Ocean-Going Vessel Energy Efficiency Measurement Demonstration TAP Project: Energy and Fuel Parameters Report

for
San Pedro Bay Ports
Technology Advancement Program

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Prepared by:

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ACRONYMS & ABBREVIATIONS

CAMS	Control, Alarm, and Monitoring System
EMS	Engine Management System
FMS	Flow Meter System
g	gram
GPS	Global Positioning System
GVPC	Global Vessel Performance Centre
HFO	heavy fuel oil
kW	kilowatt
kWh	kilowatt-hour
MAREX	Marine Exchange of Southern California
ME	main engine
MGO	marine gas oil
MSPS	Maersk Ship Performance System
MT	metric tons
OGV	ocean-going vessel
POLA	Port of Los Angeles
POLB	Port of Long Beach
Radical Retrofit	Maersk Radical Retrofit Program
SPBP	San Pedro Bay Ports
SFOC	specific fuel oil consumption
TAP	Technology Advancement Program
TAP Project	Ocean-Going Vessel Energy Efficiency Measurement Demonstration TAP Project
TEU	twenty-foot equivalents
ULSFO	ultra low sulfur fuel oil
USB	universal serial bus
WMO	World Meteorological Organization

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EXECUTIVE SUMMARY

The purpose of the 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 using multiple new high-resolution data streams.

The major components of the Maersk $125 million Radical Retrofit program (Radical Retrofit) focused on reducing fuel consumption and increasing vessel TEU capacity. The fuel efficiency improvement components included redesigning the bulbous bow, replacing vessel propellers, and "derating" the main engines to improve efficiency at lower speeds. Additionally, each ship's capacity was increased from about 9,500 TEUs to about 11,000 TEUs. Finally, each vessel was outfitted with high-fidelity sensors to track energy efficiency and fuel consumption.

The twelve Maersk G-class vessels were selected as the focus of this project because they are sister ships with similar configurations, and all twelve vessels have called at the San Pedro Bay Ports over the last five years. The Radical Retrofit of these vessels was accomplished through a phased implementation beginning in 2015 and ending in 2018.

Several data sources were used to analyze the effects of the Maersk Radical Retrofit program on engine power, fuel consumption, and emissions. These data sources include the Maersk Ship Performance System (MSPS) reports (also known as Noon reports), Control, Alarm and Monitoring System (CAMS) data, Flow Meter System (FMS) data, Calculated Consumption data (calculated from the FMS data), Port Call Schedule, and Marine Exchange of Southern California (MAREX) data.

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 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 (EMS) 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. 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.

The effects of the Radical Retrofit on energy efficiency and fuel consumption were analyzed using matched pre- and post-Radical Retrofit activities. Activities selected 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. The MSPS Sea reports were used to analyze the impact of the Radical Retrofit on the G-class vessels while in transit; whereas, the MSPS Port reports, MAREX, and Calculated Consumption datasets were used to analyze the benefits of the Radical Retrofit on the G-class vessels while maneuvering near port.

SECTION 1: INTRODUCTION

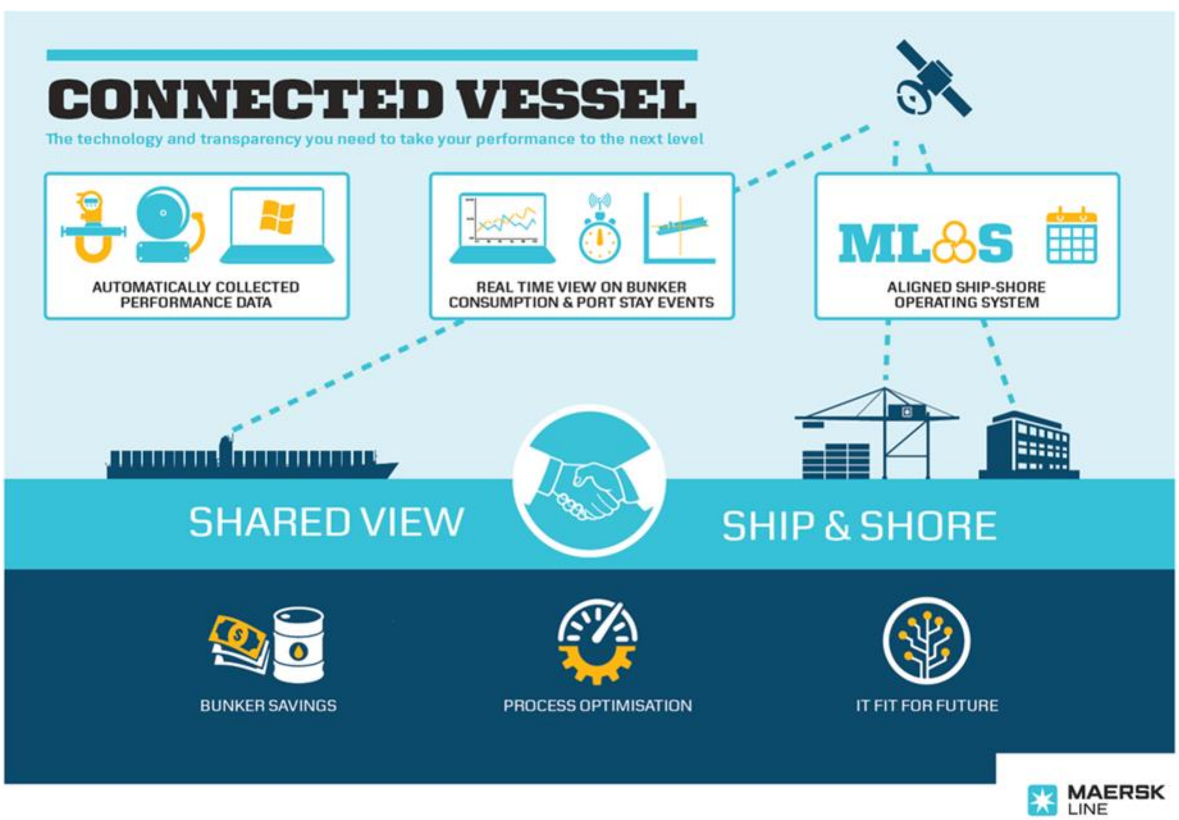
1.1 Project Description

The objective of the ground-breaking TAP Project was to evaluate and quantify the benefits of energy efficiency improvements for ocean-going vessels using multiple new high-resolution data streams.

Beginning in 2015, the Maersk G-class vessels underwent a $125 million Radical Retrofit. The major components of the Radical Retrofit program focused on reducing fuel consumption and increasing TEU capacity. The fuel efficiency improvement components included redesigning the bulbous bow of each vessel to reduce drag, 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. The Radical Retrofit also involved the installation of additional lashing bridges and raising the bridge to increase each ship's capacity from about 9,500 TEUs to about 11,000 TEUs. In addition to the efficiency and capacity modifications, each vessel was outfitted with high-fidelity sensors to track energy efficiency and fuel consumption.

In parallel with these efforts, Maersk also developed their Star Connect platform, which uploads the high-fidelity sensor data from each vessel to Maersk servers via satellite. Using this data, Maersk's Global Vessel Performance Centre (GVPC) can communicate with each vessel in real-time to increase operational efficiency. See Figure 1.1 for an overview of the program.

Figure 1.1: Overview of Maersk's Connected Vessel Program



1.2 Vessel Characteristics Pre- and Post-Radical Retrofit

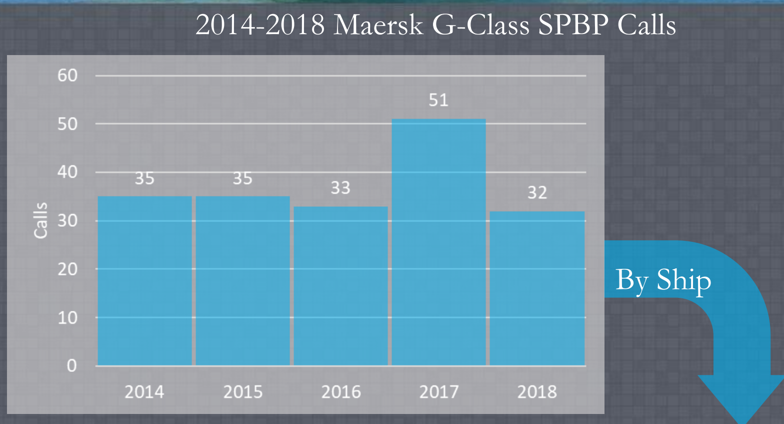
The Radical Retrofit resulted in changes to several key characteristics of the G-class vessels. A comparison of these characteristics is illustrated in Figure 1.2. More detailed information on the vessel characteristics is provided in the Maersk TAP Project Milestone 1 & 2 report.

Figure 1.2: Comparison of Key Vessel Characteristics Pre- and Post-Radical Retrofit

1.3 Selection of Maersk G-Class Vessels

The twelve Maersk G-class vessels were selected as the focus of this project because they are sister ships with similar configurations, and all twelve vessels have called at the San Pedro Bay Ports over the last five years. All vessels were built between 2005 and 2008, have an overall length of about 366 meters, a beam of about 42 meters, and a draught of about 16 meters. See Table 1.1 for vessel calls to the San Pedro Bay Ports from January 2014 through December 2018.

Table 1.1: Maersk G-Class Vessel Calls to the San Pedro Bay Ports



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**

1.4 Vessel Radical Retrofit Schedule

The Radical Retrofit of the Maersk G-class vessels was accomplished through a phased implementation beginning in 2015 and ending in 2018. Table 1.2 outlines the timeline for the Radical Retrofit, showing the dry-dock stages and the dates when high resolution data from the Flow Meter Systems (FMS) and Control, Alarm, and Monitoring Systems (CAMS) came online. FMS systems were installed on three vessels prior to the Radical Retrofit, the *Gerda Maersk*, *Gustav Maersk*, and *Gunhilde Maersk*, but were in the "Proof-of-Concept" phase until after the Radical Retrofit. CAMS data was only available post-Radical Retrofit.

Table 1.2: G-Class Vessel Radical Retrofit Timeline

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 resolution 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.

1.5 Project Challenges

The original intention of the Maersk TAP Project was to utilize high-resolution 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 perform the detailed analysis as originally planned.

1.5.1 Administrative

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. 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, data was downloaded directly from four G-class vessels' existing engine management systems (EMS) onto universal serial bus (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 didn't begin until 2018 due to the delays from the cyber-attack (see 1.5.2 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.

1.5.2 Cyber-Attack

Maersk was hit by system-wide cyber-attack in June 2017[1], 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.

[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/*

SECTION 2 DATA SOURCES

2.1 Overview

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 Maersk Ship Performance System Report (MSPS)

Also known as the Noon report, the MSPS report contains information about vessel performance and sea 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 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]

2.2.1 MSPS Sea Reports and Port Reports

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 or sea and 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.

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

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. For the purposes of analysis, only MSPS Sea reports with a performance code of 1 (Constant Main Engine Load; Normal Cruising) were included. Maersk strives to operate at constant power as much as possible because it increases engine efficiency and is the most fuel-efficient mode of operation.[3]

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 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).

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

Table 2.2: Beaufort Wind Scale[4]

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	

[4] National Oceanic and Atmospheric Administration (NOAA). Beaufort Wind Scale. Retrieved on May 9, 2019. *https://www.spc.noaa.gov/faq/tornado/beaufort.html*

MSPS data received for the TAP project was dated from July 2010 to March 2018. MSPS Sea report data included 24,264 reports for the G-class vessels with an average of 2,022 Sea reports per vessel. After removing reports with a reporting period of zero (2), main engine load of zero (291), vessel speed greater than 30 knots (1), and performance code <> 1 (8,431) there were 15,539 Sea reports available for analysis, which was 64% of the original data.

MSPS Port report data included 5,744 reports for the G-class vessels, with an average of 479 reports per vessel. No Port reports were removed from the analysis.

The benefit of the MSPS data was that it is a long-standing report that was collected both pre- and post-Radical Retrofit. The downside of the MSPS data was 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 is a greater degree of uncertainty with the MSPS data than with the high-fidelity CAMS and FMS data sources, which are logged automatically and aggregated over much shorter timeframes.

2.3 High-Fidelity Data Sources

As part of the Radical Retrofit, the Maersk G-class vessels were equipped with 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. Two types of sensor systems were installed on each vessel: CAMS and FMS.

2.3.1 Control, Alarm, and Monitoring System (CAMS) data

The CAMS data contains many of the same data points found in the MSPS reports, including 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.

CAMS data received for the TAP project was dated from November 2016 through February 2018. Data for each vessel came online per the timeline in Table 1.2. Raw CAMS data included 535,892 log entries, with an average of 48,717 log entries per vessel. After removing entries with an error status (82,648), 453,244 log entries remained available for analysis, which was 85% of the original data set.

The advantage to the CAMS data was that it is a more detailed data set that is 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.

2.3.2 Flow Meter System (FMS) data

Also known as the fuel consumption data, the FMS data contains the same fuel-related data points found in the MSPS reports, in addition to new information, such as inlet/outlet mass, flow, density, and temperature.

FMS data received for the TAP project was dated from November 2015 through February 2018. Data for each vessel came online per the timeline in Table 1.2. Raw FMS data included 1,091,226 log entries, with an average of 90,936 log entries per vessel. After removing entries with an error status (79,348), 1,011,878 log entries remained available for analysis, which was 93% of the original data set.

As with the CAMS data, the advantage to the FMS data was that it is 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 is a level of uncertainty about its reliability for use in analysis.

2.3.3 Calculated Consumption data

The Calculated Consumption data is a dataset that Maersk calculates 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 engines, auxiliary engines, and boilers since the previous measurement (typically every 10 minutes).

2.4 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 if the dates are scheduled (future dates) or if they are actuals.

2.5 Marine Exchange of Southern California (MAREX) Data

MAREX data for the San Pedro Bay Ports was used to determine when the G-class vessels were maneuvering in and around the ports.

SECTION 3: DATA AVAILABILITY

Analysis of the effects of the Radical Retrofit on energy efficiency and fuel consumption required that data be available both pre- and post-Radical Retrofit. Table 3.1 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 fuel consumption (FMS) data was available for the *Gerda Maersk* and *Gustav Maersk* only.
- Only post-Radical Retrofit vessel operational (CAMS) data was available.

Pre-Radical Retrofit data was limited due to the project challenges described in Section 1.5.

Table 3.1: 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

* Limited amount pre-Radical Retrofit FMS data was 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 Consulting Group, the *Gunhilde Maersk* had not yet gone into dry dock for the Radical Retrofit; therefore, no post-Radical Retrofit data is available for the *Gunhilde Maersk*. If additional time were available this could now be downloaded for analysis.

Section 4 Matching Pre- and Post-Radical Retrofit Vessel Activities for Analysis

4.1 General Approach

In order to analyze the effects of the Radical Retrofit on energy efficiency and fuel consumption, pre- and post-Radical Retrofit activities must be identified to make the comparison. It is important that these activities have similar operating conditions so that differences in engine load and fuel consumption cannot be attributed to confounding factors, such as vessel speed, sea state, and meteorological conditions.

4.2 Identifying Transit Activities for Analysis

The MSPS Sea reports were used to analyze the impact of the Radical Retrofit on the G-class vessels while in transit. This dataset was chosen because (1) pre- and post-Radical Retrofit MSPS Sea reports were available for eleven of the G-class vessels, and (2) MSPS Sea reports included data points that were needed to identify pre- and post-Radical Retrofit transit activities with similar operating conditions. Table 4.1 lists the data fields and match criteria used to identify pre- and post-Radical Retrofit transit activities.

Table 4.1: MSPS Sea Report 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 a 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 more deeply 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 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.[5]
- **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.

4.3 Identifying Maneuvering Activities for Analysis

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 4.2 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.

[5] 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.

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 4.2: 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

SECTION 5 SUMMARY

The Maersk's Radical Retrofit program was designed to decrease fuel consumption and increase capacity on 12 Maersk G-class vessels. The objective of the ground-breaking San Pedro Bay Ports 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.

5.1 Pre- and Post-Radical Retrofit Data Sources

As stated before, the objective of the TAP Project was to use multiple new high-resolution data streams to determine how much energy each engine uses before and after Radical Retrofit in conjunction with speed, engine power, weather, operational mode, and other operational variables. Collected data was uploaded to Maersk servers via satellite using the company's Star Connect platform, which allows each ship to communicate in real-time with Maersk's GVPC to increase operational efficiency. Program data sources were:

- **MSPS**: Also known as the Noon report. 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.
- **CAMS**: CAMS is a high-fidelity dataset containing information on engine operations and sea and meteorological conditions.
- **FMS**: FMS is a high-fidelity dataset containing information on fuel usage and inlet/outlet mass, flow, density, and temperature.
- **Calculated Consumption**: Calculated Consumption data is derived 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 engines, auxiliary engines, and boilers since the previous measurement (typically every 10 minutes).
- **Port Call Schedule**: The G-class vessel port call schedule data was extracted from Maersk's Global Scheduling Information System and included vessel arrival and departure dates to each port.
- **MAREX**: MAREX data for the San Pedro Bay Ports was used to determine when the G-class vessels were maneuvering in and around the ports.

5.2 Pre- and Post-Radical Retrofit Matching Parameters

Pre- and post-Radical Retrofit data sources were matched in order to eliminate factors such as sea and meteorological conditions that could impact fuel consumption but were not part of the objectives of this study. The parameters used to match the pre- and post-Radical Retrofit trips were:

- **Vessel Name**: 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 a performance code = 1 were considered, indicating that the vessel was cruising normally and maintaining a constant main engine load during the reporting period.
- **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, while the trim can have a significant impact on a vessel's energy demand for propulsion while underway.
- **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.
- **Water Depth**: 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.

5.3 Data Processing and Review

Due to the lack of availability of pre-Radical Retrofit CAMS data and limited FMS data, the originally 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 performed by the project partners (Maersk Vessel Performance Team, Duke University Nicholas School of the Environment, and Starcrest) are summarized. The data processing and review is fully documented in the final report entitled "Ocean-Going Vessel Energy Efficiency Measurement Demonstration TAP Project: Final Report".

ANNEXES

A.1 Data Fields

Tables A.1.1 and A.1.2 contain information about the data fields that were used in the analysis of the Radical Retrofit's effect on energy efficiency and fuel consumption.

Table A.1.1: MSPS Data Fields Used in Analysis of Radical Retrofit

Name	Description	Units	Type	Use
Shortname	Vessel name	-	-	Context
Report Date/Time	Date and time the report was filed	UTC	-	Context
Report Period	Time since previous report	Hours	-	Analysis
Report Type	1 = Sea report; 2 = Port report	-	-	Context
Draught Fore	Draft at the bow of the ship	Meters	Average	Pre-/Post-RR Match
Draught Aft	Draft at the stern of the ship	Meters	Average	Pre-/Post-RR Match
Draught Average	Average of fore and aft draft	Meters	Calculated	Pre-/Post-RR Match
Trim	Difference between fore and aft draft	Meters	Calculated	Pre-/Post-RR Match
Sea Temperature	Sea temperature	°C	Average	Pre-/Post-RR Match
Vessel Speed Log	Speed through water	Knots	Average	Pre-/Post-RR Match; Analysis
Water Depth	Water depth	Meters	Average	Pre-/Post-RR Match
Performance Code	See Table 2.1	-	-	Pre-/Post-RR Match
Wind Direction	Wind direction relative to the bow of the ship	Degrees	Average	Pre-/Post-RR Match
Wave Height	Wave height	Meters	Average	Pre-/Post-RR Match
Beaufort	See Table 2.2	-	Average	Pre-/Post-RR Match
ME 1 Running Hours	Main engine 1 running hours since previous report	Hours	Actual	Analysis
ME 1 Load	Main engine 1 load	kW	Average	Analysis
ME Fuel Total	Main engine fuel consumption during report period	Metric Tons	Actual	Analysis
Reefer Energy	Reefer power (all reefers)	kWh	Average	Analysis
SGkWh	Shaft Generator power; from the main engine; used to drive the reefers	kWh	Average	Analysis
Dist Obs	Distance observed	Nautical Miles	Actual	Analysis
Dist Log	Distance logged	Nautical Miles	Actual	Analysis
ME SFOC	Main engine specific fuel oil consumption (SFOC)	gHFO/kWh	Calculated	Analysis
Total Energy SFOC	Total energy specific fuel oil consumption	gHFO/kWh	Calculated	Analysis
TEU Estimate	TEU estimate based on average draught	TEUs	Calculated	Analysis

Table A.1.2: Calculated Consumption Data Fields Used in Analysis of Radical Retrofit

Name	Description	Units	Type	Use
vessel_name	Vessel name	-	-	Context
log_dt	Date and time of log entry	UTC	-	Context
me_hfo_dff	Mass heavy fuel oil (HFO) fuel consumed since the last log entry	Metric Tons	Calculated	Analysis
me_ulsfo_diff	Mass ultra low sulfur fuel oil (ULSFO) fuel consumed since the last log entry	Metric Tons	Calculated	Analysis
me_mgo_dff	Mass marine gas oil (MGO) fuel consumed since the last log entry	Metric Tons	Calculated	Analysis

A.2 Data Samples

Tables A.2.1 and A.2.2 contain samples of the data sets used in the analysis of the Radical Retrofit's effect on energy efficiency and fuel consumption.

Table A.2.1: MSPS Data Sample from one G-Class Vessel

Report Date/Time [UTC]	Report Period [hrs]	Report Type [-]	Draught Fore [m]	Draught Aft [m]	Draught Average [m]	Trim [m]	Sea Temperature [°C]	Vessel Speed Log [Knot]	Water Depth [m]	Performance Code [-]	Wind Direction [°]	Wave Height m	Beaufort [-]	ME 1 Running Hours [hrs]	ME 1 Load [kW]	ME Fuel Total [tons]	Reefer Energy [kWh]	SGkWh [kWh]	Dist Obs [m]	Dist Log [m]	ME SFOC [gHFO/kWh]	Total Energy SFOC [gHFO/kWh]	TEU Estimate [TEU]
3/2/2018 2:00 AM	125.0	2	12.68	12.78	12.73	-0.10	12							5	5679.0	15.9	19266	151			553.6	271.9	6969
3/3/2018 2:00 PM	36.0	2	13.30	13.48	13.39	-0.17	14							9	25873.3	50.3	10258	648			213.3	265.8	7482
3/4/2018 9:00 AM	19	1	15.10	12.60	13.85	2.50	19	21.0	102	1	31	0.9	4	19	32210.0	121.0	6305	0	400	398	195.4	0.0	8003
3/5/2018 8:00 AM	23	1	15.10	12.60	13.85	2.50	22	20.7	2157	1	0	1.1	4	23	32620.0	145.6	8401	201	476	477	191.7	191.7	8003
3/6/2018 12:00 AM	16	1	13.15	13.25	13.20	-0.10	22	20.6	86	1	21	2.0	5	16	34220.0	106.2	6134	0	332	329	191.7	0.0	7482
3/7/2018 2:38 AM	26.6	2	14.03	14.13	14.08	-0.10	26							4	9100.9	10.5	13501	129			324.5	254.3	8532
3/7/2018 1:00 PM	10.4	2	14.90	15.00	14.95	-0.10	26							10	4881.2	11.5	8159	610			225.1	253.7	9068
3/8/2018 7:00 AM	18	1	14.90	15.00	14.95	-0.10	26	14.9	47	1	13	0.4	2	18	12690.0	45.1	15391	23893	261	268	195.0	220.6	9068
3/8/2018 10:30 AM	3.5	1	14.90	15.00	14.95	-0.10	26	15.4	1000	1	36	0.5	3	4	13420.0	9.2	3097	4784	51	54	193.7	217.4	9068
3/9/2018 7:00 AM	20.5	1	14.90	15.00	14.95	-0.10	26	12.7	697	1	44	0.4	3	21	7710.0	32.3	18459	23081	261	260	201.7	222.1	9068
3/10/2018 5:00 AM	22	2	14.35	14.50	14.43	-0.15	26							5	10916.5	11.7	19098	1006			206.8	201.8	8532
3/11/2018 7:00 AM	26	1	15.47	12.99	14.23	2.48	30	21.5	546	1	7	2.0	3	26	35900.0	178.3	22852	0	555	559	188.7	0.0	8532
3/12/2018 6:00 AM	23	1	15.43	13.00	14.22	2.43	30	21.3	1215	1	15	1.4	4	23	37140.0	163.6	19859	709	489	491	189.3	189.3	8532
3/12/2018 10:00 PM	16	1	15.43	13.00	14.22	2.43	30	21.7	1637	1	3	0.6	2	16	33560.0	104.5	13903	886	343	346	192.2	192.2	8532
3/14/2018 5:30 AM	31.5	2	13.43	13.50	13.46	-0.07	25							3	11920.2	8.0	22804	1442			221.6	131.6	7482
3/14/2018 9:00 AM	3.5	1	14.75	12.24	13.50	2.51	31	18.3	2100	1	28	0.5	3	4	19600.0	13.1	2543	3300	64	64	189.3	189.3	8003

Table A.2.2: Calculated Consumption Data Sample from one G-Class Vessel

log_dt [UTC]	me_hfo_diff [Metric Tons]	me_ulsfo_diff [Metric Tons]	me_mgo_diff [Metric Tons]
2017-12-26 04:20	0	0	0.406
2017-12-26 04:30	0	0	0.41
2017-12-26 04:40	0	0	0.41
2017-12-26 04:50	0	0	0.366
2017-12-26 05:00	0	0	0.366
2017-12-26 05:10	0	0	0.37
2017-12-26 05:20	0	0	0.201
2017-12-26 05:30	0	0	0.171
2017-12-26 05:40	0	0	0.179
2017-12-26 05:50	0	0	0.178
2017-12-26 06:00	0	0	0.163
2017-12-26 06:10	0	0	0.182
2017-12-26 06:20	0	0	0.179
2017-12-26 06:30	0	0	0.183
2017-12-26 06:40	0	0	0.162
2017-12-26 06:50	0	0	0.179