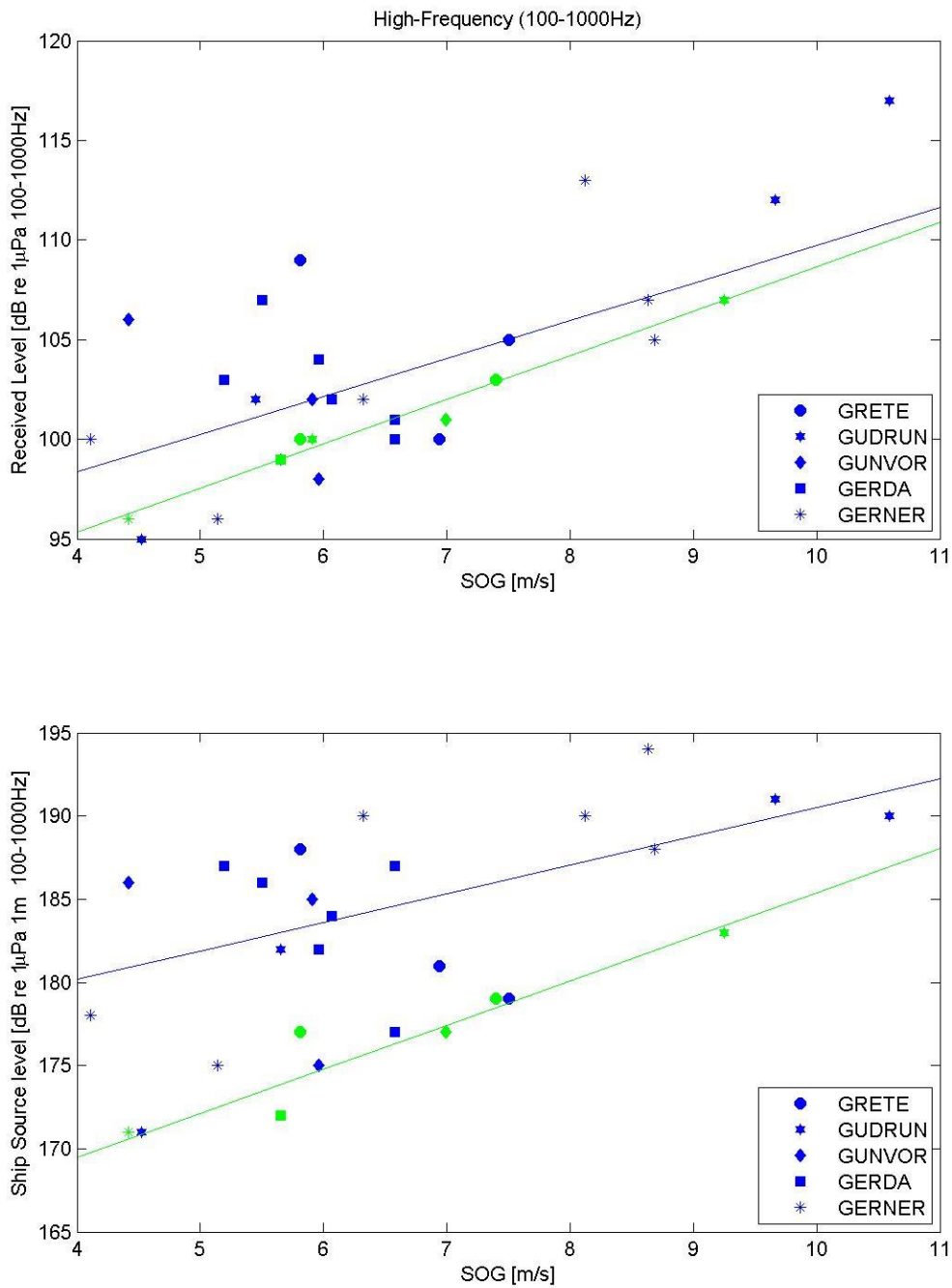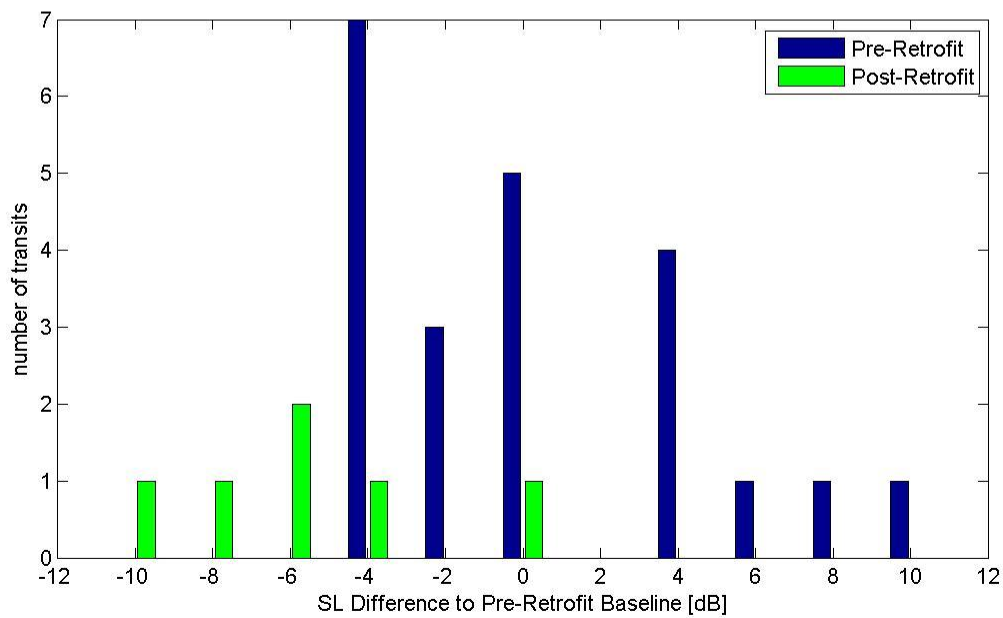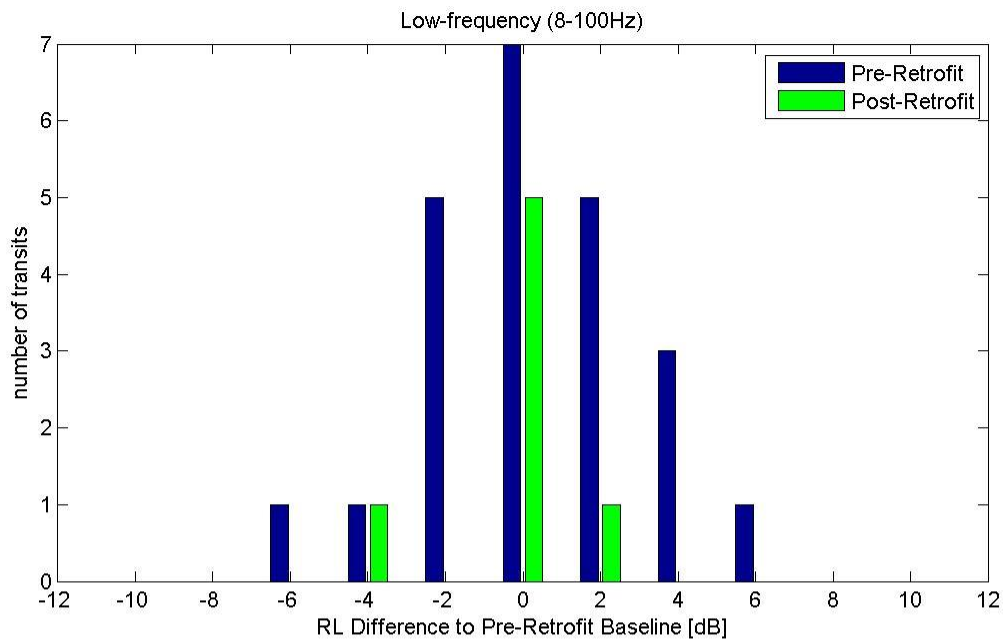
Figure 7 Histogram of differences between post-retrofit levels (green) and pre-retrofit baselines in the low-frequency band (8 – 100 Hz). Upper panel shows differences for received sound pressure levels; lower panel for source sound pressure levels. The goodness of fit for the pre-retrofit baselines (blue lines in Figure 5) is illustrated by the differences between pre-retrofit levels and pre-retrofit base lines in blue.

Figure 8 Histogram of differences between post-retrofit levels (green) and pre-retrofit baselines in the high-frequency band (100 – 1000 Hz). Upper panel shows differences for received sound pressure levels; lower panel for source sound pressure levels. The goodness of fit for the pre-retrofit baselines (blue lines in Figure 5) is illustrated by the differences between pre-retrofit levels and pre-retrofit base lines in blue.
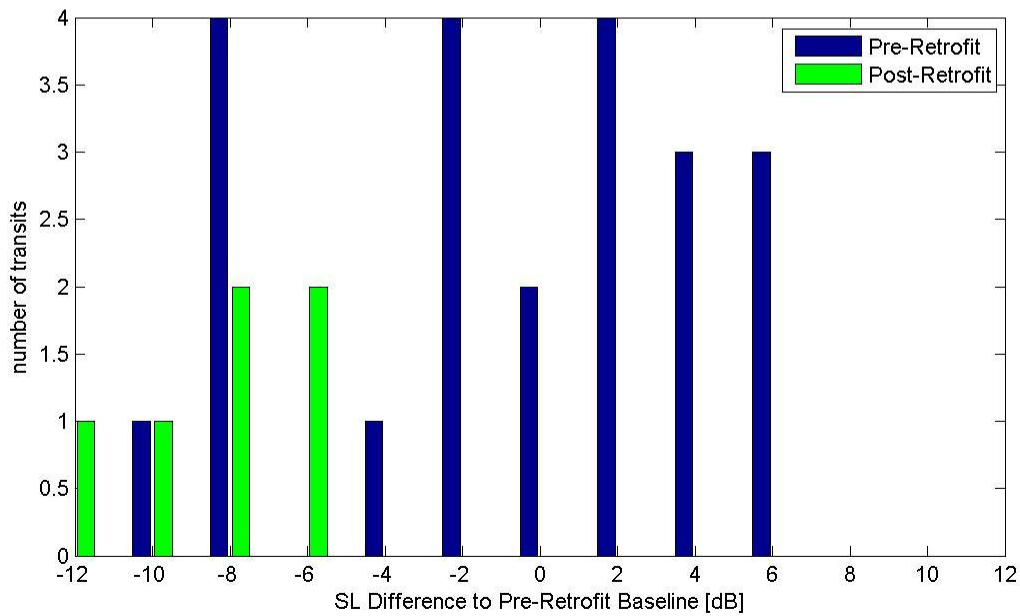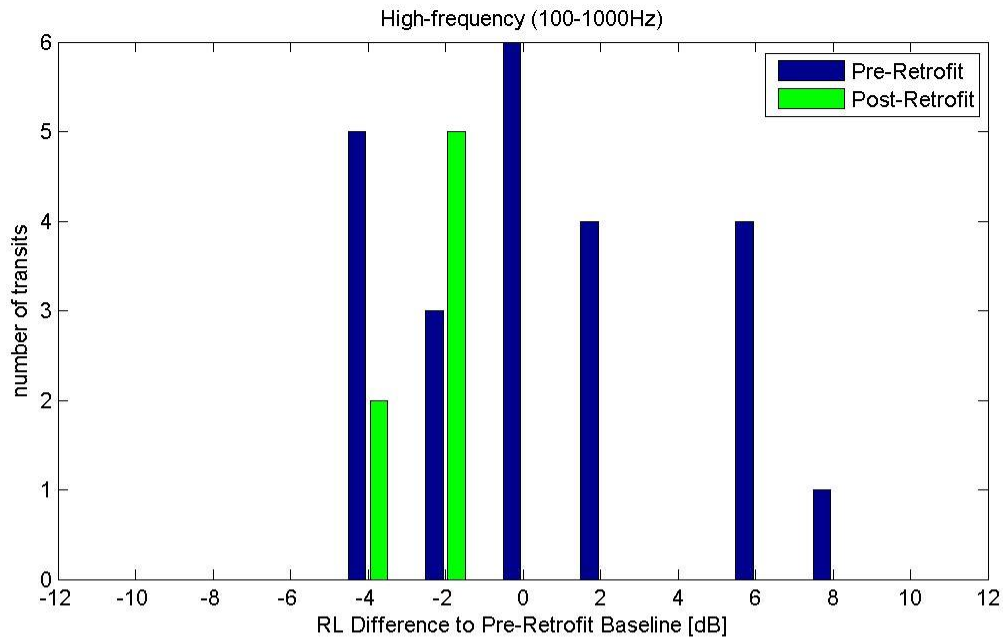
Histograms of the differences between the post-retrofit levels and the pre-retrofit baselines are shown in Figure 7 and Figure 8. Reductions in SL of the retrofitted MARSK G-class vessels were 6 and 8 dB for the low- and high-frequency band, respectively. Reductions in RL as measured by the HARP, however, were slightly lower and at a median of 0 and 2 dB for the low- and high-frequency band, respectively, as the reductions in SL were largely compensated by the lower sound transmission loss resulting from the greater draft during the transits of the retrofitted MAERSK G-class vessels.

Discussion and Conclusion

Five container vessels of MAERSK LINE's G-class fleet, GRETE, GUDRUN, GUNVOR, GERDA and GERNER, were selected to compare the underwater noise radiated during a total of 36 opportunistic transits at speeds of 4 – 11 m/s in a shipping lane off the coast of California before and after the vessels' radical retrofit. As the vessels operate at near-surface depths, the Lloyd's mirror effect of reflection from the sea surface must be taken into account to estimate the source sound pressure level of the vessels (Gassmann *et al.*, 2017). The Lloyd's mirror effect involves interference between the source signal and the reflected signal and changes with the depth of the source, that is, the draft of the vessel. Since the draft during the post-retrofit transits examined was up to several meters deeper, less destructive inference is expected. After compensating the Lloyd's mirror effects, the estimated underwater source sound pressure levels of the vessels, were found to be lower after the vessels' retrofit by a median of 6 dB in the low-frequency band (8 - 100 Hz) and a median of 8 dB in the high-frequency band (100 - 1000 Hz). The reduction in source sound pressure levels, in particular in the low-frequency band, may result from less cavitation due to both the retrofitted propellers with boss cap fins, and to propeller operation at greater depth where ambient pressure is higher.

The greater drafts during transits of retrofitted vessels, however, result in smaller sound transmission losses (Lloyd's mirror effect), which largely compensated the reductions in SL of the retrofitted vessels when measured at 3.4 - 5 km distance in 565 m deep water at the

location of the acoustic recorder. This effect may be more pronounced at shallower angles lateral to the vessel than at steep angles such as underneath the vessel. Reductions of ship source sound pressure level due to changes such as those employed by the radical retrofits may result in ocean-basin-wide noise reductions.

Acknowledgments

References

Erbe, C., MacGillivray, A., and Williams, R. (**2012**). "Mapping cumulative noise from shipping to inform marine spatial planning," J. Acoust. Soc. Am. **132**, EL423-EL428.

Gassmann, M., Wiggins, S. M., and Hildebrand, J. A. (**2017**). "Deep-water measurements of container ship radiated noise signatures and directionality," J. Acoust. Soc. Am. **142**, 1563-1574.

Gilbert, R. O. (**1987**). "6.5 Sen's Nonparametric Estimator of Slope," John Wiley and Sons **Statistical Methods for Environmental Pollution Monitoring**, pp. 217–219.

Gray, L. M., and Greeley, D. S. (**1980**). "Source level model for propeller blade rate radiation for the world's merchant fleet," J. Acoust. Soc. Am. **67**, 516-522.

Hildebrand, J. A. (**2009**). "Anthropogenic and natural sources of ambient noise in the ocean," Marine Ecology-Progress Series **395**, 5-20.

Jansen, H. W., and de Jong, C. A. F. (**2015**). "Experimental assessment of underwater radiated sound of different ship types," in *OCEANS 2015 - Genova*, pp. 1-8.

MAERSK LINE (**2017**). "Maersk Ocean-Going Vessel Energy Efficiency Demonstration Project," Technology Advancement Project (TAP) Project Milestone Report.

McKenna, M. F., Katz, S. L., Wiggins, S. M., Ross, D., and Hildebrand, J. A. (**2012a**). "A quieting ocean: Unintended consequence of a fluctuating economy," J. Acoust. Soc. Am. **132**, EL169-EL175.

McKenna, M. F., Ross, D., Wiggins, S. M., and Hildebrand, J. A. (**2012b**). "Underwater radiated noise from modern commercial ships," J. Acoust. Soc. Am. **131**, 92-103.

McKenna, M. F., Wiggins, S. M., and Hildebrand, J. A. (**2013**). "Relationship between container ship underwater noise levels and ship design, operational and oceanographic conditions," Scientific Reports **3**, 1760.

Redfern, J. V., Hatch, L. T., Caldow, C., DeAngelis, M. L., Gedamke, J., Hastings, S., Henderson, L., McKenna, M. F., Moore, T. J., and Porter, M. B. (**2017**). "Assessing the risk of chronic shipping noise to baleen whales off Southern California, USA," Endangered Species Research **32**, 153-167.

Ross, D. (**1976**). "Mechanics of underwater noise," (Pergamon Press, New York).

Simard, Y., Roy, N., Gervaise, C., and Giard, S. (**2016**). "Analysis and modeling of 255 source levels of merchant ships from an acoustic observatory along St. Lawrence Seaway," J. Acoust. Soc. Am. **140**, 2002-2018.

UNCTAD (**2016**). "Review of Maritime Transport," http://unctad.org/en/PublicationsLibrary/rmt2016_en.pdf.

Urick, R. J. (**1975**). *Principles of Underwater Sound* (McGraw-Hill, New York).

Webb, S. C. (**1998**). "Broadband seismology and noise under the ocean," Reviews of Geophysics **36**, 105-142.

Wenz, G. M. (**1962**). "Acoustic ambient noise in the ocean: spectra and sources," J Acoustic Soc Am **34**, 1936-1956.

Wiggins, S. M., and Hildebrand, J. A. (**2007**). "High-frequency Acoustic Recording Package (HARP) for broad-band, long-term marine mammal monitoring," in *International Symposium on Underwater Technology 2007 and International Workshop on Scientific Use of Submarine Cables & Related Technologies 2007* (Institute of Electrical and Electronics Engineers, Tokyo, Japan), pp. 551-557.

Appendix A

GERDA MAERSK

Legend for OTO Source Level plot:
- 11-Jan-2012 22:37 v=6.1m/s
- 17-May-2012 21:50 v=5.5m/s
- 07-Sep-2012 20:10 v=6.6m/s
- 05-Dec-2013 13:02 v=5.2m/s
- 25-Apr-2015 12:14 v=6.7m/s
- 30-Jul-2015 11:29 v=6.0m/s
- 30-Oct-2016 22:41 v=6.6m/s

GERNER MAERSK

Legend:
- 19-Apr-2012 20:34 v=7.9m/s
- 02-Aug-2012 16:26 v=8.1m/s
- 22-Nov-2012 09:45 v=8.6m/s
- 16-Jan-2014 20:53 v=8.7m/s
- 16-Mar-2015 23:47 v=6.3m/s
- 19-Aug-2015 00:56 v=6.2m/s
- 26-Sep-2016 01:09 v=8.9m/s

GERNER MAERSK

Legend (lower plot):
- 19-Apr-2012 20:34 v=7.9m/s
- 02-Aug-2012 16:26 v=8.1m/s
- 22-Nov-2012 09:45 v=8.6m/s
- 16-Jan-2014 20:53 v=8.7m/s
- 16-Mar-2015 23:47 v=6.3m/s
- 19-Aug-2015 00:56 v=6.2m/s
- 26-Sep-2016 01:09 v=8.9m/s

GRETE MAERSK

Legend for lower plot:
14-Dec-2011 21:59 v=7.5m/s
05-Apr-2012 11:13 v=5.8m/s
08-Nov-2012 11:40 v=7.6m/s
27-Sep-2015 22:52 v=6.9m/s
15-Aug-2016 20:03 v=6.4m/s

GRETE MAERSK

Legend (lower plot):
- 14-Dec-2011 21:59 v=7.5m/s
- 05-Apr-2012 11:13 v=5.8m/s
- 08-Nov-2012 11:40 v=7.6m/s
- 27-Sep-2015 22:52 v=6.9m/s
- 15-Aug-2016 20:03 v=6.4m/s

GUDRUN MAERSK

Legend:
- 24-Nov-2011 19:57 v=10.6m/s
- 07-Mar-2012 13:49 v=5.4m/s
- 26-Apr-2012 08:16 v=9.7m/s
- 16-Aug-2012 20:31 v=5.7m/s
- 06-Mar-2015 15:52 v=8.7m/s
- 09-Sep-2015 08:52 v=4.5m/s
- 07-Nov-2016 10:14 v=5.9m/s

GUDRUN MAERSK

Legend:
- 24-Nov-2011 19:57 v=10.6m/s
- 07-Mar-2012 13:49 v=5.4m/s
- 26-Apr-2012 08:16 v=9.7m/s
- 16-Aug-2012 20:31 v=5.7m/s
- 06-Mar-2015 15:52 v=8.7m/s
- 09-Sep-2015 08:52 v=4.5m/s
- 07-Nov-2016 10:14 v=5.9m/s

GUNVOR MAERSK

Legend:
- 01-Nov-2012 11:47 v=6.2m/s
- 17-Nov-2014 11:45 v=5.9m/s
- 22-May-2015 08:21 v=6.0m/s
- 10-Oct-2016 11:40 v=4.4m/s

GUNVOR MAERSK

Legend (lower plot):
- 01-Nov-2012 11:47 v=6.2m/s
- 17-Nov-2014 11:45 v=5.9m/s
- 22-May-2015 08:21 v=6.0m/s
- 10-Oct-2016 11:40 v=4.4m/s