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Hull Coating and Propeller Condition Renewal for Emission Reduction

Final Report

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Algoma Central Corporation / Vard Marine Inc

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17. Abstract

This report presents the results of a study undertaken by Vard Marine Inc and Algoma Central Corporation for TC-IC to evaluate the potential fuel efficiency improvement and resulting emissions reductions and cost savings of performing propeller polishing and hull coating renewal for a conventional Great Lakes self-unloading bulk carrier. Two vessels were part of the study. Extensive performance and operational data was collected before and after propeller polishing for the MV Algoma Conveyor, and before and after hull coating renewal for the MV Algoma Mariner.

The study's analysis suggests a 5% reduction of power and fuel consumption for hull coating renewal, and a 6% improvement of transport efficiency. This is equivalent to an approximate annual reduction of 928mt of CO_2 emissions, and has a payback period of 5.6 years. The study analysis was unable to calculate these results for propeller polishing due to insufficient data, but numerical analysis suggests that a modest improvement should be possible, and that undertaking polishing is desirable given the low cost of the work.

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17. Résumé

Ce rapport présente les résultats d'une étude réalisée par Vard Marine Inc. et Algoma Central Corporation pour le compte du Centre d'innovation de Transports Canada. L'étude en question avait pour but d'évaluer l'amélioration potentielle du rendement du carburant ainsi que les réductions d'émissions et les économies que permettraient le polissage de l'hélice et le rafraîchissement du revêtement de la coque d'un vraquier autodéchargeur conventionnel naviguant dans les Grands Lacs. Deux navires ont fait l'objet de l'étude. Des données exhaustives sur la performance et l'exploitation ont été recueillies avant et après le polissage de l'hélice du NM *Algoma Conveyor*, ainsi qu'avant et après le rafraîchissement du revêtement de la coque du NM *Algoma Mariner*.

L'analyse de l'étude laisse supposer une réduction de 5 % de la consommation d'énergie et de carburant pour le rafraîchissement du revêtement de la coque, et une amélioration de 6 % de l'efficacité du transport. Cela équivaut à une réduction annuelle approximative de 928 tonnes métriques (tm) d'émissions de dioxyde de carbone (CO^{2}) et à une période de récupération de 5,6 ans. L'analyse de l'étude n'a pas permis de calculer ces résultats pour le polissage de l'hélice en raison de données insuffisantes, mais l'analyse numérique suggère qu'une amélioration modeste devrait être possible, et qu'il est souhaitable d'effectuer le polissage étant donné le faible coût des travaux.

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EXECUTIVE SUMMARY

This report presents the results of a project intended to explore the effect of a fresh hull coating and propeller polishing on the propulsive performance of two large vessels from Algoma Central Corporation (Algoma) carrying bulk cargo and operating in the Great Lakes. With this project, and with the support of the Transport Canada Innovation Centre (TC-IC) Clean Marine initiative, Algoma intends to make further reductions in GHG and criteria air contaminants (CAC).

Algoma's recent introduction of the Equinox Class provides an ideal opportunity for a systematic exploration of the benefits of both coating and propeller maintenance by long-term condition monitoring during normal operation of the vessels of various operational parameters (like vessel speed, power, and loading condition).

The two vessels (both part of the Equinox Class) selected are the Algoma Mariner, with an overall length of 256 m, which received a fresh hull coating (previous hull coating was performed 5 years prior). And the other vessel will be the Algoma Conveyor, with an overall length of 226 m, which underwent propeller polishing (previous propeller polishing was performed 2 years earlier).

The coated hull below the waterline represents approximately 58% of the hull below a 10.5 m waterline. No roughness measurements are available prior or after the hull coating.

All four blades on the pressure and suction face of the Conveyor were polished. Prior to polishing, the propeller roughness was a "D" on the Rubert scale, and after polishing the propeller was a "A" on the Rubert scale.

A theoretical hydrodynamic analysis was performed to hypothesise the expected improvements. The hull coating improvement expectation is a 6% power reduction at the operational speed of the vessel. The propeller polishing improvement expectation is a 6% power reduction for the operational speed of the vessel.

Data for the project is provided by the Prism system developed by Beaverlabs for Algoma to monitor their fleet's performance. The system is collecting real-time performance data for all Algoma vessels. The system provides data with a 1-minute timestep for the following signals: time, vessel speed, lateral and longitude position, relative wind speed and direction, propeller revolution rate, propeller torque, fuel consumption and, (for the Algoma Conveyor only) propeller generated thrust.

In total about 850,000 timestamps are recorded. The data was filtered to remove the following (operational) situations: acceleration or deceleration of the vessel, shallow water, ballast load, possible ice interaction, wind speed exceeded 5 knots and, course deviation exceeding 5 degrees.

The following conclusions can be drawn from the long-term data set for the hull coating renewal:

- Hull coating resulted in a 5 % reduction of power and fuel consumption.
- Hull coating resulted in a 6 % improvement of transport efficiency.
- The payback period for the hull coating is approximately 5.6 years.
- The CO_2 emissions reduction due to the hull coating is 928 metric tons.

Unfortunately, once data filtering was complete there was insufficient data available to determine valid estimates of change to power, efficiency, emissions, and the associated payback period for propeller polishing. Given the low cost of the procedure and the numerically estimated potential for improvement the report recommends it as having value to an operator interested in improved efficiency.

RÉSUME

Ce rapport présente les résultats d'un projet qui avait pour but d'examiner l'incidence du rafraîchissement du revêtement de la coque et du polissage de l'hélice sur la puissance de propulsion de deux grands navires d'Algoma Central Corporation (Algoma) transportant des marchandises en vrac et naviguant dans les Grands Lacs. Grâce à ce projet et au soutien de l'initiative pour le transport maritime propre du Centre d'innovation de Transports Canada, Algoma compte réduire davantage ses émissions de gaz à effet de serre et ses principaux contaminants atmosphériques (PCA).

Le lancement récent de la classe Equinox par Algoma représente une occasion idéale de réaliser un examen systématique des avantages associés à l'entretien du revêtement de la coque et à l'entretien de l'hélice par la surveillance à long terme de l'état de divers paramètres opérationnels (comme la vitesse, la puissance et la condition de chargement du navire) pendant l'exploitation normale des navires.

Les deux navires sélectionnés font partie de la classe Equinox. Il y a d'abord l'*Algoma Mariner*, d'une longueur totale de 256 m, dont le revêtement de la coque a été refait (le revêtement précédent avait été fait cinq ans auparavant). Il y a ensuite l'*Algoma Conveyor*, d'une longueur totale de 226 m, qui a fait l'objet de travaux de polissage de l'hélice (le polissage précédent avait été effectué deux ans auparavant).

La partie de la coque revêtue située sous la ligne de flottaison représente environ 58 % de la coque située sous une ligne de flottaison de 10,5 m. Aucune mesure de rugosité n'est disponible, que ce soit des mesures prises avant les travaux de revêtement de la coque ou des mesures prises après les travaux.
La face intérieure et la face extérieure des quatre pales du navire *Algoma Conveyor* ont été polies. Avant le polissage, la rugosité de l'hélice était de « D » sur l'échelle de Rubert; après le polissage, elle était de « A ».

Une analyse hydrodynamique théorique a été réalisée dans le but de formuler des hypothèses sur les améliorations attendues. L'amélioration attendue par suite du rafraîchissement du revêtement de la coque se traduit par une réduction de la consommation d'énergie de 6 % à la vitesse opérationnelle du navire. L'amélioration attendue par suite du polissage de l'hélice se traduit par une réduction de la consommation d'énergie de 6 % à la vitesse opérationnelle du navire.

Les données relatives au projet proviennent du système Prism conçu par Beaverlabs pour Algoma. Ce système permet la surveillance de la performance de la flotte d'Algoma. Il recueille des données de performance en temps réel pour tous les navires d'Algoma. Le système fournit des données à un pas de temps d'une minute pour les indicateurs suivants : heure, vitesse du navire, latitude et longitude, vitesse et direction du vent relatif, vitesse de rotation de l'hélice, couple de l'hélice, consommation de carburant et (pour le navire *Algoma Conveyor* uniquement) poussée de l'hélice.

En tout, environ 850 000 horodatages sont enregistrés. Les données ont été filtrées pour éliminer les situations (opérationnelles) suivantes : accélération ou décélération du navire, eau peu profonde, lest, interaction possible avec la glace, vitesse du vent supérieure à 5 nœuds et déviation par rapport au cap supérieure à 5 degrés.

Les conclusions suivantes peuvent être tirées de l'ensemble de données à long terme obtenues concernant le rafraîchissement du revêtement de la coque :

- Le rafraîchissement du revêtement de la coque a entraîné une réduction de 5 % de la consommation d'énergie et de carburant.

- Le rafraîchissement du revêtement de la coque a entraîné une amélioration de 6 % de l'efficacité du transport.
- La période de récupération associée au rafraîchissement du revêtement de la coque est d'environ 5,6 ans.
- La réduction des émissions de CO2 associée au rafraîchissement du revêtement de la coque est de 928 tm.

Malheureusement, une fois le filtrage des données terminé, il n'y avait pas suffisamment de données disponibles pour faire des estimations valables du changement en ce qui concerne la consommation d'énergie, l'efficacité du transport, les émissions et la période de récupération associée au polissage de l'hélice. Étant donné le faible coût de la procédure et le potentiel d'amélioration estimé numériquement, le rapport en fait la recommandation aux exploitants intéressés par une efficacité accrue.

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

#DIV/0!	Divide by zero (no results can be presented)
#N/A	No results available (results cannot be calculated)
Algoma	Algoma Central Corporation
CAC	Criteria Air Contaminants
D_P	Propeller diameter
Displacement	Displacement of the vessel
FC	Fuel Consumption
GHG	Greenhouse Gas
GIS	Geographical Information System
ITTC	International Towing Tank Conference
n	Revolution rate
NOAA	National Oceanic and Atmospheric Administration
Q	Torque
SD	Standard Deviation
SOG	Speed over Ground
T	Thrust
TCI	The Coating Inspector
TC-IC	Transport Canada Innovation Centre
Vs	Vessel Speed
ρ	Density

LIST OF UNITS

dd	days (in the context of a dd hh:mm:ss timestamp)
h	hour
hh	hours (in the context of a dd hh:mm:ss timestamp)
kg	kilogram
kn	knots
kN	kilo newton
kNm	kilo newton metre
kW	kilowatt
mils	1/1000 of an inch
m	metre
m^2	square metre

m^3	cubic metre
min	minute
mm	minutes (in the context of a dd hh:mm:ss timestamp)
MT	metric tonne
nm	nautical mile
ss	seconds (in the context of a dd hh:mm:ss timestamp)
μm	micrometre

1 OVERVIEW

1.1 INTRODUCTION

The Canadian Great Lakes fleet of ships are an important part of Canada's economy, transporting large volumes of bulk cargo every year. In addition, they reduce traffic on roads and railroads and associated pollution, congestion, and cost. While marine vessels are a significant source of greenhouse gas (GHG) emissions, they are one of the most efficient modes of transporting cargo and assist in Canada's overall efforts towards sustainable movement of goods. Algoma Central Corporation (Algoma), a leading Canadian marine shipping company, and other carriers have made significant improvements in efficiency in recent years, investing in new vessels such as Algoma's "Equinox" class with greatly improved fuel efficiency and exhaust gas cleaning systems. Through this project, and with the support of the Transport Canada Innovation Centre (TC-IC) Clean Marine initiative, Algoma intends to make further reductions in GHG and criteria air contaminants (CAC).

Resistance and propeller efficiency of vessels operating in the Great Lakes are thought to have a large influence on the engine power, on GHGs, and on CACs. Re-coating the ship hull and polishing the propeller are expected to reduce resistance and increase efficiency, respectively.

The benefits of modern hull coatings are well known, and studies have been reported on vessels in service elsewhere in the world, but no practical studies have been made reflecting the unique operating environment of the Great Lakes and St. Lawrence Seaway with its mix of fresh, brackish, and seawater, frequent lock transits (which contribute to coating breakdown), occasional transits of brash ice cover, and winter layup periods. There are similar potential benefits from propeller polishing, again with a lack of relevant Canadian data to guide maintenance strategies.

Algoma Central's recent introduction of the Equinox Class provides an ideal opportunity for a systematic exploration of the benefits of both coating and propeller maintenance by long-term condition monitoring of various operational parameters (like vessel speed, power, and loading condition). This project's goal is to characterize the benefits of hull coating and propeller maintenance for the purpose of emissions reduction. The expectations are that this has significant potential overall emissions reduction in the context of an entire fleet. This will be of value not only to this class of vessels but to the whole of Algoma's fleet, and potentially to other Great Lakes operators.

1.2 PROJECT OBJECTIVE

The objective of this work is to quantify the influence of hull coating and propeller polishing on the required engine power for a typical vessel operating in the Great Lakes by means of long-term condition monitoring of various operational parameters.

1.3 ABOUT THIS PROJECT

This is the final report for the project. Initiated in November 2020, this project has provided several milestone reports to TC-IC as shown in Table 1. Note that the numbering of the milestone reports was sequential at the time of project kick off, and not chronological in terms of delivery due to changes in scheduling both the hull coating and propeller polishing.

Table 1: Milestone Project Overview

No	Delivered	Milestone Report	Milestone Details
1	Nov 2020	Milestone report - analytical framework and historical data	Includes summary of system calibration, download and analysis of historical data, development of analytical framework.
2	Mar 2021	Milestone report - preliminary baseline performance data	Report presents a summary of the analysis of first 4 months of baseline data.
3	Aug 2021	Milestone report - propeller polishing task summary	Report presents a summary of the work done for performing propeller polishing
4	Oct 2021	Milestone report - preliminary polishing performance data	Report presents a summary of the analysis of first 4 months of data with propeller polishing complete.
5	Apr 2021	Milestone report - hull coating task summary	Report presents a summary of the work done for applying new hull coating and detailed results of the work
6	Nov 2021	Milestone report - preliminary hull coating performance data	Report presents a summary of the analysis of first 4 months of data with hull coating complete.
7	Feb 2022 (draft)	Final report	Delivery of Draft Final Report including final analysis of all data collected during the project, best practices, recommendations for ongoing work and complete summary and report on entire project scope. Also includes presentation to be made after delivery of DFR

This report is the final results for the project and recommendations for future work. The details of the completed work for tasks such as coating the hull, polishing the propeller, or developing the data collection and analysis process are available in their respective milestone reports.

1.4 REPORT LAYOUT

The report is broken down into the following sections:

Section 2: The two vessels that are analysed are described.

Section 3: The propeller polishing, and hull coating method are described.

Section 4: Describes a purely theoretical analysis (not based on the long-term data collection) of the expected output of the long-term measurements of hull coating and propeller polishing.

Section 5: The long-term data collection system is described.

Section 6: The data analysis method is described.

Section 7: The results of the data collection effort for the hull coating and propeller polishing are summarized in the section.

Section 8: Additional methodology steps are presented. A statistical analysis of the analysed data is presented and the results of the average performance data for each ship’s before and after datasets are presented and compared.

Section 9: Describes the environmental factors that could have an impact on the performance of the vessels.

Section 10: Provides an economic and cost-benefit analysis of hull coating and propeller polishing.

Section 11: Presents recommendations based on the previous sections.

Section 12: Presents conclusions based on the previous sections.

2 VESSEL DETAILS

The first vessel being studied is the Algoma Mariner, pictured in Figure 1. This is a recently built (2011) 740' self unloading bulk carrier and is similar to the class of 10 Equinox Class vessels operated by Algoma. These 10 vessels are 8 Seawaymax 740' and 2 River Class 650'. The size, hull form, and propulsion system of these vessels is representative of the modern Canadian Great Lakes fleet. This vessel was chosen because coating maintenance was last carried out in December 2015. This vessel underwent a hull coating renewal in February 2021 as part of this project.

The Algoma Mariner has the following principal particulars:

- Length Overall: 225.564 m
- Length Between Perpendiculars :219.230 m
- Beam: 23.74 m
- Depth: 15.00 m
- Gross Tonnage: 24,535 Tonnes
- Deadweight Tonnage (DWT): 38,000 MT
- Design Draft: 10.00 m
- Propeller Diameter: 5750 mm
- Controllable Pitch Propeller

Figure 1: The Algoma Mariner 740' laker

The second vessel included in the study is the Algoma Conveyor, pictured in Figure 2. This is a recently built (the vessel joined the fleet early in the 2019 season) 740' self unloading bulk carrier of the class of 8 Seawaymax Equinox Class vessels operated by Algoma. The size, hull form, and propulsion system of these vessels is representative of the modern Canadian Great Lakes fleet.

The vessel was chosen on an opportunistic basis – it is one of the Equinox vessels equipped with additional shaft instrumentation installed. While all Algoma ships can measure shaft power as a function of RPM and torque (measured by from a strain gauge on a ring clamped to the shaft) with a Kyma[1] system, some vessels in the fleet such as the Algoma Conveyor can also measure thrust via the TT Sense[2] system.

The TT sense is similar but uses optical sensors instead of strain gauges to capture torque. While the systems use different physical interfaces to capture performance data, either system is appropriate for measuring an improvement in efficiency over time before and after hull coating or propeller polishing in terms of fuel consumption/power output for distance sailed vs. speed. The underlying accuracy of the system is likely better for the TT sense because optical sensors are inherently less prone to drift and noise than strain gauges, but this is also dependent on how well the system is installed.

The Algoma Conveyor underwent propeller polishing in July 2021. This ship has the following principal particulars:

- Length Overall: 225.55 m
- Length Between Perpendiculars: 222.48 m
- Beam: 23.77 m
- Depth: 14.70 m
- Gross Tonnage: 24,640 Tonnes
- Deadweight Tonnage (DWT): 38,900 MT
- Design Draft: 8.15 m
- Propeller Diameter: 6000 mm
- Controllable Pitch Propeller

[1] Kyma marine shaft power meter https://kyma.no/shaftpower/
[2] TT Sense shaft power and thrust meter https://www.vaf.nl/products-solutions/overview/tt-sense-shaft-power-thrust-meter/

Figure 2: The Algoma Conveyor 740' laker

3 VESSEL WORK CARRIED OUT

3.1 HULL COATING AND CLEANING

The refurbishment of the Algoma Mariner's hull coating was performed starting on February 12, 2021, and took approximately 3 weeks to complete. The vessel was dry docked in Verreault Shipyard for the duration of the procedure. The procedure required three to four manlifts and about 12 crew. The coating was removed from and reapplied to the vessel's topside, bow, stern, and underwater hull. Algoma is satisfied that the coating refurbishment is up to the industry standard, and the results will enable further data collection and comparison against the baseline data. Hull roughness measurements were not completed as part of the docking.

The coated hull below the waterline represents approximately 58% of the hull below a 10.5 m waterline. The bottom was not coated because it is not subjected to wear and tear like the sides of the hull are – it does not scrape against sides or locks or make physical contact when docking or alongside.

3.1.1 Original Coating Condition

In Figure 3 the condition of the coating of the Mariner can be seen before any work was carried out.

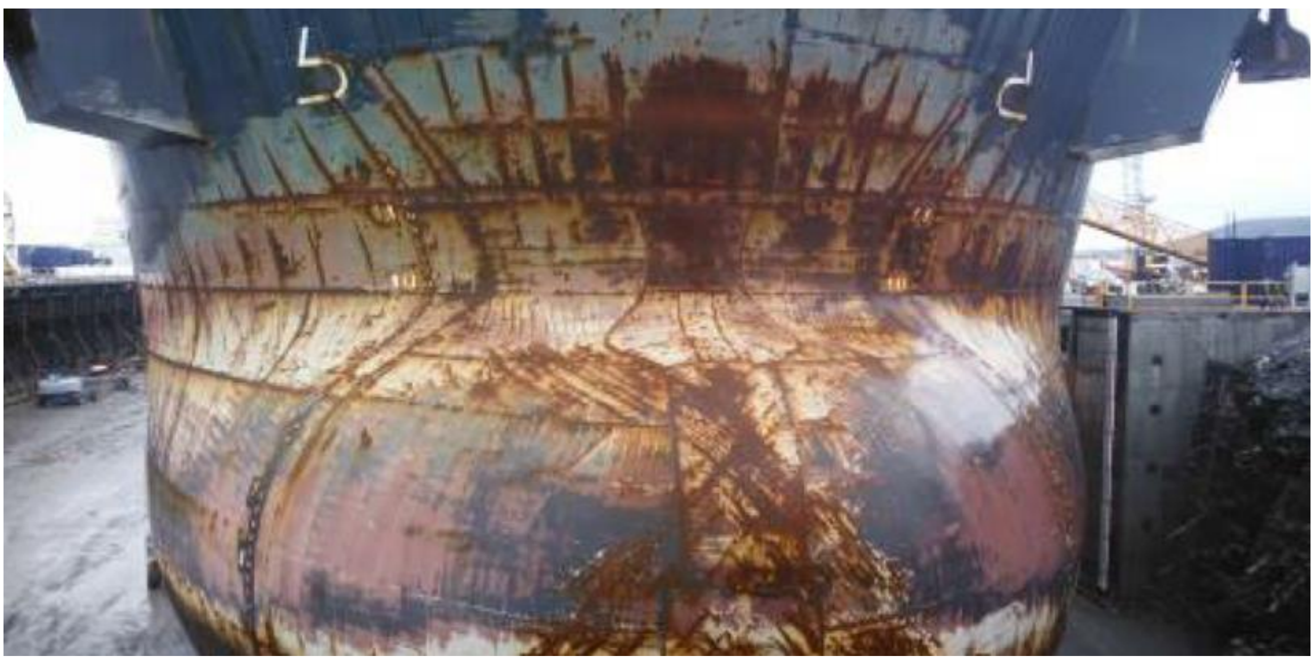

Figure 3: The vessel's bow before upgrades[3]

3.1.2 Hull Cleaning and Coating Application

The first step in the refurbishment process was a condition survey performed by the company The Coating Inspector (TCI). This work began on February 12, 2021 and took three days. The inspection results provided to Algoma primarily presented the degree of coating failure; while these are expected to generally correlate with hull roughness, no roughness measurements were made. Algoma then

[3] Algoma Mariner Project Summary February/March 2021

determined the scope of work for the Verreault Shipyard. Following the inspection, the crew began to pressure wash the hull to remove any residue or fouling before removing the old hull coating (see Figure 4).

Figure 4: The vessel being washed.

The old hull coating was removed using an abrasive blasting process. The blasting was performed to meet two of the HU929 standards; SSPC SP10 (Near White Metal Blast Cleaning), and SSPC SP7 (Brush-off Blast Cleaning). 6,000 m^2 of the hull below the waterline was blasted to the SSPC SP10 standard. It is estimated that 175 tons of JetMag (Olivine) 30/60 abrasives were used during the blasting process (of the whole vessel, above and below the waterline). See Figure 5 and Figure 6 for an impression of the vessel's hull after blasting.

Figure 5: A portion of the hull after blasting.

Figure 6: The vessel after blasting.

Anchor profile measurements were taken from ground level for the blasted surfaces. They ranged from 3.3-4.3 mils. It is recommended that the depth of the indentations not exceed 2.0-3.0 mils. It is, however, common to observe measurements greater than recommended on surfaces that have been previously re-coated.

Once the hull was inspected, cleaned, and stripped of its old coating, the new coating was applied (see Figure 7). The coating itself has a very thick and viscous consistency and is sprayed onto the vessel. 5552 m^2 of the hull below the waterline received one coat each of International Intershield 300 (Bronze) and International Intergard 5377 (Red Oxide). In general, all products used for the coating are industry standard and all were applied within acceptable temperature tolerances following their manufacturer's procedures and guidance.

Figure 7: Hull Coating being applied.

3.1.3 Refurbished Condition

The hull coating refurbishment on the Algoma Mariner has been completed and is satisfactory. There are, however, some sags, runs, and inclusions in both the red oxide and Algoma blue coatings. Furthermore, there are some water blisters in the red oxide coating near the keel on both port and starboard sides. These deficiencies are common in paint jobs for ships and hence the measured performance change due to the refurbished hull coating is representative for the industry.

After pictures of the vessel are presented in Figure 8 and Figure 9.

Figure 8: Bow section, after hull coating refurbishment

Figure 9: Side section, after hull coating refurbishment

3.2 PROPELLER POLISHING

Propeller polishing for the Algoma Conveyor was performed in the water on August 4, 2021, while the vessel was alongside at Pier #11 in Hamilton, Ontario.

3.2.1 Original Propeller Condition

Figure 10 shows an example of a blade surface of the propeller in the "pre-polish" condition of the Conveyor. Using the industry standard Propellers Roughness Comparator Scale by Rubert Co. Ltd. (generally referred to as the "Rubert Scale") for roughness it was determined that the "as-found" condition was approximately "D". (For the Rubert scale 'A' is the smoothest and 'F' is the roughest.) See Figure 11 for the Rubert Scale reference.

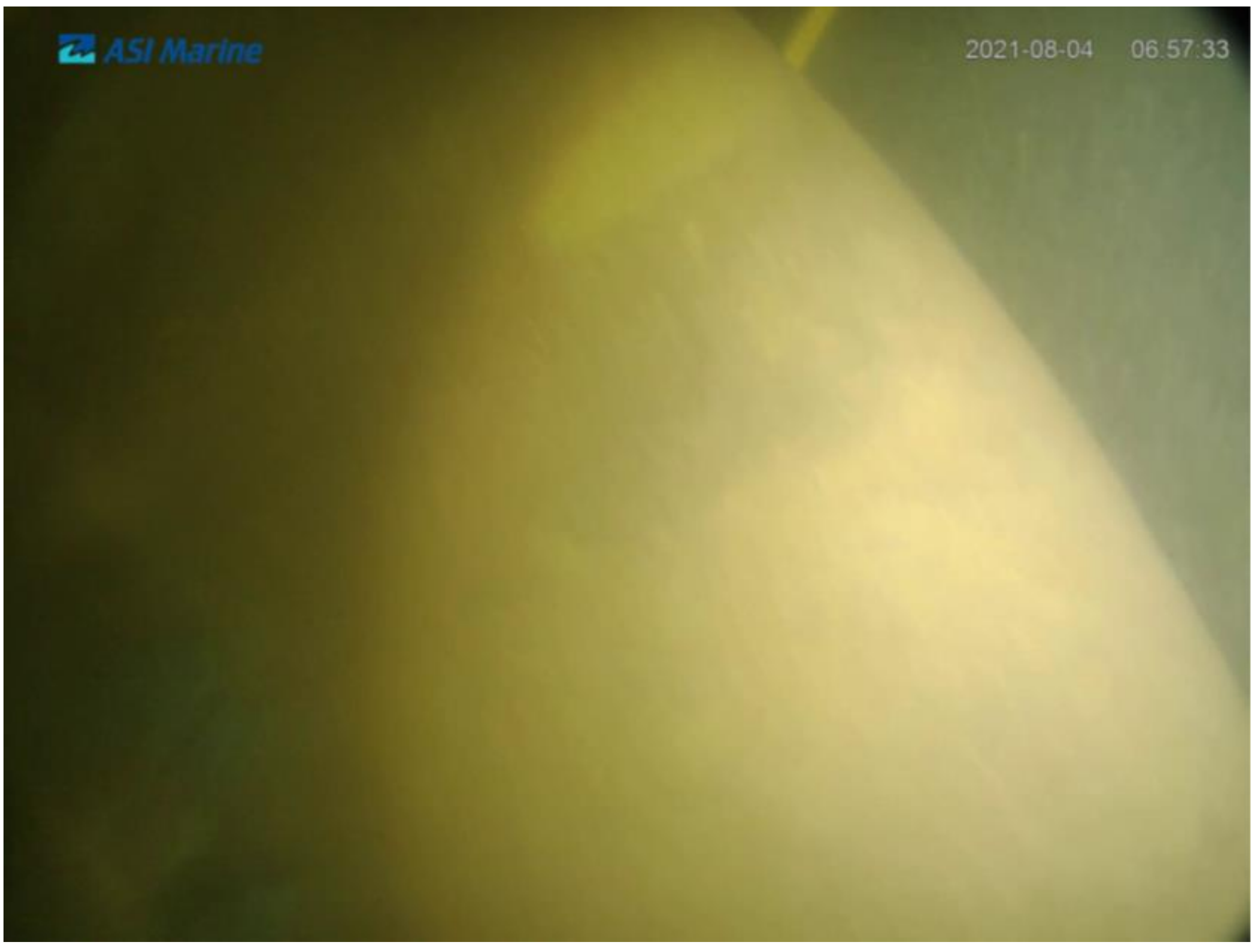

Figure 10: Blade #1 – Pre-polishing

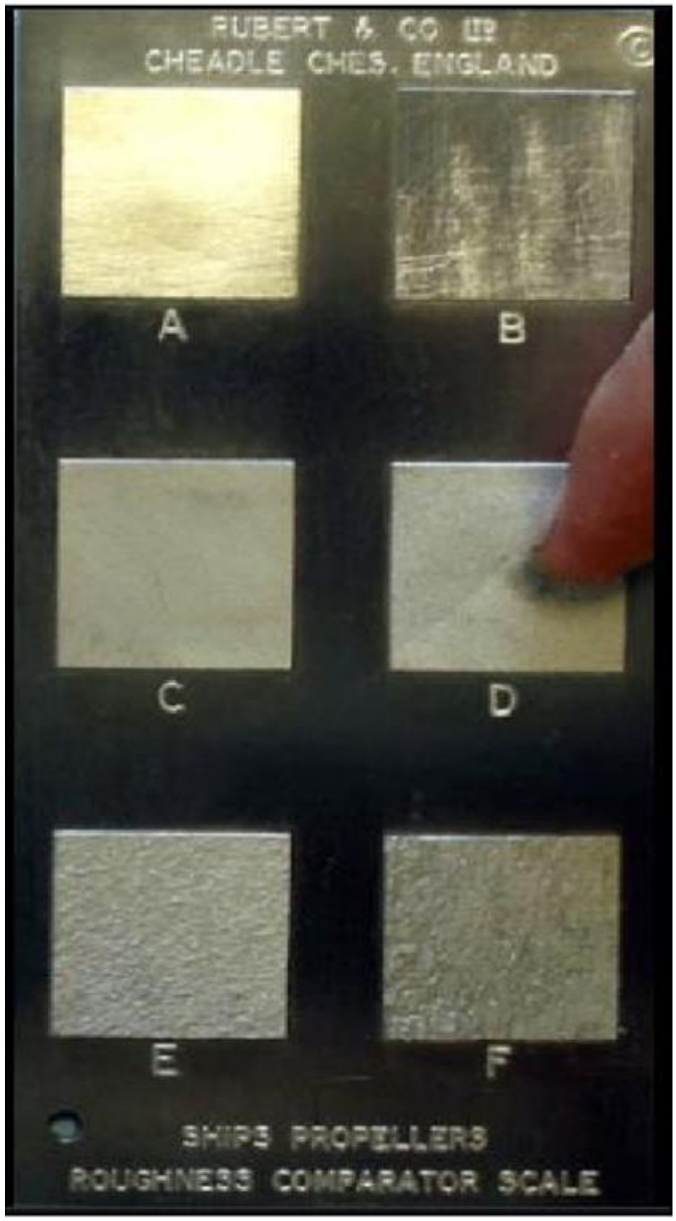

Figure 11: Rubert Scale

3.2.2 Propeller Polishing

Figure 12 shows the propeller polishing operation in progress and illustrates the contrast between polished and unpolished surfaces. The propeller polish was carried out using a hydraulically powered polisher on all four blades on both the pressure and suction face sides.

Figure 12: Propeller polishing

3.2.3 Polished Propeller Condition

Final condition post-polishing was observed as ‘A’ on the Rubert Scale (see Figure 13).

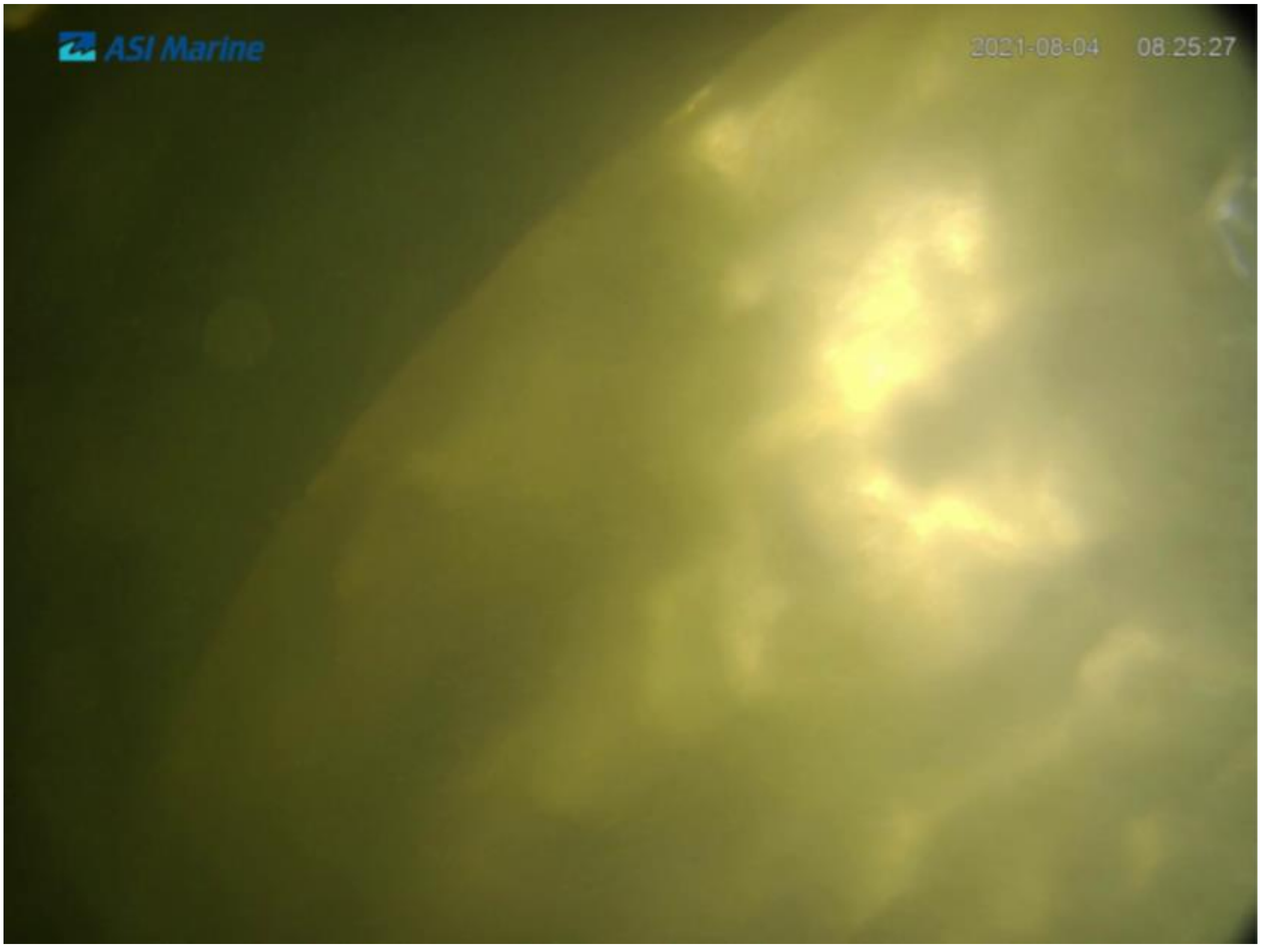

Figure 13: Blade #1 – Post-polishing (pressure face)

4 THEORETICAL HYDRODYNAMICS ANALYSIS

A theoretical hydrodynamic analysis was completed to predict the expected impacts of the new coating applied on the Algoma Mariner and the propeller polishing of the Algoma Conveyor. The analysis was based on theoretical relationships commonly used in ship design, and based on the measured degradation of the propeller (for the degradation of the hull coating VARD needed to make some assumptions, since the hull roughness was not measured before and after the drydocking). The theoretical hydrodynamic analysis is not based on the measured (long term) performance data of the Algoma Mariner or Algoma Conveyor. The loss in hydrodynamic performance due to increase in hull/propeller roughness was quantified in relative terms of power consumption for each vessel. In the theoretical numerical hydrodynamic analysis, the roughness is assumed to be homogeneously distributed to the entire surface.

4.1 VESSEL PARTICULARS

The vessel particulars for Algoma Mariner and Algoma Conveyor were obtained from general arrangement drawings, similar to those shown in Figure 14 and Figure 15, and stability booklets.

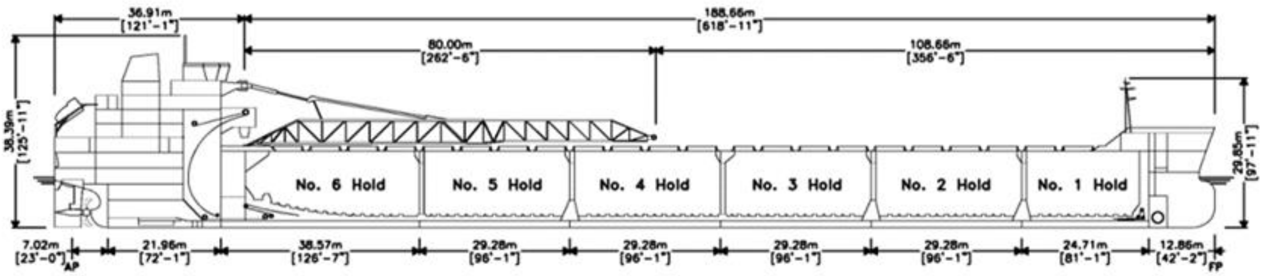

Figure 14: Algoma Mariner[4]

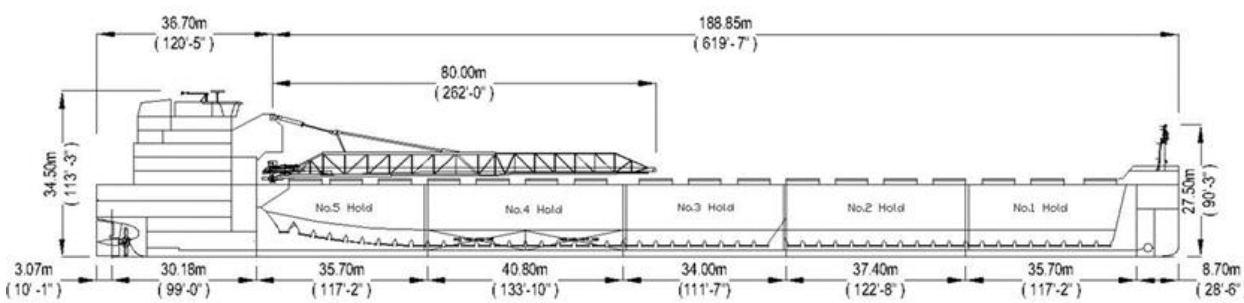

Figure 15: Algoma Conveyor[5]

The following particulars were used in the numerical hydrodynamic analysis based on draft restrictions and operating profiles in the Great Lakes with even keel:

[4] Algoma Mariner Data Sheet.

[5] Algoma Conveyor Data Sheet.

Table 2: Vessel particulars used in numerical hydrodynamic analysis

Parameter	Algoma Mariner[6]	Algoma Conveyor[7]	Unit
Length on waterline	220.51	225.55	m
Beam on waterline	23.74	23.77	m
Draft on waterline	8.15	8.15	m
Displacement†	38066[8]	38959[9]	MT
Wetted surface	8310[8]	8542[9]	m^2
Max. section area	193.2	193.2	m^2
Waterplane area	4931.8	5163.3	m^2
Submerged hull length	220.86	225.55	m
Exposed transverse area	435	445	m^2
Number of rudders	1	1	-
Projected rudder area	42.5	35.89	m^2
Number of tunnel thrusters	1	1	-
Tunnel diameter	2.15	2.15	m
Number of propellers	1	1	-
Propeller diameter	5.75	6.00	m

† In fresh water with a density of 999.1 kg/m³.

In addition to the vessel particulars in Table 2, other commercially sensitive hull data were also used in the calculations, such as the half entrance angle at the waterline, bow and stern shape data, etc.

4.2 NUMERICAL ANALYSIS METHODOLOGY

VARD uses HydroComp's NavCad[10] as the primary tool in performing resistance and propulsion/powering calculations of marine vessels. In this project, NavCad Version 2020 [Premium] (Build code: 20.01.0086.1004.CF-N5-ZZ) was used for the analysis of hull and propeller roughness influence on the overall hydrodynamic performance of the vessels in question.

NavCad is an integrated resistance and propulsion design tool for the parametric analysis of ship resistance and propulsion. Moreover, it allows for the selection and analysis of propulsion systems and components. NavCad has an extensive library of resistance prediction algorithms that are based on many different model test series and incorporates the International Towing Tank Committee (ITTC) recommended procedures and guidelines[11] for model-to-full size scaling, the prediction of resistance, speed and powering characteristics of a hull form of any size.

The Holtrop regression algorithm[12,13,14] was selected as the resistance and powering prediction method. Algoma Mariner and Algoma Conveyor particulars are in line with the allowable range of hull particulars

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[6] Algoma Mariner, General Arrangement, AALTOCXF10301F, 2011.4.6.
[7] Algoma Conveyor, General Arrangement, F3870.1112.01, 2018.11.24.
[8] Algoma Mariner, Loading Manual, E3776.1174.01-A, Rev. A, 2011-05-16.
[9] Algoma Niagara (Conveyor), Loading Manual, B3870.1174.01H, Rev. H, Dec. 2021.
[10] https://www.hydrocompinc.com/solutions/navcad/
[11] https://ittc.info/downloads/quality-systems-manual/recommended-procedures-and-guidelines/
[12] Holtrop, J., "A Statistical Re-Analysis of Resistance and Propulsion Data", International Shipbuilding Progress, Vol. 31, No. 363 Nov 1984.
[13] Holtrop, J. and Mennen, G.G.J., "An Approximate Power Prediction Method", International Shipbuilding Progress, Vol. 29, No. 335, July 1982.
[14] Holtrop, J., and Mennen, G.G.J., "A Statistical Power Prediction Method", International Shipbuilding Progress, Vol. 25, October 1978.

for the algorithm. More importantly, Holtrop regression algorithm considers the influences of relatively subtle differences in hull forms on the final resistance prediction of ships. For example, it captures the influence of the different underwater bow forms of the Algoma Mariner and Algoma Conveyor.

Added appendage drag was predicted and included in the resistance calculation for the following appendages:

- Bow Thruster Tunnel
- Rudder

The calculations were carried out in deep water and calm environmental conditions. Air resistance due to superstructure and exposed hull were included in the resistance calculation using Taylor's method[15]. As customary, an additional 10% margin was applied to the appended hull resistance to account for uncertainties.

The wake fraction, thrust deduction and relative rotative efficiency were determined using the Holtrop algorithm. B Series[16] propellers were matched to the vessels to meet thrust requirements and to determine the propulsive efficiency and power requirements. For this analysis a fixed pitch propeller (FPP) is assumed to simplify the analysis, however both vessels have (in real life) a controllable pitch propeller (CPP). The absolute powers will differ; however it is VARDs engineering judgement that the analysed power gains (in percentages) are similar between a FPP and a CPP for the analysed vessel speeds. The matched propellers are then used in determining the influence of hull and propeller roughness on vessel hydrodynamic performance using the ITTC78 procedures[17]. Cavitation levels were kept well below the 5% cavitation criterion that is most suitable for such vessels.

This analysis is by no means a replacement of the long-term measurement campaign, but it will give good insight in what one might expect if the hull is recoated or if the propeller is polished.

4.2.1 Hull coating

Algoma Mariner was drydocked in 2021 when a fresh hull coating was applied (Section 3.1). During this work, hull roughness measurements were not taken. Roughness measurements before and after the hull coating are therefore absent to make a definitive analytical assessment.

However, in the absence of hull roughness measurements, ITTC78 procedures recommend a standard hull roughness of 150 µm for a freshly coated hull to be used in the resistance calculations. Lower initial roughness values can be used for modern coating systems applied on brand new ships. Considering that Algoma Mariner is not a new ship and went through a refurbishment, the standard roughness of 150 µm was taken as the initial roughness out of the dock (or when newly re-coated) for this analysis.

A docking interval of 8 years is typical for the Algoma fleet, and that interval has been used in the analysis. There is no agreed or recommended annual roughness increase in the industry for such a study. An annual hull roughness increase can range from 10 µm for very high-performance coating with good cathodic

[15] Taylor, D.W., "The Speed and Power of Ships", 2nd. Rev., U.S. Maritime Commission, 1943.
[16] Oosterveld, M.W.C. and Oossanen, P. van, "Further Computer-Analyzed Data of The Wageningen B-Screw Series", International Shipbuilding Progress, Vol. 22, No. 251, July 1975.
[17] http://www.ittc.info/media/9872/75-02-03-014.pdf

protection up to 150 µm for resinous coatings without cathodic protection[18]. The data available is very heterogeneous with a large variation in measured hull roughness values (Table 3).

Table 3: Average hull roughness (AHR) at various ages[19]

Ship Condition	AHR [µm]
New ship coated with anticorrosive and antifouling paint	80 – 180
Ship after 3 years in service	110 – 350
Ship after 6 years in service	130 – 650
Ship after 14 years in service	380 – 1100

Based on the information in Table 3, a weighted average of the minimum and maximum AHR values for a new ship was used to achieve the ITTC recommended 150 µm AHR for a newly coated ship. Based on the weighting functions, the rest of the values for years in service were determined. Finally, a 580 µm AHR was interpolated for a ship that has been 8 years in service (Figure 16). This is the hull roughness that was used in the present analysis, in the assessment of performance impact of hull roughness increase after 8 years in service.

[18] Molland, A.F., et al. (2011) *Ship Resistance and Propulsion: Practical Estimation of Ship Propulsive Power*. Cambridge University Press, ISBN 978-0-521-76052-2 Hardback.
[19] Daehne, B., et al., "Hydrodynamic effects", Ship & Offshore, pp. 20 – 23, No. 4, 2012.

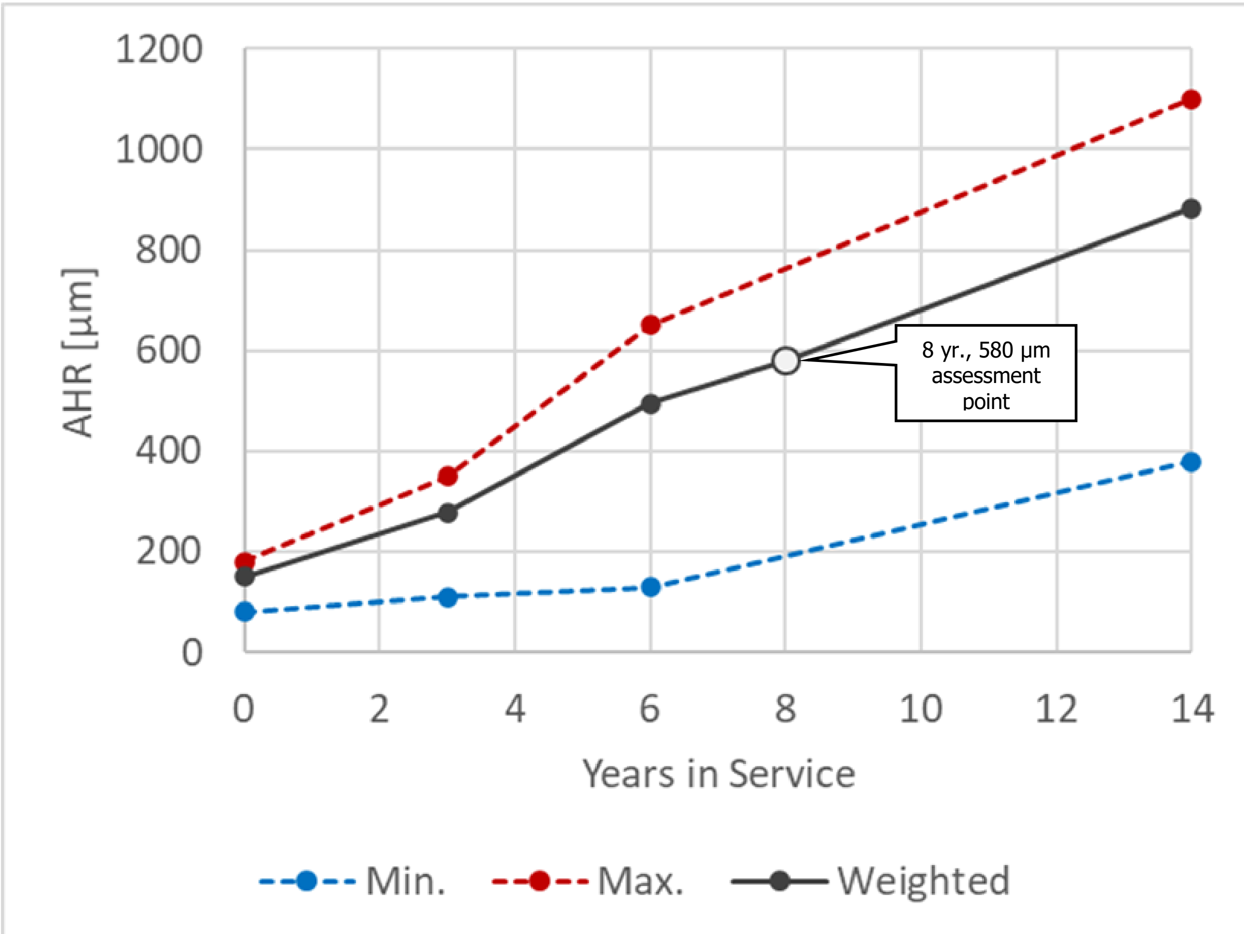

Figure 16: Average hull roughness (AHR) increase over the years in service

4.2.2 Propeller polishing

As explained in Section 3.2, the propeller of Algoma Conveyor was polished from condition D to A according to the Rubert Scale (Table 4). This is an eight-time (8x) improvement (reduction) in propeller roughness. In the hydrodynamic analysis, the performance loss due to an increase in roughness from condition A to D was determined by applying the same (8x) roughness increase. According to the ITTC78 procedures[17], the drag of the propeller was correspondingly increased and the performance impact on the thrust, torque, efficiency and eventually the power was determined as a percentage of the power required by the vessel with a polished propeller.

Table 4: Rubert scale of propeller roughness[20]

Condition	Ra [µm]	Rz (Rtm) [µm]
A	1	6
B	2	12
C	4	24
D	8	48
E	16	96
F	30	180

Ra: Roughness Average, Rz: Roughness Depth

4.3 RESULTS

4.3.1 Hull coating

The impact of hull roughness increase over 8 years in service was estimated between 7.5 and 15.5 kn speeds for the Algoma Mariner. While hull coating is the primary focus of this, it was postulated that the result may be slightly different if this were completed on a vessel with a rough or newly polished propeller. The calculations were hence performed both for a ship with a newly polished propeller (Rubert A) and one with a rough propeller (Rubert D). The following increases in resistance and propulsive power due to hull roughness increase were found:

Table 5: Relative resistance and power consumption increase due to hull roughness, comparing a freshly re-coated hull with a hull 8-years post recoating

Hull roughness investigated	Relative Resistance Increase	Relative Propulsive Efficiency Penalty	Relative Power Consumption Increase
for a hull with a polished propeller (Rubert A)	7.7 – 8.9%	2.3 – 2.6%	10.2 – 11.7%
for a hull with a rough propeller (Rubert D)	7.7 – 8.9%	2.2 – 2.5%	10.1 – 11.6%

This means that a rough hull (580 µm AHR) with a polished propeller (Rubert A) may consume 10.2 – 11.7% more power compared to a newly coated hull (150 µm AHR) with the same polished propeller. In the same sense, if the propeller is rough (Rubert D), the ship with the rough hull could consume 10.1 – 11.6% more power compared to a newly coated hull with the same rough propeller. This sensitivity calculation shows that the hull roughness should have about the same impact on the relative performance of the vessel regardless of the propeller condition. Based on this, due to partial coating of the hull, approximately 6% improvement could be expected in power consumption regardless of propeller roughness in reality.

It is no surprise that the hull roughness could cause a resistance increase of 7.7 – 8.9% in the investigated speed range regardless of the propeller's surface condition; in other words, the propeller roughness does not affect the total resistance increase.

Interestingly, this increase in resistance could cause the propeller to be more heavily loaded and work in a non-ideal regime at a given pitch (Figure 17). As a result, the overall propulsive efficiency could suffer in the range of 2.3 – 2.6% in the case of a polished propeller and 2.2 – 2.5% in the case of a rough propeller.

[20] https://www.abcdiving.com/pages/cleaning/performances.html (The original Propeller Roughness Comparator Scale, also called the Rubert scale, shown with the roughness values provided with the scale).

This penalty on the propulsive efficiency is reflected in the power consumption increase due to hull roughness. However, the vessel is actually fitted with a controllable pitch propeller, so it is possible that a different pitch setting may be used before/after the propeller polishing. This would directly cause the entire efficiency curve in Figure 17 to raise or lower. This could reduce the predicted changes in propulsive efficiency, such that the actual power changes for the ship may be more in line with the predicted changes in resistance shown in Table 5.

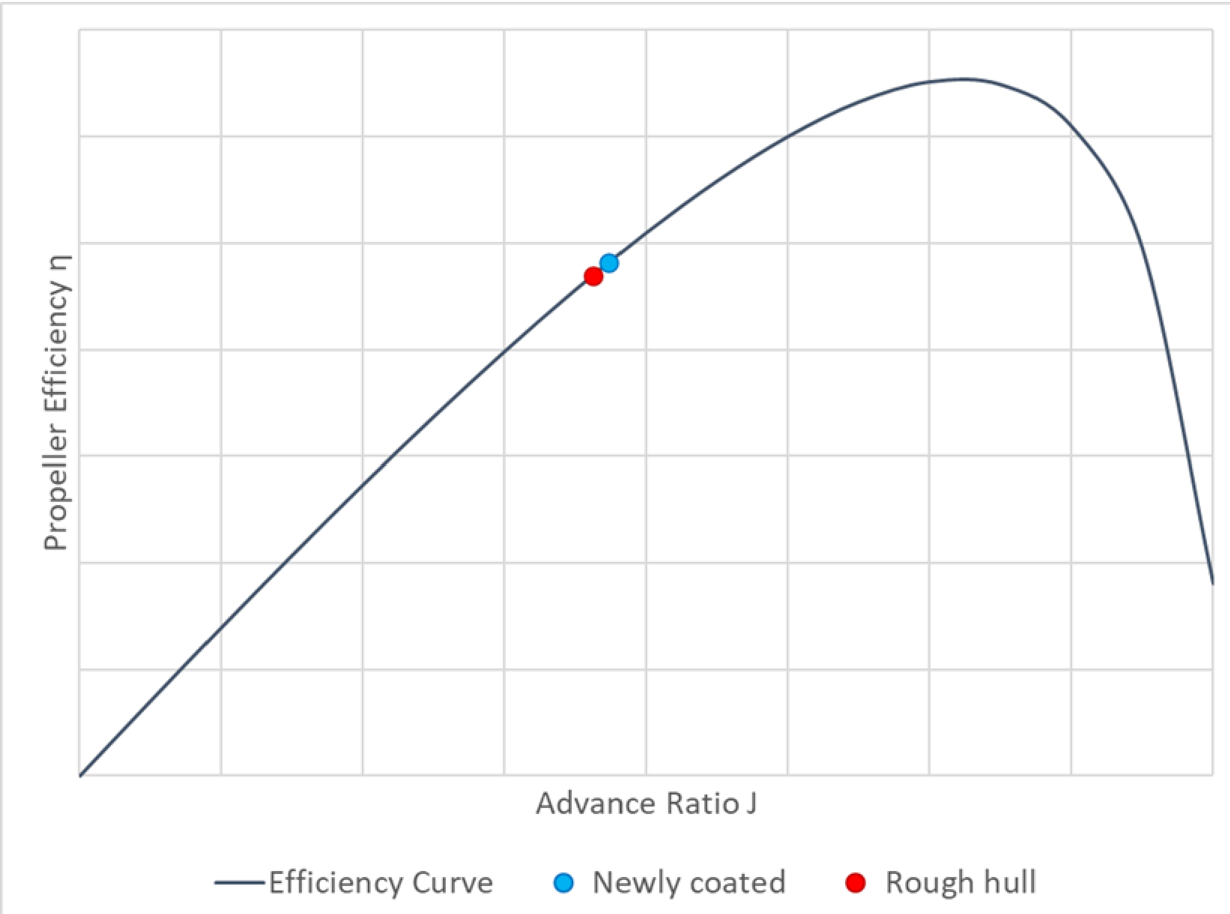

Figure 17: Impact of hull roughness on propeller efficiency at a given pitch and operating point

Here, advance ratio J is the ratio of the freestream fluid speed to the propeller's tip speed and is non-dimensional. Propeller efficiency η is the ratio of the power required for thrust to advance the propeller to the power required for torque to spin the propeller and is non-dimensional.

4.3.2 Propeller polishing

The impact of propeller roughness increase from Rubert scale A to D was estimated between 7.5 and 15.5 kn speeds for the Algoma Conveyor. The calculations were performed for a hull with a newly applied coating (150 µm AHR) and after 8 years in service (580 µm AHR). The following increase in propulsive power due to propeller roughness increase was found:

Table 6: Relative power consumption increase due to propeller roughness (going from a Rubert's scale of "A" to "D")

Propeller roughness investigated	Relative Power Consumption Increase
for a propeller of a newly coated ship (150 µm AHR)	5.6 – 6.0%
for a propeller of a ship 8 years in service (580 µm AHR)	5.5 – 5.8%

This means that a ship with a freshly coated hull (150 µm AHR) and a rough propeller (Rubert D) may consume 5.6 – 6.0% more power compared to the same ship with a polished propeller (Rubert A). In the same sense, if the hull coating is not fresh (580 µm AHR), the ship with the rough propeller could consume 5.5 – 5.8% more power compared to the same ship with a polished propeller. This sensitivity calculation shows that the propeller roughness should have about the same impact on the relative performance of the vessel regardless of the hull condition.

It is important to note, however, that the improvements shown here are for a propeller operating at the same pitch before and after polishing. Any difference in the pitch setting (via the combinator curve) before and after the polishing work would render this comparison invalid since the blade pitch would be different. For example, if the original blade pitch was set lower than the optimum condition, with a rough propeller that is less effective at generating thrust, an efficiency increase could be achieved via:

a) Increased pitch. This could raise the entire efficiency curve as well, which may counteract the efficiency losses otherwise expected with a rough propeller.

b) Increased RPM. This could align with the predictions above.

c) Some combination of the above. This could yield intermediate performance degradation with a rough propeller.

d) A substantial increase in pitch, enabling reduced RPM. This could increase the efficiency curve by a larger amount, while shifting the operating point to the right. This could yield very small performance degradation with a rough propeller, or perhaps even a performance improvement.

This does not mean that increasing the propeller pitch indefinitely would increase the efficiency. Other factors such as the engine torque limit, cavitation, and the design pitch of the propeller blades have to be taken into account in such an assessment. After a certain point, the propeller efficiency is likely to degrade with increased pitch. Detailed information regarding the combinator curve would be required to determine which of the above scenarios is most likely.

5 DATA COLLECTION

5.1 THE PRISM SYSTEM

Data for the project is provided by the Prism system developed by Beaverlabs for Algoma to monitor their fleet's performance. The system is currently deployed across the entire fleet, collecting real-time performance data for all Algoma vessels. The system provides data on the present and past performance of any of Algoma's assets. For this project, the system is used to track the location and performance of the Algoma Conveyor and the Algoma Mariner.

The two systems on board, The Electronic Chart Display and Information System (ECDIS) and Signal Processing Unit (SPU) report the following every minute.

ECDIS:

- Timestamp
- Speed through water (sensor based, absolute) (kn)
- Lat/Long position
- Absolute wind angle (deg)
- Absolute wind speed (kn)
- Relative wind angle (deg)
- Relative wind speed (kn)

SPU:

- Timestamp
- Lat/Long position
- Speed over ground (GPS based)
- Speed through water (drawn from sensor, same signal as ECDIS)
- Prime mover shaft speed (rpm)
- Prime mover shaft torque (kNm)
- Prime mover generated power (kW)
- Prime thrust (kN) (Algoma Conveyor only)
- Prime mover fuel consumption rate (kg/h)

5.2 DATA CAPTURING

This final report presents the overall efficiency changes from the propeller polishing and hull coating for the project vessels. The data has been collected from Jan 1st, 2020 to Nov 21st, 2021 to capture a before and after record of the various signals, including: engine power, fuel consumption rate, vessel speed, and wind speed and direction for both vessels.

6 METHODOLOGY

The following overarching methodology was followed for the Algoma Conveyor and the Algoma Mariner data analysis:

1. The available data (about 400,000 datapoints for the Mariner and about 450,000 datapoints for the Conveyor) were split in two parts. One part consisting operational data from the measurements before the condition upgrade, and one part consisting of data from after the condition upgrade.
2. The data was filtered to focus on data of interest – primarily steady state operations:
    a. All datapoints where the vessels were accelerating or decelerating were excluded as those datapoints will have higher or lower than normal fuel consumption (FC) and power use. The data sampling rate was once per minute.
        i. All measured speeds over ground (SOG) that vary more than 0.2 knots with the measured speed before or after the analysed timestamp are removed from the analysis. The used data is from open areas in the Great Lakes, hence the influence of current is assumed to be negligible.
        ii. Data that was more than 2 minutes from the preceding or next point were removed from the analysis.
    b. A very small number of spurious signals were removed, such as measured powers that are larger than the installed power.
    c. All measured powers that are smaller or equal to zero are removed from the analysis.
3. The data was filtered to avoid shallow water effects. Specifically, for the purposes of this study "deep water" is a water depth larger than 12 m. The water depth limit is based upon the Froude water depth number[21] of 0.7. All data with unknown or water depths smaller than 12 m are disregarded for these analyses. The used data is from open areas in the Great Lakes. While it is possible that some resistance components may still be influenced by shallow water frictional increase effects at depths greater than 12 m, these effects have been assumed to be small.
4. The recorded delivered power measurements are presented as 200kW bins. The average (or centre) of the power bins in presented throughout this report, for instance the power bin that ranges from 800 kW up to 1000 kW is presented as 900 kW average power bin. The use of power bins is based on common practices for planned vessel sea trials include speed measurements, during which the vessel's power is usually set to a fixed value[22]. The average of a speed run up and down the dominant environmental condition (wind or current) is then considered the final vessel speed. The data analysis has followed the same approach and all power measurements processed per steps (2) or (3) are binned in 200 kW bins.
5. The filtered speed over ground (SOG) measurements are binned in the same bins as the measured power. SOG was selected for further processing instead of the speed through water. This is because the speed through water transducer appeared to have been re-calibrated multiple times

[21] Schlichting, O. 1934, Schiffswiderstand auf beschrankter Wassertiefe, Jahrbuch Schiffbautechnisches Gezellschaft.
[22] ITTC – Recommended Procedures and Guidelines, Preparation, Conduct and Analysis of Speed/Power Trials, 7.5-04-01-01.1, 2017, revision 05

during the measurement campaign, did not align with SOG in deep lake conditions where no current is expected, and showed similar or greater scatter in the end results.

6. The filtered fuel consumption measurements are binned in the same bins as the measured power.
7. The relative wind direction is binned over 360 degrees in 45 degree increments.
8. The cargo load is binned in 2500 MT increments.
9. The transport efficiency[23] is determined. The transport efficiency (in the remaining section of this report called "efficiency") is the amount of cargo that is carried times the speed at which the vessel is sailing divided by the used power. As these parameters are each presented as percentages, the used unit of transport efficiency in this report is therefore "(speed %) × (cargo %) / (power %)". It is important to recognize that this does not follow traditional definitions of efficiency (i.e. output power / input power), and so the values are not bound to be les than 100. Supposing the cargo, speed, and power are all independent, the transport efficiency will increase if the ship speed or the amount of carried cargo increases or if the amount of used power decreases. In realistic situations, the cargo, speed and power are interrelated; for example, speed decreases typically cause a dramatic reduction in power and hence an increase in transport efficiency.
10. The Algoma Conveyor has installed and configured (in April 2021, during the prior propeller polishing period) a Lean Marine FuelOpt system during the data collection period. The Lean Marine FuelOpt system can optimise the pitch of the propeller (instead of having a pitch set directly by the lever setting and combinator curve). The FuelOpt system can optimise the pitch in such a way that the least amount of fuel is consumed. To compare the prior and after propeller polishing situation of the Algoma Conveyor, it has been decided to remove all data prior to the installation of the Lean Marine FuelOpt system.

[23] Harries, S. Abt, C. Hochkirch, K. 2006. Advanced Hydrodynamic Design of Container Carriers for Improved Transport Efficiency. Royal Institution of Naval Architects.

7 SUMMARY OF COLLECTED DATA

The collected data are summarized in this section following the processing in Section 6, but with no further assessment of the influence on hull coating or propeller polishing. See Section 8 for a detailed analysis of these results, including determination of the influence of hull coating and propeller polishing.

The most important signals for this report are presented in this section (however each timestamp has the data that is presented in Section 5.1). Most of the data is presented as non-dimensioned values that are a percentage of the vessel's design speed, maximum available engine power, and maximum fuel consumption, rather than absolute measured values. This has no effect on the data analysis or the results.

This dataset includes a variety of conditions including open versus ice-infested water, laden versus ballast condition.

7.1 HULL COATING

The applicable datapoints before and after the hull coating upgrade are presented in this section (no analysis is presented in this section).

7.1.1 Data - Before Hull Coating

Data for the Algoma Mariner for the period prior to the hull coating was collected from November 2019 to February 2021. The amount of datapoints after filtering the data as described in Section 6 is approximately 36,000. This dataset is used to determine the speed, power, and fuel consumption relationships presented in Section 8.

Table 7 is a summary of this data set. It lists the power bins used for the analysis, and shows the average power, the average Speed over Ground (SOG), and the average Fuel Consumption (FC) for each bin. Note that these values are shown as a percentage of the maximum design value for power, speed, and FC instead of absolute measured values. This has no effect on the calculations of the relative change in performance before and after either hull coating or propeller polishing.

Table 7: Summary of Datapoints Prior to Hull Coating

Average Power Bin [kW]	Count of Datapoints [-]	Total Duration [dd hh:mm:ss]	Average Power [% of maximum power]	Average SOG [% of maximum design speed]	Average FC Measured [% of maximum design FC]
300	121	00 02:01:00	5	15	27
500	287	00 04:47:00	7	31	26
700	506	00 08:26:00	10	38	21
900	203	00 03:23:00	12	43	23
1100	35	00 00:35:00	14	49	28
1300	19	00 00:19:00	18	47	31
1500	25	00 00:25:00	21	61	27
1700	29	00 00:29:00	24	62	32
1900	38	00 00:38:00	27	66	31
2100	309	00 05:09:00	29	64	34
2300	187	00 03:07:00	32	66	37
2500	200	00 03:20:00	35	71	42

Average Power Bin [kW]	Count of Datapoints [-]	Total Duration [dd hh:mm:ss]	Average Power [% of maximum power]	Average SOG [% of maximum design speed]	Average FC Measured [% of maximum design FC]
2700	360	00 06:00:00	38	74	44
2900	665	00 11:05:00	40	74	47
3100	636	00 10:36:00	43	76	50
3300	770	00 12:50:00	46	78	53
3500	1250	00 20:50:00	49	81	56
3700	5179	03 14:19:00	52	83	59
3900	7234	05 00:35:00	54	83	62
4100	6484	04 12:04:00	57	84	65
4300	6035	04 04:35:00	60	84	68
4500	3394	02 08:34:00	62	83	70
4700	1516	01 01:16:00	65	87	73
4900	659	00 10:59:00	68	89	76
5100	143	00 02:23:00	70	88	78
5300	4	00 00:04:00	73	88	82
5500	2	00 00:02:00	75	89	84

Table 8 shows the distribution of the cargo capacity by the cargo load bins.

Table 8: Distribution of Cargo Capacity Prior to Hull Coating

Cargo Load bin [MT]	Count of Datapoints [-]
0 - 2500	337
20000 - 22500	3099
22500 - 25000	7562
25000 - 27500	9428

Table 9 shows the distribution of the relative wind angle by the relative wind angle bins.

Table 9: Distribution of Relative Wind Angle Prior to Hull Coating

Relative Wind Angle bin [deg]	Count of Segment [-]
0-45	10322
45-90	6118
90-135	3698
135-180	691
180-225	473
225-270	2117
270-315	4185
315-360	11061

7.1.2 Data - After Hull Coating

Data for the Algoma Mariner for the period after the hull coating was completed was collected from March 2021 to November 2021. The number of datapoints after filtering the data as described in Section 6 is approximately 29,000. This dataset is used to determine the speed, power, and fuel consumption relationships as is presented in Section 8.

Table 10 is a summary of the dataset after the hull coating was applied. It lists the power bins used for the analysis, and shows the average power, the average Speed over Ground (SOG), and the average Fuel Consumption (FC) for each bin. Note that these values are shown as a percentage of the maximum design value for power, speed, and FC instead of absolute measured values. This has no effect on the calculations of the relative change in performance before and after either hull coating or propeller polishing.

Table 10: Summary of Datapoints After Hull Coating

Average Power Bin [kW]	Count of Datapoints [-]	Total Duration [dd hh:mm:ss]	Average Power [% of maximum power]	Average SOG [% of maximum design speed]	Average FC Measured [% of maximum design FC]
100	2	00 00:02:00	2	24	13
300	30	00 00:30:00	5	16	12
500	40	00 00:40:00	6	19	13
700	245	00 04:05:00	10	40	14
900	214	00 03:34:00	12	43	15
1100	33	00 00:33:00	14	45	17
1300	23	00 00:23:00	18	57	21
1500	17	00 00:17:00	21	60	24
1700	17	00 00:17:00	24	63	29
1900	248	00 04:08:00	27	56	31
2100	289	00 04:49:00	29	56	34
2300	143	00 02:23:00	32	61	37
2500	122	00 02:02:00	35	69	41
2700	107	00 01:47:00	38	62	44
2900	122	00 02:02:00	40	73	47
3100	896	00 14:56:00	44	81	51
3300	3003	02 02:03:00	46	81	53
3500	4051	02 19:31:00	49	84	56
3700	6354	04 09:54:00	51	84	59
3900	5390	03 17:50:00	54	85	62
4100	3693	02 13:33:00	57	84	65
4300	1833	01 06:33:00	60	85	68
4500	1185	00 19:45:00	62	86	71
4700	495	00 08:15:00	65	85	74
4900	59	00 00:59:00	68	85	77
5100	12	00 00:12:00	70	84	79

Table 11 shows the distribution of the cargo capacity by the cargo load bins.

Table 11: Distribution of Cargo Capacity After Hull Coating

Cargo Load bin [MT]	Count of Datapoints [-]
15000 - 17500	1831
22500 - 25000	11142
25000 - 27500	2628
27500 - 30000	126

Table 12 shows the distribution of the relative wind angle by the relative wind angle bins.

Table 12: Distribution of Relative Wind Angle After Hull Coating

Relative Wind Angle bin [deg]	Count of Segment [-]
0-45	12794
45-90	2359
90-135	827
135-180	276
180-225	112
225-270	458
270-315	1808
315-360	10677

7.1.3 Hull Coating Basic Results

Figure 18 and Figure 19 show the power consumption versus vessel speed before and after the coating was applied. This dataset includes a variety of conditions including open versus ice infested water, laden versus ballast condition.

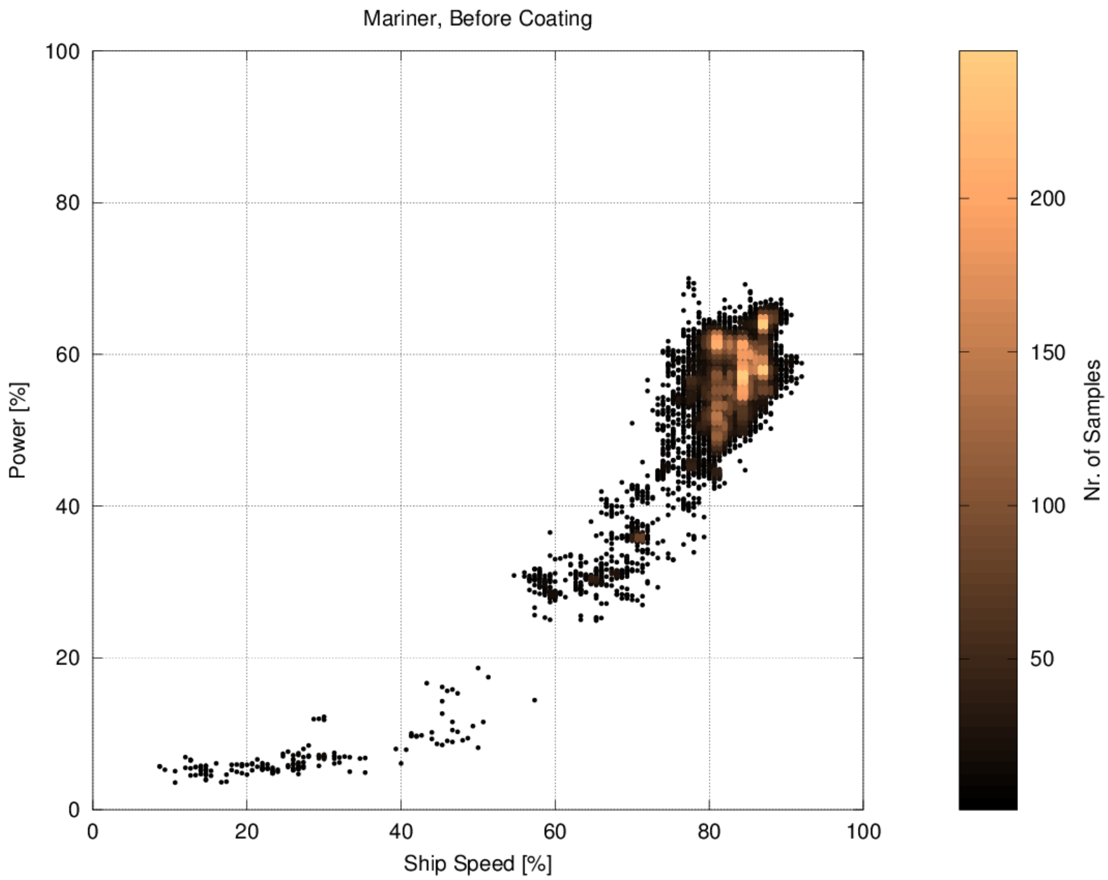

Figure 18: Power versus SOG for Mariner before Coating

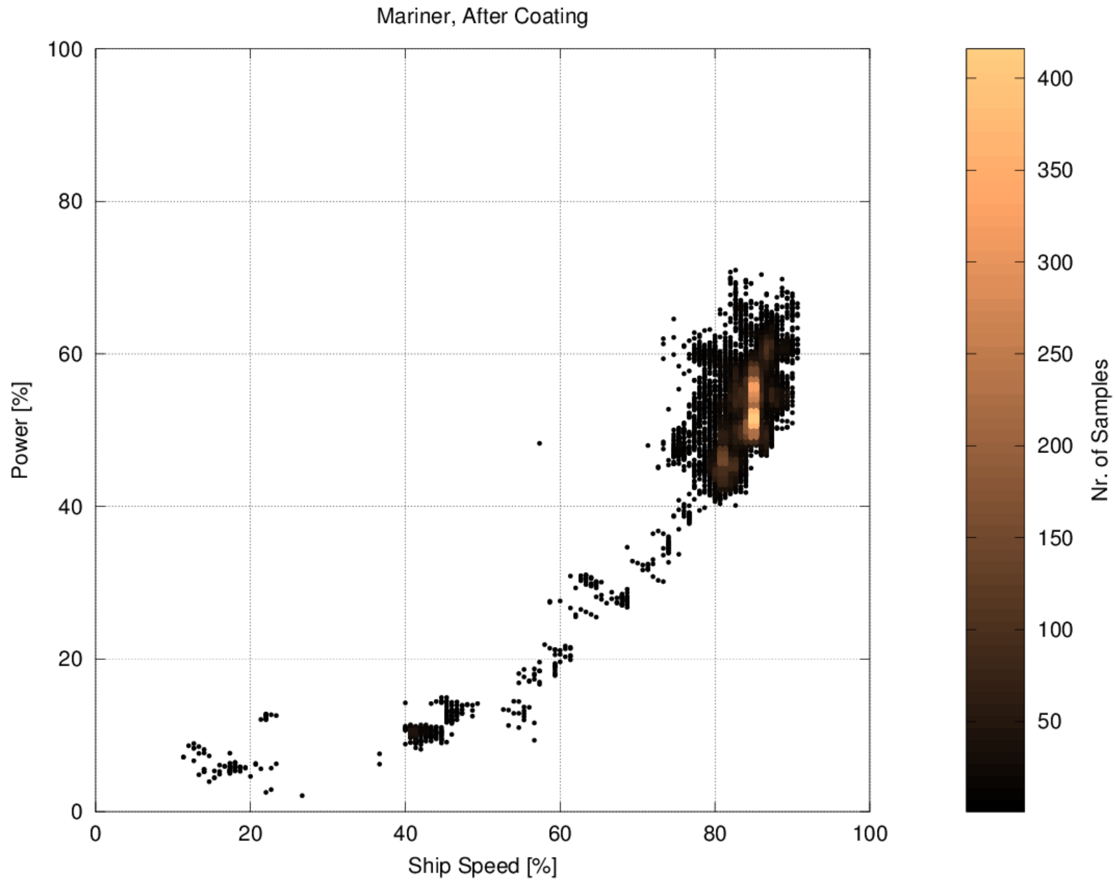

Figure 19: Power versus SOG for Mariner after Coating

Figure 20 and Figure 21 show the fuel consumption rate versus vessel speed before and after the coating was applied. The fuel consumption measurements in Figure 20 in the lower speed regions are above the overall distribution (see the red circle in the graph), most likely due to the wider variety of operational activities undertaken at lower speeds compared to higher speeds typically associated with longer transits. This is further investigated in Section 8.

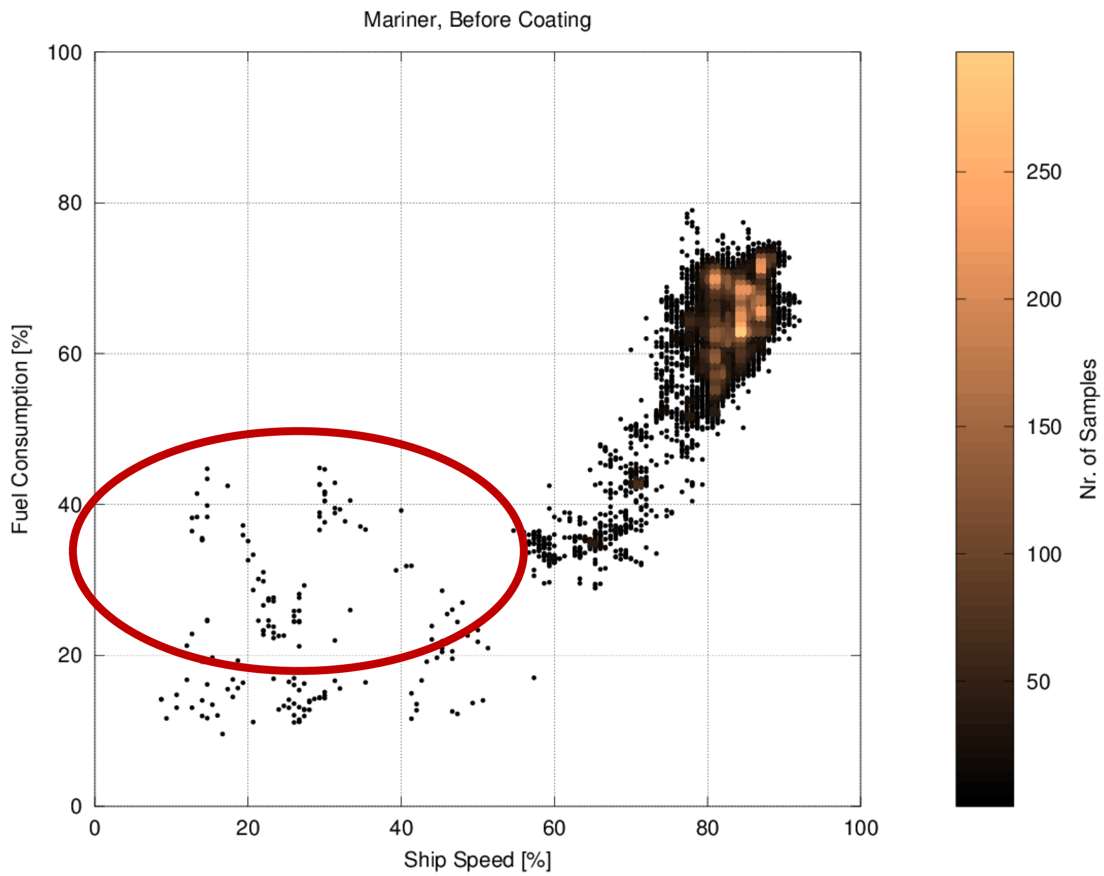

Figure 20: Fuel Consumption (measured) versus SOG for Mariner before Coating

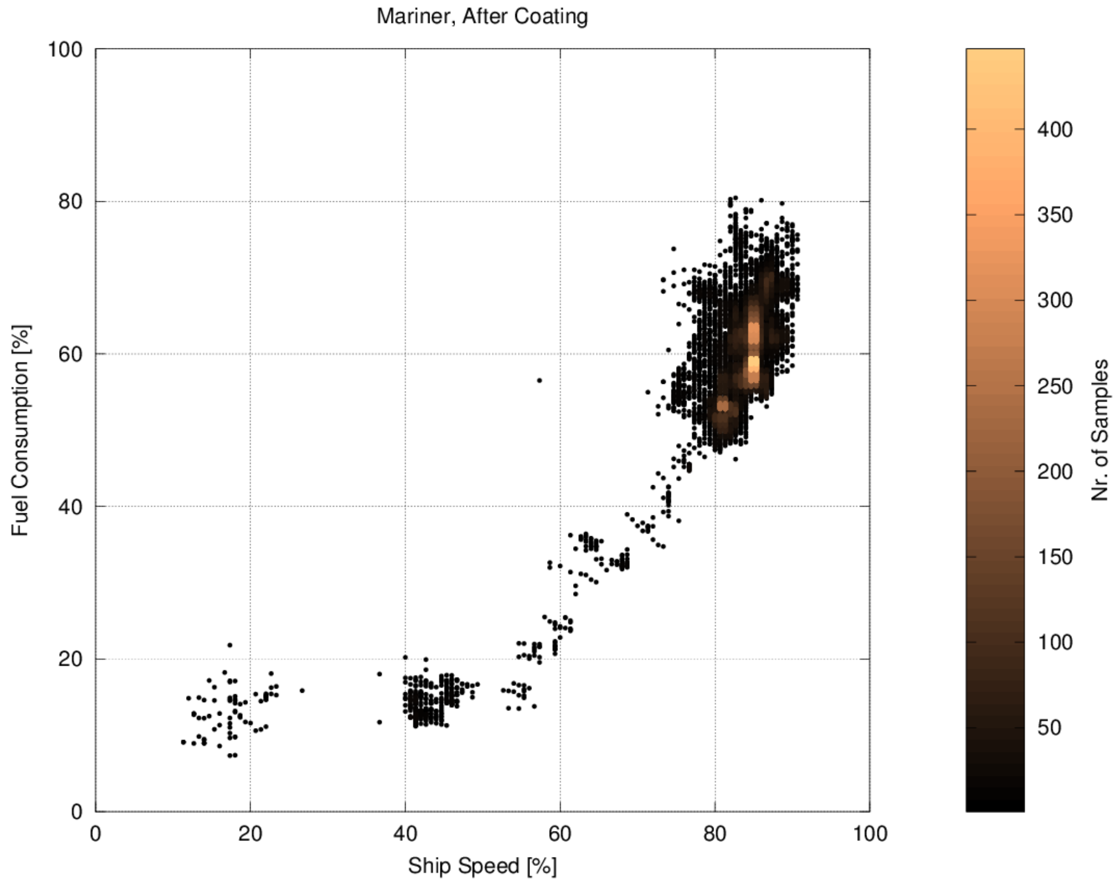

Figure 21: Fuel Consumption (measured) versus SOG for Mariner after Coating

Figure 22 and Figure 23 show the efficiency versus vessel speed before and after the coating was applied. At lower speeds the data is scattered (this is expected since the environmental factors play a larger role on the resistance of the vessel at low vessel speeds than at higher vessel speeds). At higher vessel speeds (see the red circle in the graph) the relatively close distribution of datapoints is sufficient to determine a trendline for the transport efficiency. Section 8 presents a detailed discussion of the data trends and distributions.

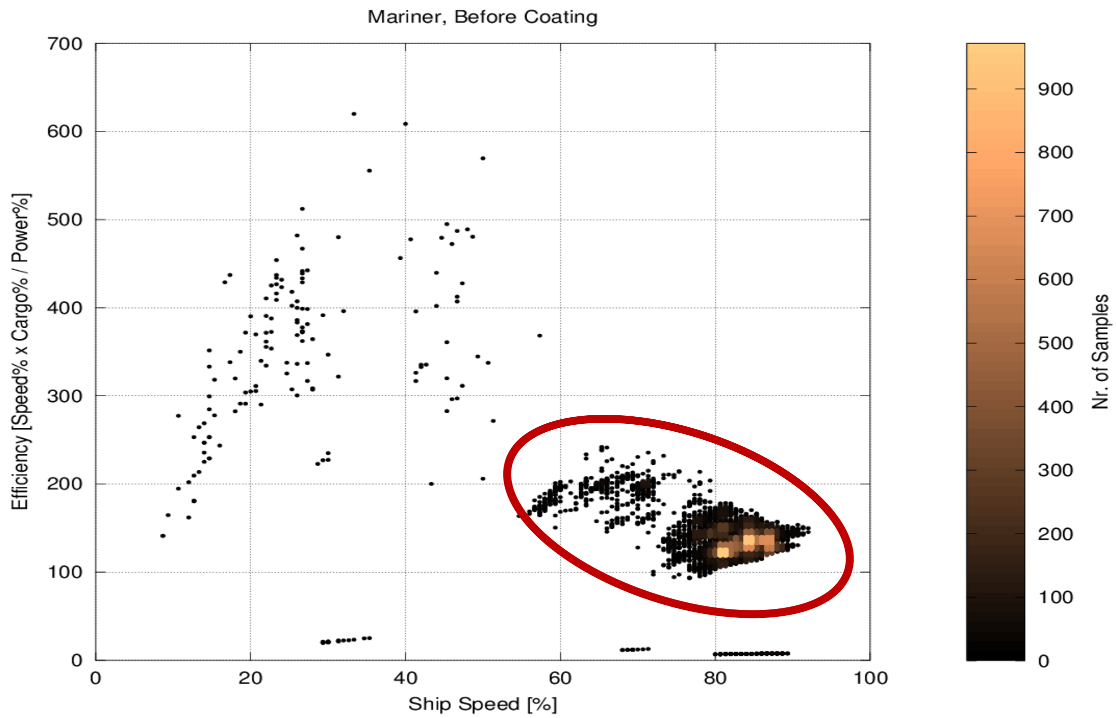

Figure 22: Efficiency versus SOG for Mariner before Coating

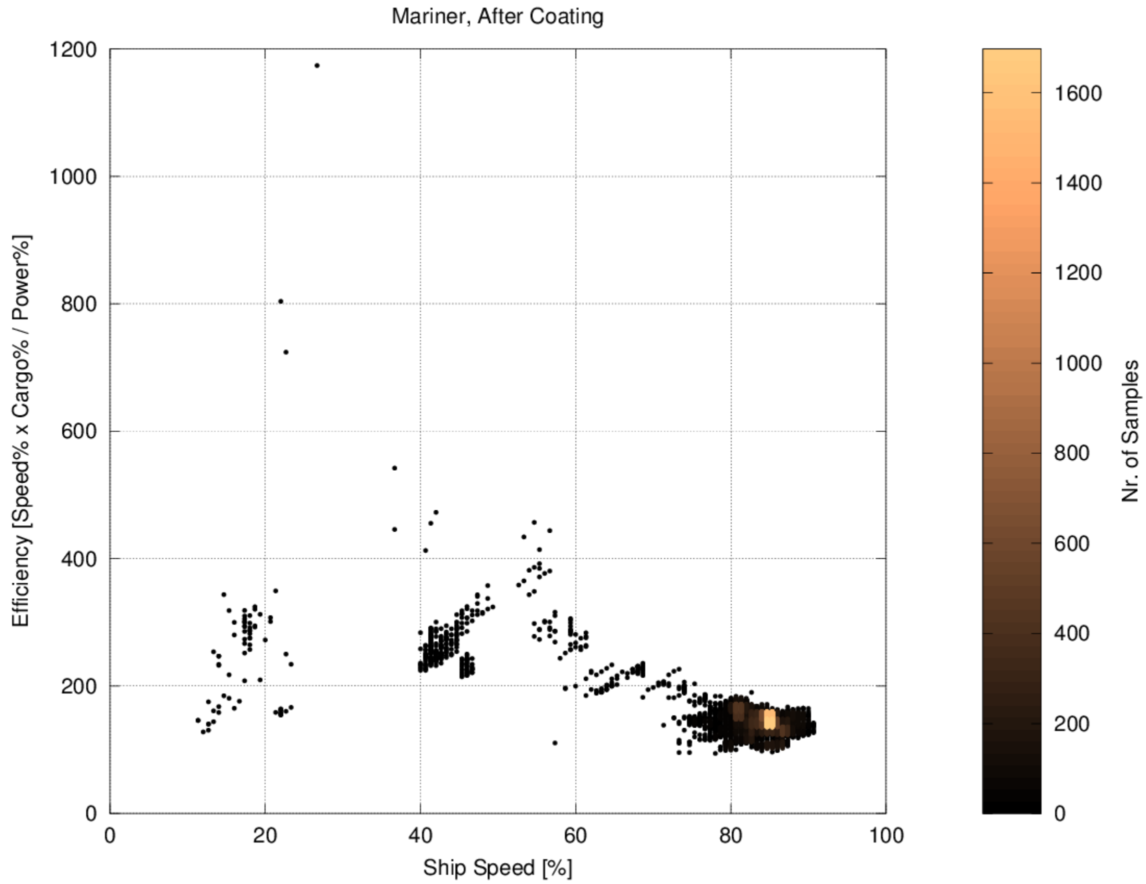

Figure 23: Efficiency versus SOG for Mariner after Coating

7.2 PROPELLER POLISHING

The applicable datapoints before and after propeller polishing are presented in this section (no analysis is presented in this section).

7.2.1 Data - Before Propeller Polishing

Data for the Algoma Conveyor for the period prior to the propeller polishing was collected from January 1, 2020, to August 1, 2021. This dataset was used to determine the speed, power, fuel consumption relationships as presented in Section 8. The number of datapoints after filtering the data as described in Section 6 is approximately 47,000. This dataset is used to determine the speed, power, and fuel consumption relationships presented in Section 8.

Table 13 is a summary of this data set. It lists the power bins used for the analysis, and shows the average power, the average Speed over Ground (SOG), and the average Fuel Consumption (FC) for each bin. Note that these values are shown as a percentage of the maximum design value for power, speed, and FC instead of absolute measured values. This has no effect on the calculations of the relative change in performance before and after either hull coating or propeller polishing.

Table 13: Summary of Datapoints Prior to Propeller Polishing

Average Power Bin [kW]	Count of Datapoints [-]	Total Duration [dd hh:mm:ss]	Average Power [% of maximum power]	Average SOG [% of maximum design speed]	Average FC Measured [% of maximum design FC]
300	2	00 00:02:00	6	17	9
500	307	00 05:07:00	7	31	11
700	590	00 09:50:00	11	42	14
900	15	00 00:15:00	13	48	17
1100	306	00 05:06:00	15	52	19
1300	2053	01 10:13:00	19	53	22
1500	941	00 15:41:00	21	54	25
1700	132	00 02:12:00	24	60	28
1900	57	00 00:57:00	27	62	31
2100	60	00 01:00:00	30	68	35
2300	66	00 01:06:00	33	70	38
2500	42	00 00:42:00	35	71	41
2700	50	00 00:50:00	39	73	44
2900	50	00 00:50:00	41	76	48
3100	51	00 00:51:00	44	77	49
3300	52	00 00:52:00	47	78	51
3500	79	00 01:19:00	50	77	54
3700	60	00 01:00:00	53	79	57
3900	28	00 00:28:00	56	81	60
4100	44	00 00:44:00	59	83	63
4300	498	00 08:18:00	62	83	69
4500	2085	01 10:45:00	64	85	70
4700	376	00 06:16:00	67	85	72
4900	706	00 11:46:00	70	86	76
5100	14552	10 02:28:30	73	88	79
5300	23846	16 13:23:30	75	87	79
5500	70	00 01:10:00	78	85	82
5700	5	00 00:05:00	81	86	85
5900	85	00 01:25:00	84	93	90
6100	84	00 01:24:00	86	89	91

Table 14 shows the distribution of the cargo capacity by the cargo load bins.

Table 14: Distribution of Cargo Capacity Prior to Propeller Polishing

Cargo Load bin [MT]	Count of Datapoints [-]
10000 - 12500	1693
25000 - 27500	759
27500 - 30000	14938
30000 - 32500	205
32500 - 35000	1113

Table 15 shows the distribution of the relative wind angle by the relative wind angle bins.

Table 15: Distribution of Relative Wind Angle Prior to Propeller Polishing

Relative Wind Angle bin [deg]	Count of Segment [-]
0-45	10157
45-90	4089
90-135	2556
135-180	1156
180-225	1012
225-270	1011
270-315	2543
315-360	11143

7.2.2 Data - After Propeller Polishing

Table 16 provides a summary of the dataset from the Algoma Conveyor after the propeller polishing, from August 5, 2021, to November 21, 2021. The amount of datapoints after filtering the data as described in Section 6 is approximately 15,000. This dataset provides detailed information to determine the speed, power, fuel consumption relationships as is presented in Section 8.

Table 16 is a summary of the dataset after the hull coating was applied. It lists the power bins used for the analysis, and shows the average power, the average Speed over Ground (SOG), and the average Fuel Consumption (FC) for each bin. Note that these values are shown as a percentage of the maximum design value for power, speed, and FC instead of absolute measured values. This does not have any effect on the calculations of the relative change in performance before and after either hull coating or propeller polishing.

Table 16: Summary of Datapoints After Propeller Polishing

Average Power Bin [kW]	Count of Datapoints [-]	Total Duration [dd hh:mm:ss]	Average Power [% of maximum power]	Average SOG [% of maximum design speed]	Average FC Measured [% of maximum design FC]
300	1	00 00:01:00	5	16	8
500	43	00 00:43:00	7	25	12
700	9	00 00:09:00	10	39	15

Average Power Bin [kW]	Count of Datapoints [-]	Total Duration [dd hh:mm:ss]	Average Power [% of maximum power]	Average SOG [% of maximum design speed]	Average FC Measured [% of maximum design FC]
900	3	00 00:03:00	13	31	19
1100	3	00 00:03:00	15	47	19
1300	1	00 00:01:00	20	33	27
1500	3	00 00:03:00	22	58	27
1700	7	00 00:07:00	24	60	28
1900	2	00 00:02:00	28	41	34
2100	4	00 00:04:00	31	63	37
2300	103	00 01:43:00	33	67	39
2500	14	00 00:14:00	35	68	41
2700	5	00 00:05:00	39	74	52
2900	10	00 00:10:00	41	76	48
3100	10	00 00:10:00	44	78	51
3300	26	00 00:26:00	47	78	54
3500	30	00 00:30:00	49	76	55
3700	10	00 00:10:00	54	81	62
3900	51	00 00:51:00	56	81	62
4100	25	00 00:25:00	58	82	65
4300	82	00 01:22:00	61	84	69
4500	135	00 02:15:00	64	84	71
4700	321	00 05:21:00	67	84	74
4900	672	00 11:12:00	70	83	76
5100	5909	04 02:29:00	73	87	79
5300	7586	05 06:26:00	75	87	80
5500	131	00 02:11:00	79	85	86
5700	82	00 01:22:00	81	86	88
5900	1	00 00:01:00	83	85	91
6100	1	00 00:01:00	86	86	105

Table 17 provides information of the distribution of the cargo capacity by the cargo load bins.

Table 17: Distribution of Cargo Capacity After Propeller Polishing

Cargo Load bin [MT]	Count of Datapoints [-]
20000 - 22500	504
27500 - 30000	4623
30000 - 32500	2520

Table 18 shows the distribution of the relative wind angle by the relative wind angle bins.

Table 18: Distribution of Relative Wind Angle After Propeller Polishing

Relative Wind Angle bin [deg]	Count of Segment [-]
0-45	6709
45-90	931
90-135	282
135-180	170
180-225	157
225-270	398
270-315	975
315-360	5975

7.2.3 Propeller Polishing Basic Results

Figure 24 and Figure 25 shows the power consumption versus vessel speed before and after the propeller was polished. This dataset includes a variety of conditions including open versus ice infested water, laden versus ballast condition.

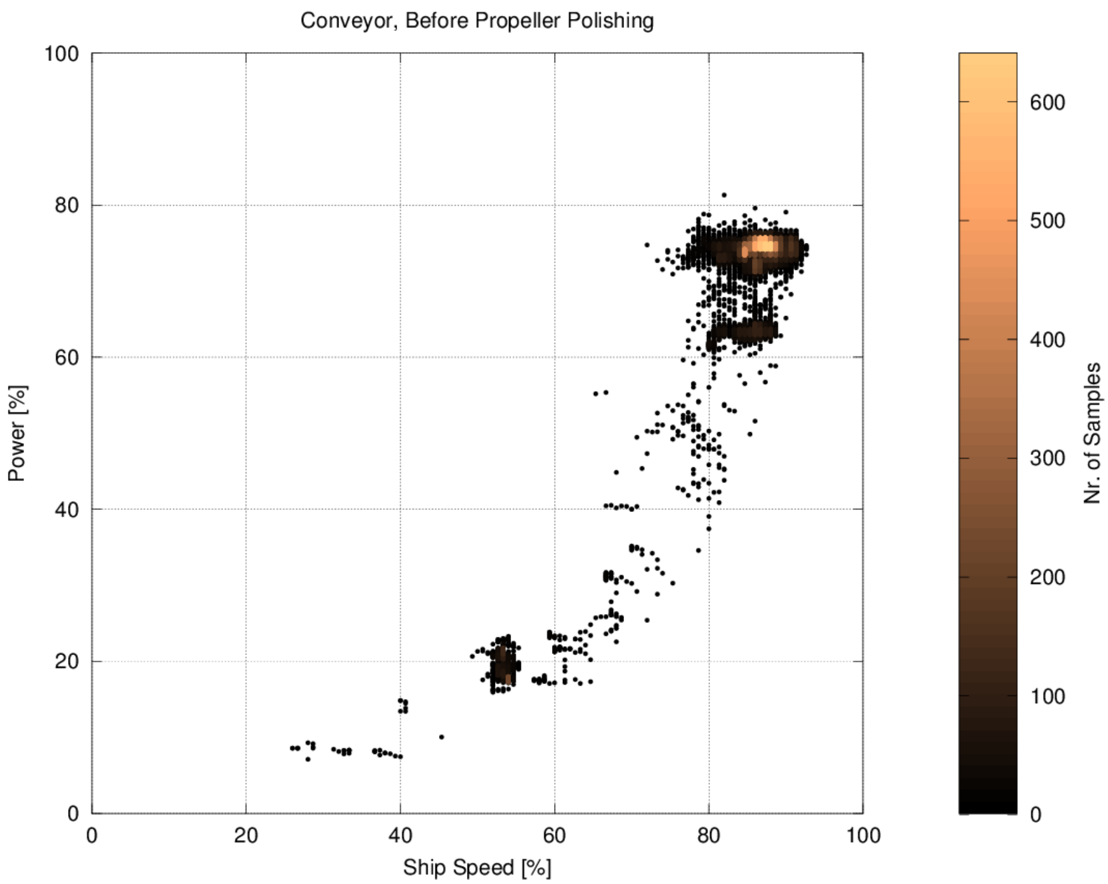

Figure 24: Power versus SOG for Conveyor before Propeller Polishing

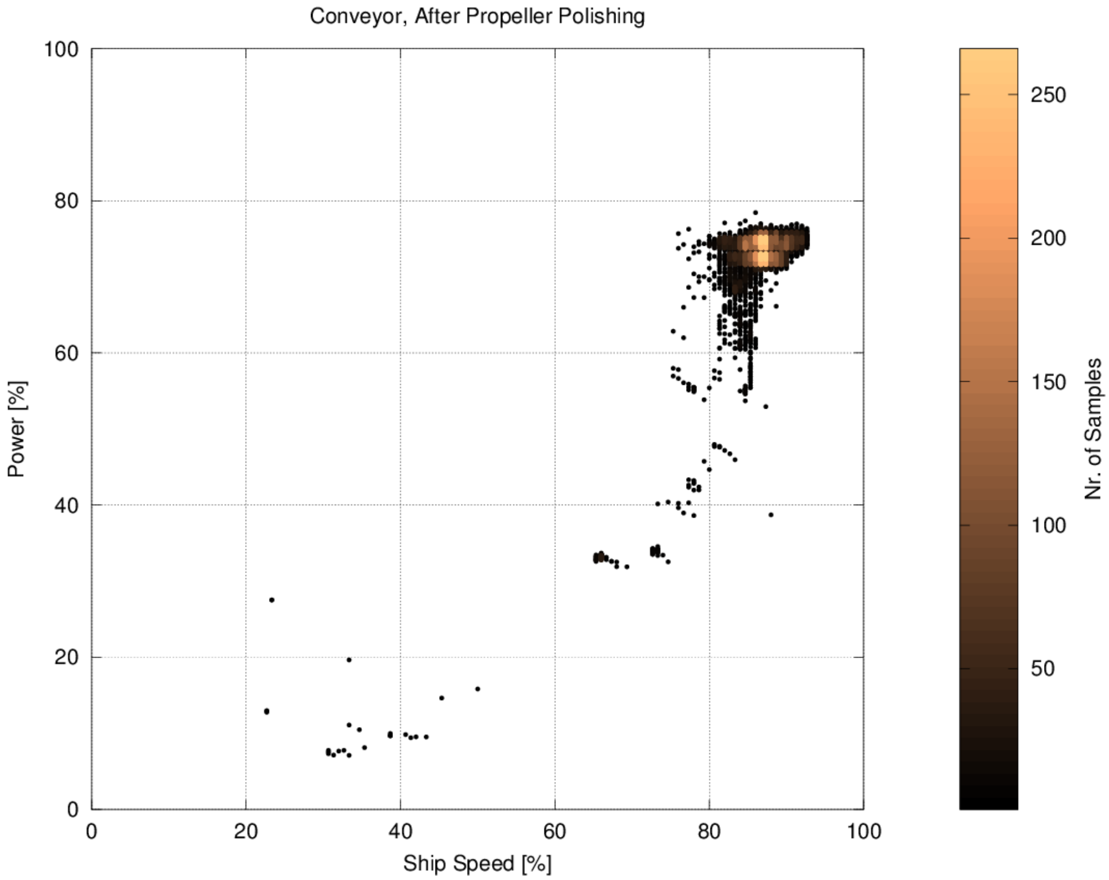

Figure 25: Power versus SOG for Conveyor after Propeller Polishing

Figure 26 and Figure 27 shows the fuel consumption rate versus vessel speed before and after the propeller was polished.

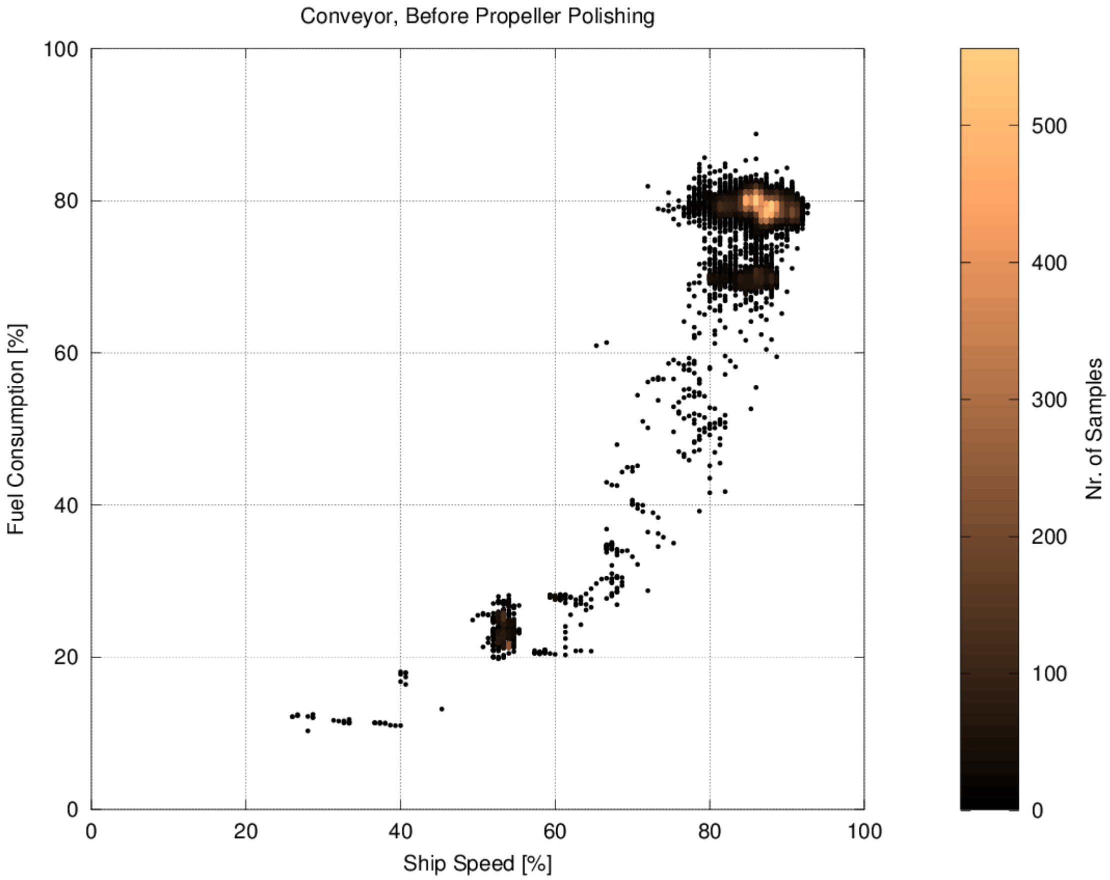

Figure 26: Fuel Consumption (measured) versus SOG for Conveyor before Propeller Polishing

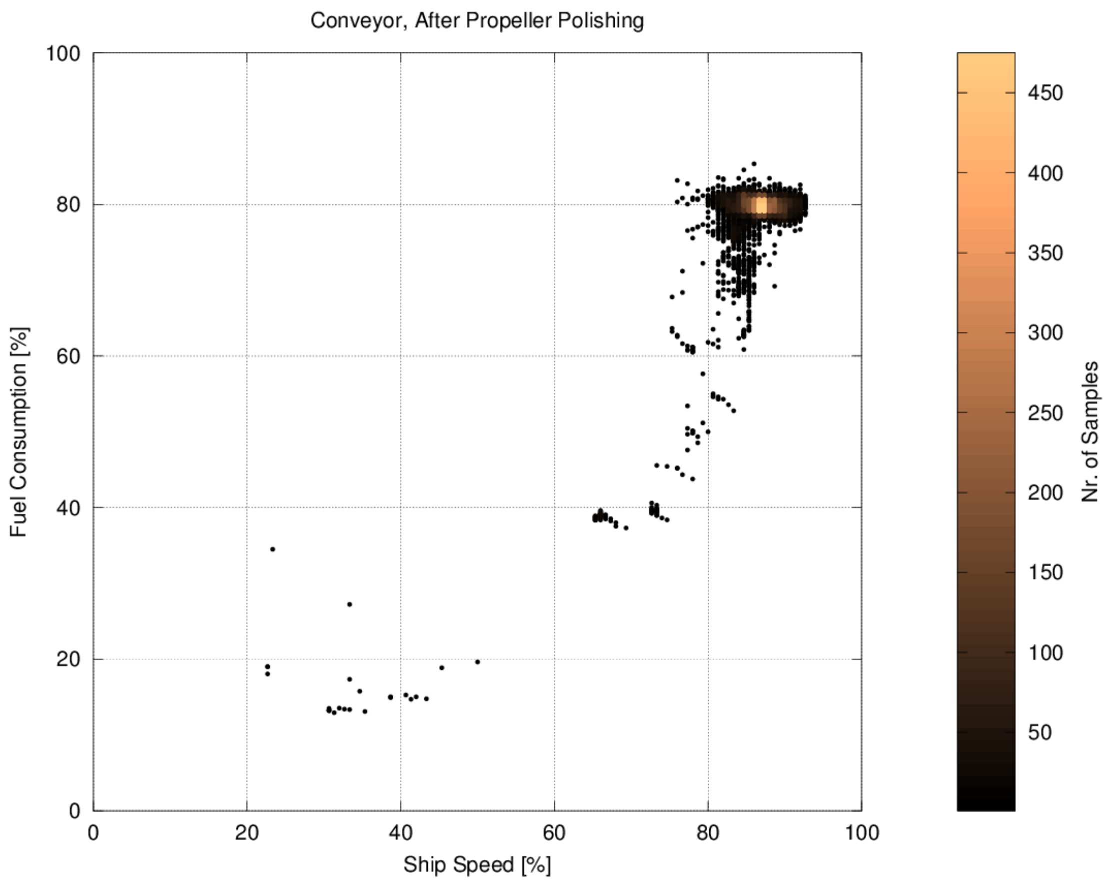

Figure 27: Fuel Consumption (measured) versus SOG for Conveyor after Propeller Polishing

Figure 28 and Figure 29 shows the efficiency versus vessel speed before and after the propeller was polished. The amount of datapoints collected for the period prior and after the propeller polishing is limited (compared to the data available prior and after hull coating). Hence, the analysis in Section 8 will focus on relatively high vessel speeds.

Furthermore, the collected data indicates the efficiency generally increases with reduced speed (see the red circle in Figure 29). This is in keeping with the conventional wisdom. Given the current formulation for transport efficiency and that power approximately relates to speed cubed, it follows that the transport efficiency relates approximately to the inverse of speed squared. Such a theoretical curve would show very high transport efficiencies at low speeds, and lower transport efficiencies at high speeds; this generally agrees with the data. There is some scatter in the data, however, which may be due to varying cargo loads, pitch of the controllable pitch propeller, or various other factors.

VARD has seen (with previous projects for several different clients) that optimization of the combinator curve (a relationship between lever setting, engine revolution rate and propeller pitch) can result in tremendous efficiency increases. A review of the operational guidance and practices used on the ship as well as more data collection should be considered for any future studies. Note that Algoma is aware of the opportunity for optimization of the combinator curve, and have recently installed the Lean Marine FuelOpt[24] speed and consumption management system for this purpose.

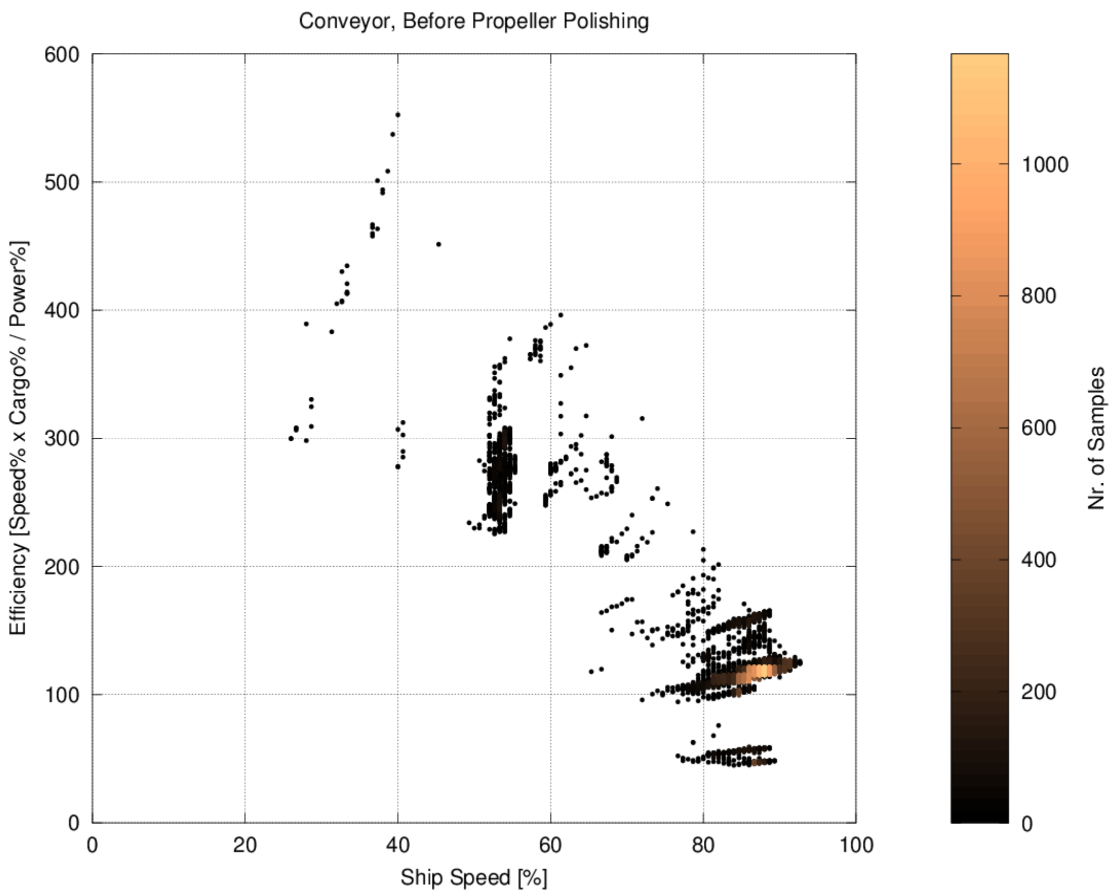

Figure 28: Efficiency versus SOG for Conveyor before Propeller Polishing

[24] https://leanmarine.com/fuelopt/

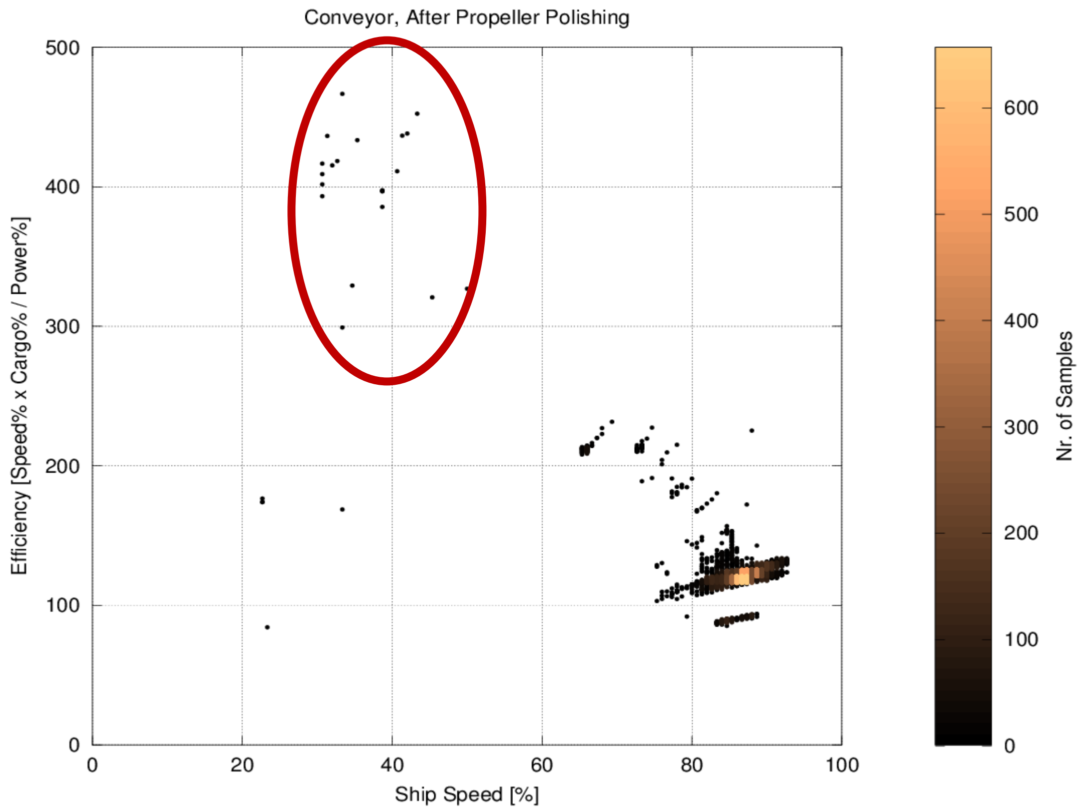

Figure 29: Efficiency versus SOG for Conveyor after Propeller Polishing

8 ANALYSIS OF COLLECTED DATA

This report presents two analyses for the collected project data.

Section 8.2 presents a statistical analysis of the trends and scatter in the overall dataset. This analysis was completed to reconcile the collected data with the expected theoretically-derived performance for the ships, and to characterize the overall datasets in terms of their data distribution spread, expected performance, and potential change in efficiency relative to this overall data distribution spread. This analysis is a starting point for identifying areas of future study, where confidence in the ability to numerically model performance could be increased through additional data collection and/or dedicated data collection trials.

Section 8.3 presents a comparative analysis of the data – effectively reporting on the collected real-world data for the project and deriving an estimate of the change in efficiency for the Algoma Mariner and Algoma Conveyor by directly comparing the average performance data trends for each ship's before and after datasets. This is a report on the absolute performance of the ship as measured by the on-board instrumentation and shows results by interpreting what was observed, including the impact of operating in varying conditions, by comparing performance trends before and after the ship's condition upgrade.

There are several general approaches that could be taken to analyzing collected full-scale data, such as:

1. Calculating high-level metrics of performance over a large data set, such as average fuel consumed per Tonne-nautical mile of cargo carried. Given the seasonal and year-to-year variability in environmental, cargo, and other conditions, this requires an extremely large amount of data, and is not practical for the present project.
2. Completion of a small number of trials in carefully controlled conditions.
3. Filtering a data set of moderate size to identify conditions in which known sources of uncertainty or scatter are small. For example, restricting the data to steady operation in deep water and calm conditions, with a similar loading condition both before and after the change to the hull/propeller.
4. Attempting to correct the data to account for known sources of uncertainty or scatter, which can be accomplished in various ways.
    a. One way to do this is by directly correcting the final results (e.g. power) based on the expected effects of acceleration, shallow water, etc.
    b. Another option[25] is to develop a theoretical prediction of the final result (e.g. power required) at each data point using the other data and expected corrections for known sources of scatter, then to compare this against the actual result to develop a correlation factor. Changes in the correlation factor from before to after the hull/propeller change then yield the overall performance change.

In this work, the third approach has been taken. It as a reasonable fit for the data collected and offers a simpler analysis technique than the fourth approach.

[25] ISO 19030, "Ships and marine technology – measurement of changes in hull and propeller performance," ISO, First edition, 2016-11-15.

8.1 ADDITIONAL DATA FILTERING PERFORMED

The following are additional steps to the analysis in addition to those described in Section 6:

1. The performance analysis is based on open water conditions – Data that was collected between the 15th of December and 15th of April was disregarded to eliminate any possible ice interaction.
2. For each datapoint the loading condition has been determined. Furthermore, the average loaded loading condition has been the benchmark to determine the influence of the upgrade on the power consumption. All loading conditions that are within the bandwidth of the average loading condition plus/minus the standard deviation (SD) are called “Laden”, all remaining loading conditions are called “Outside of Range". All ballast conditions are called “Ballast”.
3. The average before and after loading condition will vary slightly. In order to correct for the cargo load difference (the delta) between the before and after condition, we have corrected for the cargo load delta by the use of the Admiralty Coefficient[26]. The average measured power in the after condition has been corrected for the minor cargo load difference.
4. All remaining loading conditions where the carried load is unknown are not further analysed.
5. The data set has been filtered by wind speed, in order to minimise the influence of wind on the measured power, fuel consumption, propeller shaft torque, propeller shaft revolution rate and thrust. A maximum wind speed according to Beaufort 2 (which is 5 knots as presented by the ITTC) has been chosen as an acceptable limit[27].
6. The data set has been filtered by course deviation, in order to minimise the influence of course deviations on the measured power, fuel consumption, propeller shaft torque, propeller shaft revolution rate and thrust. A maximum course deviation of 5 degrees has been chosen, since (from practical experience) 2 to 3 degrees course deviation is normal for autopilot systems to act upon for cargo vessels.
7. The vessel speed versus power relationship of each condition has been derived. As mentioned in Section 6, the used speeds are the speeds over ground (SOG).
8. The vessel speed versus fuel consumption relationship of each condition has been derived.
9. The standard deviation of the measured vessel speed has been derived to give insight in spread of the measurements.
10. The transport efficiency has been derived.
11. To further eliminate noise, 3 sets of trendlines of the vessel speed versus power, fuel consumption and transport efficiency are created. All presented trendlines are of the so called “power” type, with an equation in the form of $y = a*Vs^b$ (Vs is the vessel speed, and *y* is either power, fuel consumption or transport efficiency). For the power versus speed, the factor *b* is set to 3 as is common in the ship design industry[26].
12. The speed signals +/- the standard deviation are as well presented in the graphs and tables.

All the data provided in this section (Section 8) is processed data, for deep water conditions, no ice interaction (open water), wind speed below 10 knots, and laden loading condition (processed according to Section 6 and 8.1). The data will be provided in power bins (as discussed in Section 6). Most of the

[26] Klein Woud, H. Stapersma, D. 2003. Design of Propulsion and Electric Power Generation Systems. Imarest.
[27] ITTC – Recommended Procedures and Guidelines, Full Scale Measurements Speed and Power Trials, 7.5-04-01-01.2, 2005, revision 0

data is presented non-dimensionalised by a constant factor per ship (hence speed, power and fuel consumption are presented as percentages).

8.2 ANALYSIS OF SCATTER AND TRENDS

For most results presented in this section the values for Standard Deviation (SD) for the data have been calculated and plotted. This is to establish "error bands" for the data that define the variability of the data. The data was collected in a variety of conditions which would not be part of a controlled experiment where ideally any measured change in performance data would be measured outside these bands to provide a high degree of statical confidence in the results.

Most of the observed changes in vessel performance reported in Section 8.3 fall within or very close to these error bands, as shown in the following sections. This does not mean that these conclusions are invalid. It does mean that the observed results fall within the range where the results vary, and as such are low confidence for the purposes of predictive modeling.

Any future work or studies which require a statistical or numerically modelled set of performance results (rather than the theoretical hydrodynamic analysis as presented in Section 4) should consider addressing statistical uncertainty. This does not need to be done for the entire dataset – priority should be given to the most important aspects of the ship's performance:

1. Operations where the ship spends most if it's time at higher fuel consumption rates for longer periods, such as sailing in open water at cruising speed. This is where any efficiency improvement will pay off, and is the best target for a detailed study to improve the statistical confidence of the results.
2. Operations where the data is highly variable due to changing power outputs or external factors (due to time varying conditions or due to varying environmental conditions), such as decelerating near a lock or slow speed sailing in areas where the water depth varies. Any type of operation where the impact of condition improvement is largely unknown (and difficult to even estimate empirically due to the variable nature of those operations) would be a good candidate for further study to identify additional savings opportunities.

Future work or detailed analysis that requires a high level of statistical confidence could consider supplementing the data collected during regular operations with dedicated sea trial measurements (according to ITTC recommendations[28]) before and after the ship's condition upgrades. Analysis done based on data collected during regular operations should be more meaningful to vessel operators, but targeted trials can help to more precisely characterize performance gains. In addition, trials data correlated to real world data could help increase confidence in estimates based on the latter and validate assumptions about observed performance changes.

Most of the presented graphs show non-dimensionalised numbers on the axis in order to protect the sensitive (commercial) data.

Furthermore, the presented data is an average of the available steady state condition for each power bin. Measurement scatter has less influence on power bins with lots of measurements, however, some presented power bins have just a couple of measurements and the presented numbers in those power bins are less reliable. To determine the trendlines, only power bins with a sufficient number of datapoints have been considered.

[28] ITTC – Recommended Procedures and Guidelines, Preparation, Conduct and Analysis of Speed/Power Trials, 7.5-04-01-01.1, 2017, revision 05

8.2.1 Continuous Speed Data - Hull Coating

The average loading condition prior to the hull coating was with 24,844 MT.

Table 19 provides an overview of the processed data prior to the hull coating. Certain numbers cannot be calculated, since the amount of data is not sufficient to determine (for instance the standard deviation). In such an instance #DIV/0! will be presented, which shows that a number is divided by zero (0).

Table 19: Summary of Data Before Hull Coating, Laden, Open Water

Average Power Bin	Count	Power	Vs	SD Vs	$FC_{MEASURED}$	Duration
[kW]	[-]	[%]	[%]	[%]	[%]	[dd hh:mm:ss]
3100	3	44.1	78.9	0.4	50	00 00:03:00
3300	1	44.5	78.7	#DIV/0!	51	00 00:01:00
3500	4	49.0	80.7	0.0	55	00 00:04:00
3700	7	52.3	82.0	2.2	60	00 00:07:00
3900	205	54.1	84.3	1.6	62	00 03:25:00
4100	136	57.1	85.6	1.4	65	00 02:16:00
4300	87	59.5	85.9	1.2	68	00 01:27:00
4500	9	61.7	86.4	0.5	70	00 00:09:00
4700	23	65.2	88.6	0.6	73	00 00:23:00

The average loading condition after the hull coating was with 24,546 MT. The same bandwidth of loading conditions has been chosen for the after condition (as was chosen for the prior condition). The actual average loading condition prior and after hull coating differs by -298 MT.

Table 20 provides an overview of the filtered data after the hull coating. Compared to Table 19, Table 20 has an additional column where the power is corrected for the loading condition difference.

Table 20: Summary of Data After Hull Coating, Laden, Open Water

Average Power Bin	Count	Power	Vs	SD Vs	$FC_{MEASURED}$	Duration	Power Corrected
[kW]	[-]	[%]	[%]	[%]	[%]	[dd hh:mm:ss]	[%]
3100	3	44.0	80.0	0.0	52	00 00:03:00	44.2
3300	21	45.5	81.7	1.0	53	00 00:21:00	45.7
3500	7	49.5	85.0	0.8	57	00 00:07:00	49.8
3700	95	51.5	85.0	0.6	59	00 01:35:00	51.8
3900	62	54.2	86.4	1.5	62	00 01:02:00	54.5
4100	8	56.2	85.8	2.0	64	00 00:08:00	56.5
4300	24	59.9	87.0	0.4	68	00 00:24:00	60.2
4500	3	61.8	87.1	0.4	71	00 00:03:00	62.1
4700	1	65.2	80.7	#DIV/0!	73	00 00:01:00	65.6

8.2.2 Power vs. Operational Speed Before and After Hull Coating

Figure 30 presents the power versus vessel speeds as it is given in Table 19 and the corrected power as given in Table 20. At higher vessel speeds the condition after hull coating has less power usage than the condition before the hull coating. At lower vessel speeds the amount of datapoints are fairly limited (see Table 19), hence the validity of the plotted curve becomes questionable at these lower speeds.

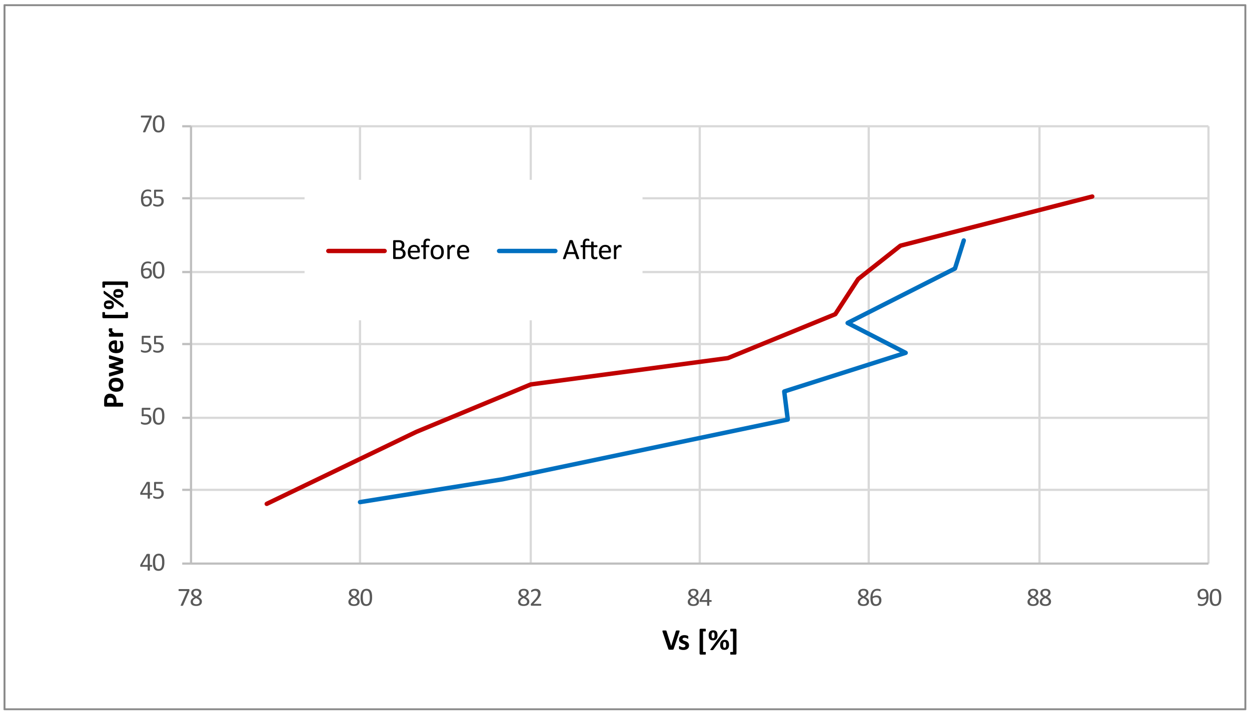

Figure 30: Power versus SOG for Mariner prior and after hull coating

Figure 31 (prior to hull coating) and Figure 32 (after the hull coating) present the same power versus vessel speed as in Figure 30, however the standard deviations (the error bands) are presented as well. Furthermore, the trendlines of the three curves is given as well. The trendlines are only given for the higher speed region where there is sufficient collected data.

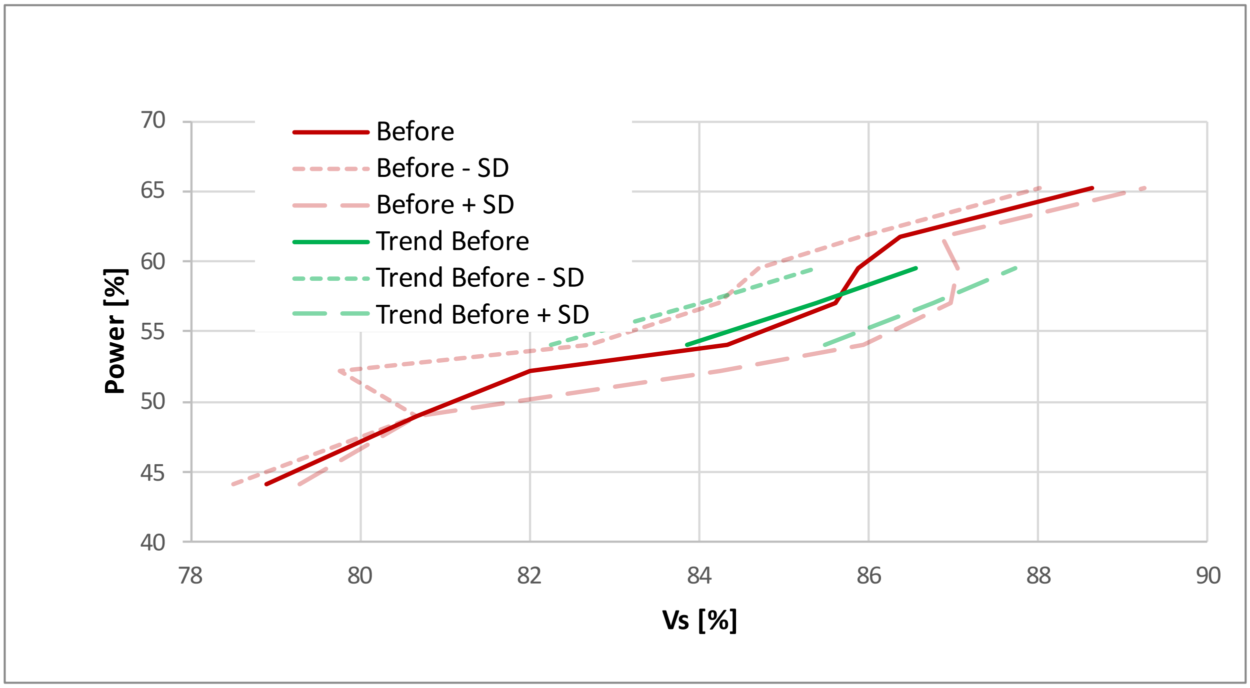

Figure 31: Power versus SOG for Mariner prior hull coating

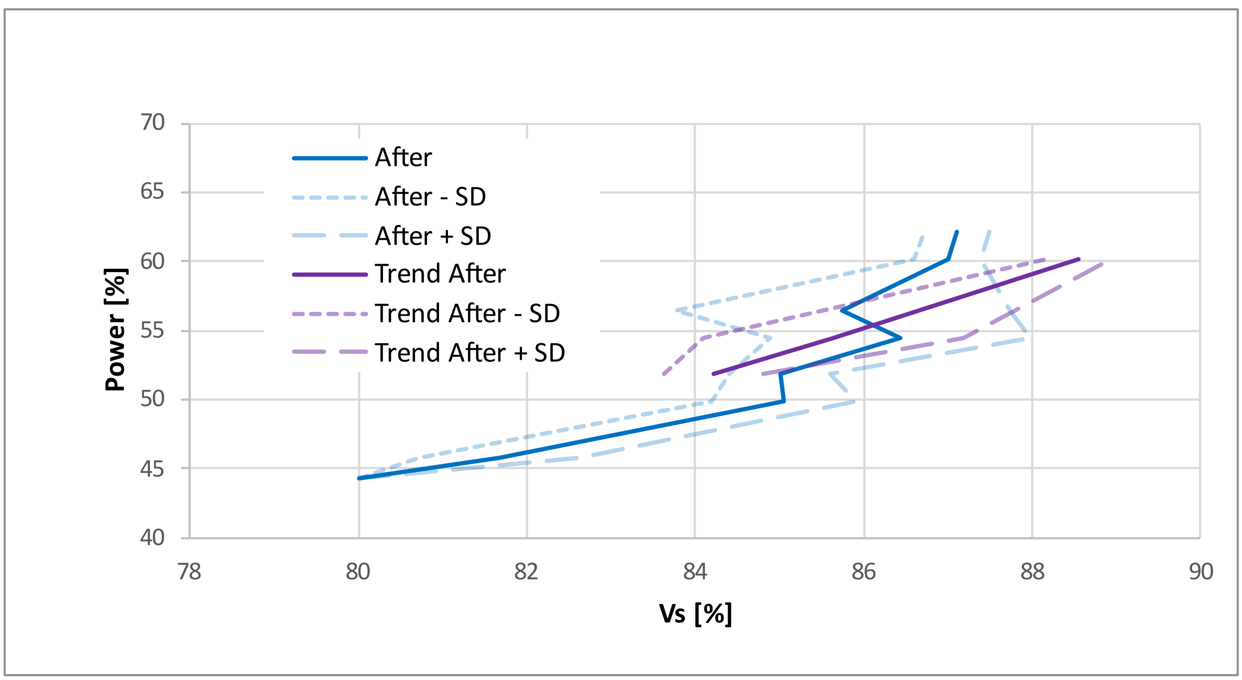

Figure 32: Power versus SOG for Mariner after hull coating

Figure 33 presents the trendlines of the power versus speed of the Mariner prior and after the hull coating.

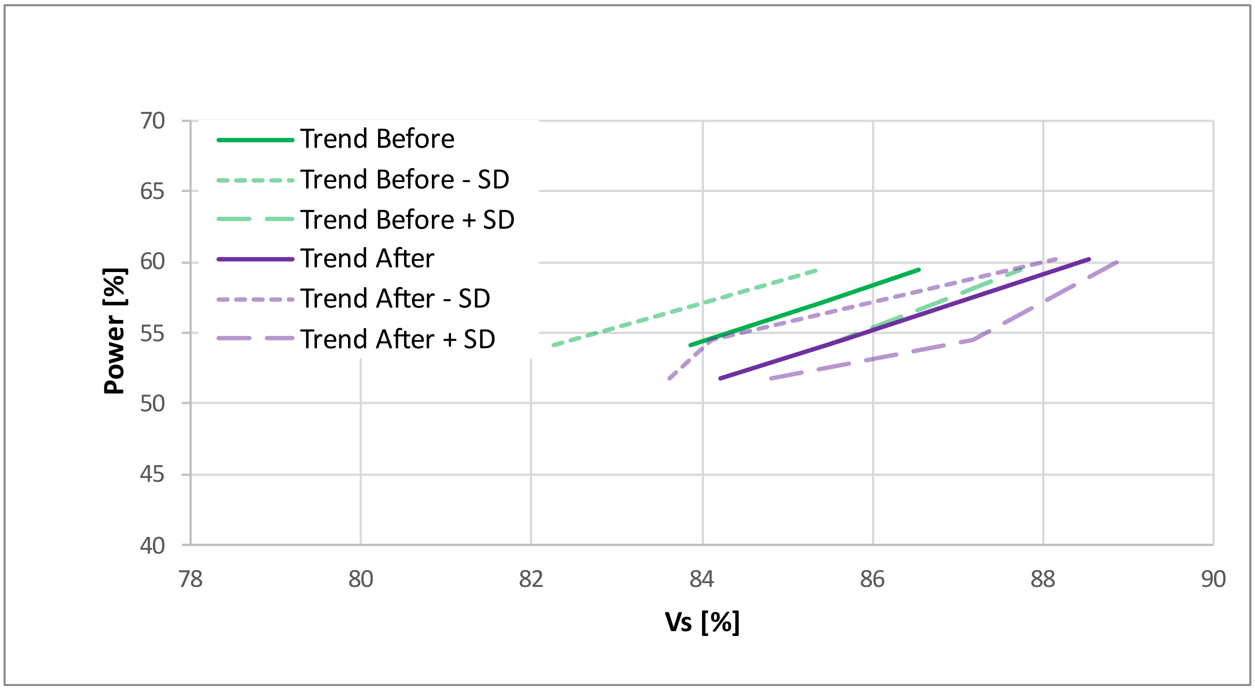

Figure 33: Power versus SOG trendline for Mariner prior and after hull coating

8.2.3 Fuel Consumption vs. Speed Before and After Hull Coating

Figure 34 presents the measured fuel consumption of the Mariner prior to hull coating.

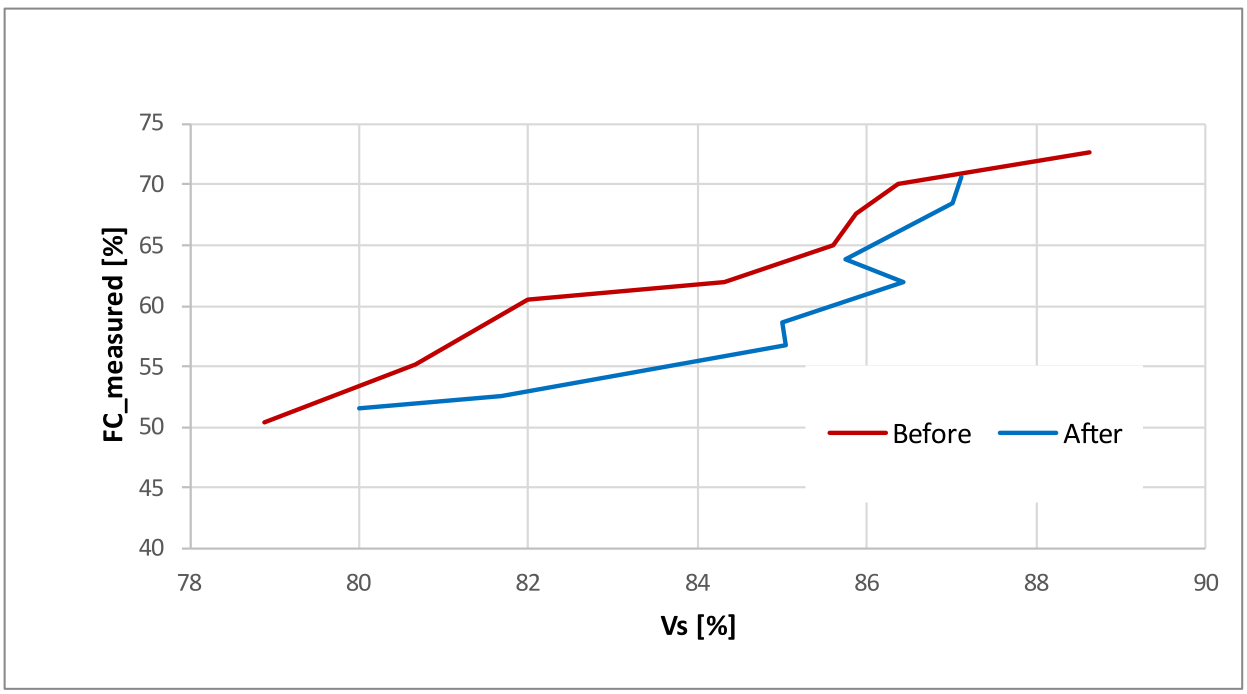

Figure 34: Fuel Consumption (measured) versus SOG trendline for Mariner prior and after hull coating

In Section 7 and specifically Figure 20 it is observed that the fuel consumption of the Mariner has some spurious data points as well as data bins where the overall data range had unexpected values, further filtering has removed most of the spurious data points. In Figure 35 the fuel consumption versus power has been presented. Inspection of the time series of some of the spurious points near the left-hand side of the graph suggested these occurred while the ship was slowly decelerating, but that the deceleration was not captured by the filtering currently applied. Based on this graph and based on the linear relationship between power and fuel consumption, all the measurements below 2,000 kW have been removed from the analysis and a linear relationship has been established to calculate the fuel consumption based on the remaining data (see Figure 36).

Additionally, it will be shown in Section 8.2.7 that the fuel consumption versus power trend for the Conveyor gives a spurious trend, which could be due to various fuel types and/or various fuel qualities. This and other unmeasured factors influencing engine efficiency may also apply to the Mariner. So although the measured fuel consumption values (as presented in Table 19 and Table 20) are in Figure 34, the trendlines in Figure 37 are developed using calculated values (based on the trendline presented in Figure 36 and the corrected power).

Future studies could measure key data points such as fuel consumption with multiple channels in case one channel gives an erroneous measurement.

Additional considerations need to focus on the different power output and fuel consumption for using different grades of MDO/MGO or switching between consuming HFO and MDO/MGO during voyages.

As shown in the Algoma PRISM dashboard, the Conveyor has dual fuel capabilities, consuming both HFO and MDO during some voyages, as well as using different blends of MDO/MGO. The Mariner similarly will consume different blends of MDO/MGO during voyages. For example, consuming both MGO and IFO380 during voyages.

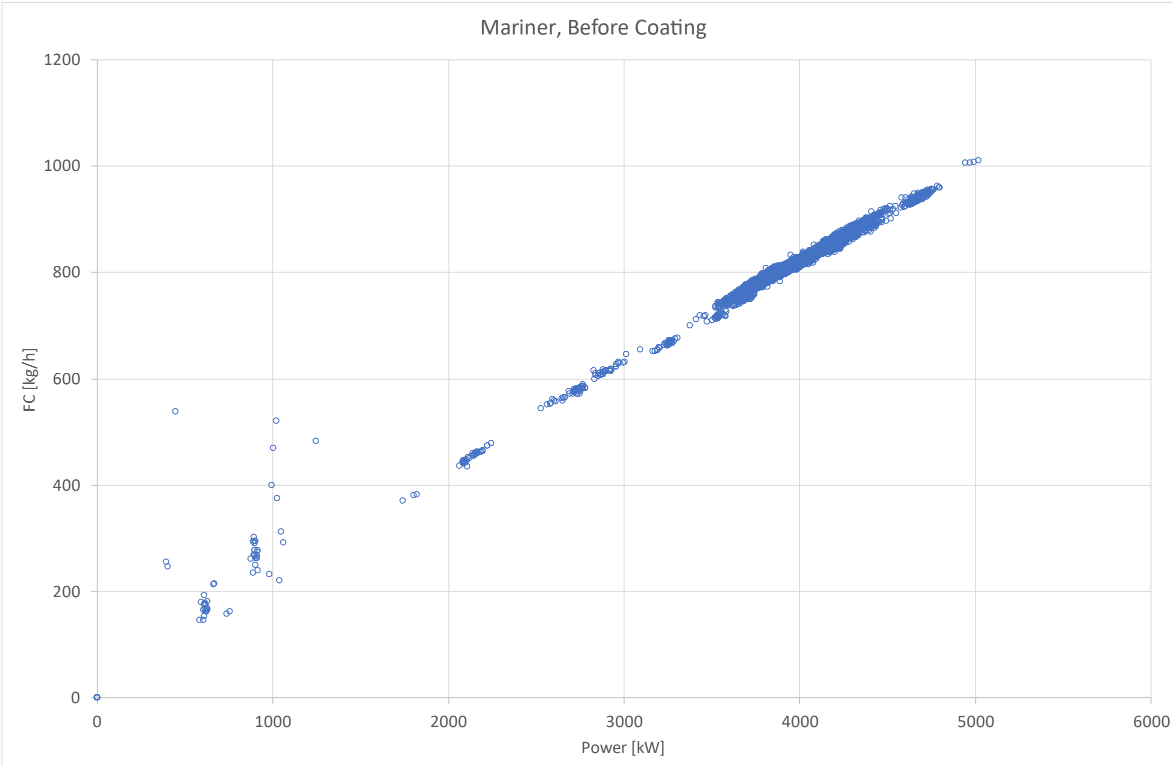

Figure 35: Measured Fuel Consumption versus Power for Mariner prior to hull coating

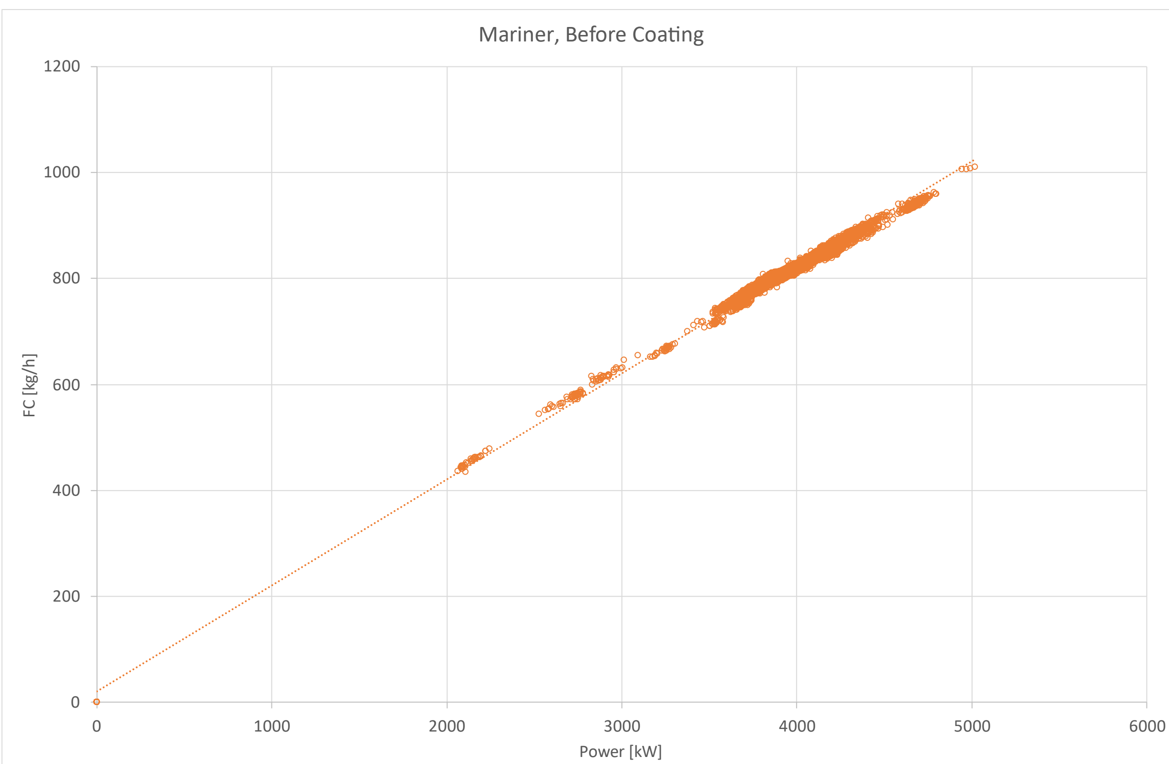

Figure 36: Revised Measured Fuel Consumption versus Power trendline for Mariner prior to hull coating

Based on the found relationship between fuel consumption and power, trendlines for fuel consumption versus vessel speed have been calculated (see Figure 37). The same conclusion can be made as for the power analysis: an estimate of the change in efficiency can be presented by taking the difference between these trendlines.

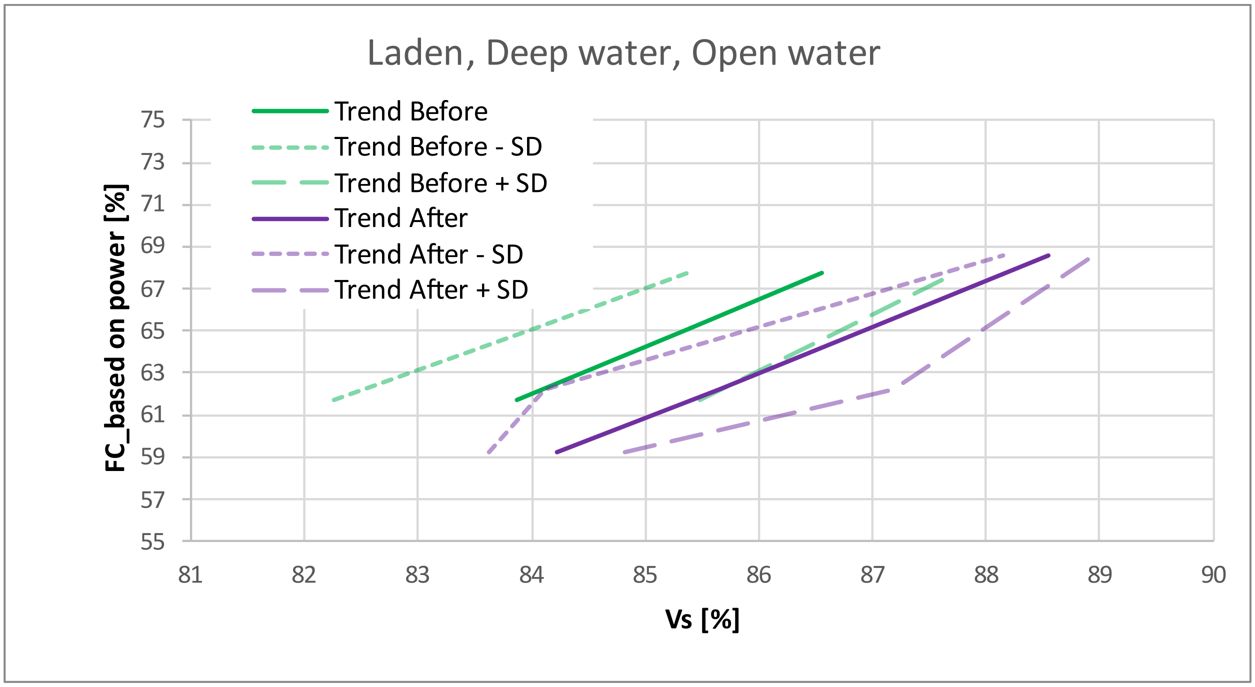

Figure 37: Fuel Consumption versus SOG trendline for Mariner prior and after hull coating

8.2.4 Efficiency vs. Speed Before and After Hull Coating

Figure 38 and Figure 39 present the efficiency analysis prior and after hull coating. The same conclusion can be made as for the power analysis: An estimate of the change in efficiency can be presented by taking the difference between these trendlines.

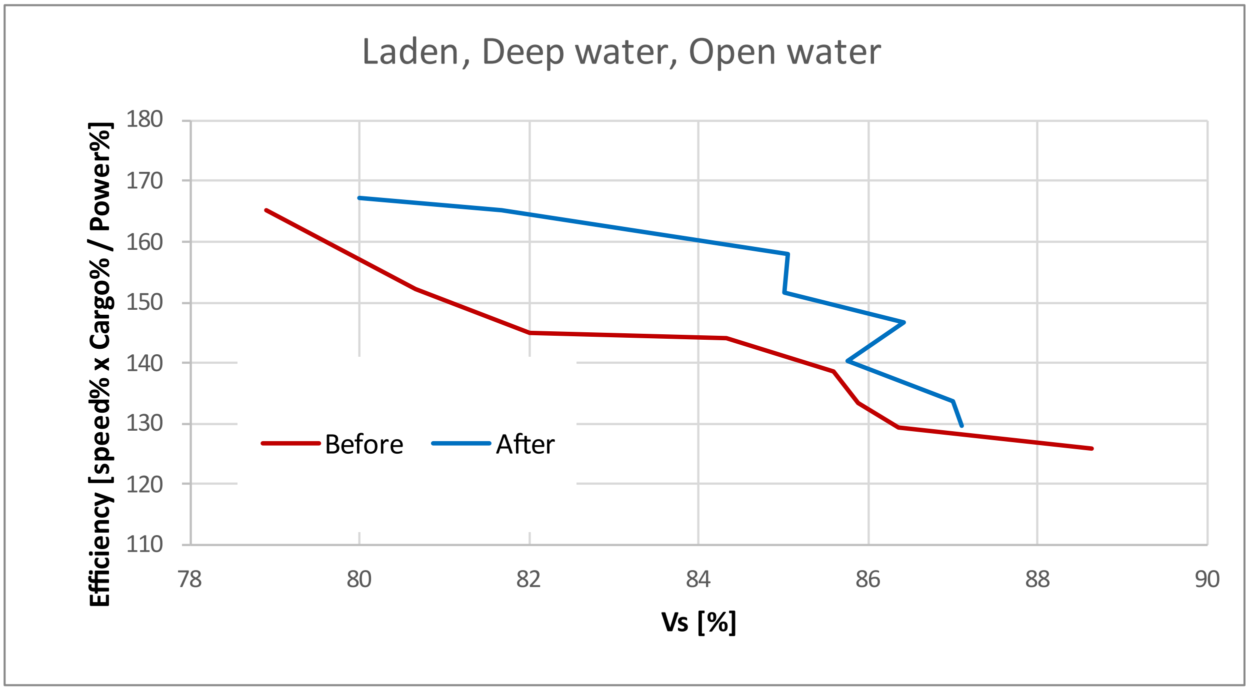

Figure 38: Efficiency versus SOG for Mariner prior and after hull coating

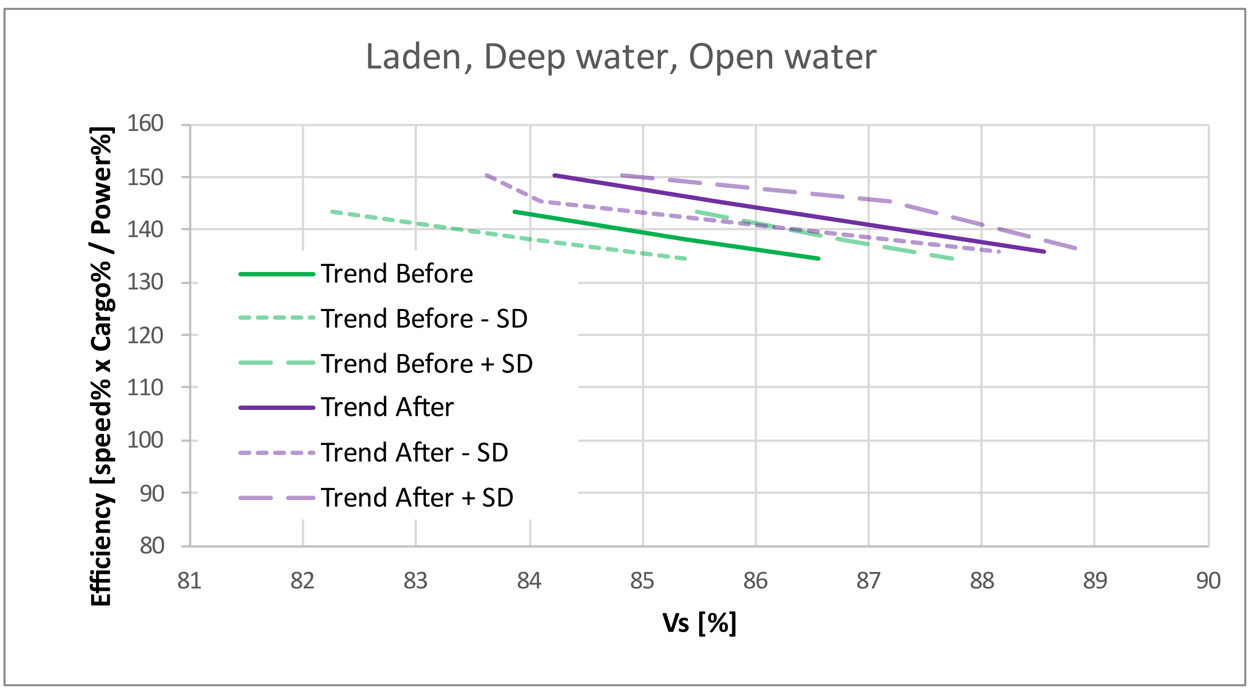

Figure 39: Efficiency versus SOG trendline for Mariner prior and after hull coating

8.2.5 Continuous Speed Data - Propeller Polishing

The average loading condition before propeller polishing was 27,777 MT.

Table 21 provides an overview of the processed data prior to the propeller polishing.

Table 21: Summary of Data Before Propeller Polishing, Laden, Open Water

Average Power Bin [kW]	Count [-]	Power [%]	Vs [%]	SD Vs [%]	$FC_{MEASURED}$ [%]	Duration [dd hh:mm:ss]
2300	1	32.1	72.0	#DIV/0!	36	00 00:01:00
2900	3	42.3	76.9	0.4	46	00 00:03:00
3100	1	42.8	76.0	#DIV/0!	47	00 00:01:00
3500	2	50.4	77.0	0.5	54	00 00:02:00
4700	5	66.7	83.1	0.4	72	00 00:05:00
4900	28	69.3	83.6	0.5	74	00 00:28:00
5100	542	73.5	86.2	2.6	79	00 09:02:00
5300	774	74.8	85.4	1.8	80	00 12:54:00

The average loading condition after polishing was 28,022 MT.

Table 22 provides an overview of the processed data prior to the propeller polishing. The same bandwidth of loading conditions has been chosen for the after condition (as was chosen for the prior condition). The actual average loading condition prior and after propeller polishing differs 245 MT.

Table 22 provides an overview of the filtered data after the propeller polishing. Compared to Table 21, Table 22 has an additional column where the power is corrected for the loading condition difference.

Table 22: Summary of Data After Propeller Polishing, Laden, Open Water

Average Power Bin [kW]	Count [-]	Power [%]	Vs [%]	SD Vs [%]	$FC_{MEASURED}$ [%]	Duration [dd hh:mm:ss]	Power Corrected [%]
2300	21	32.9	66.6	0.9	39	00 00:21:00	32.8
3100	3	45.5	76.9	0.4	52	00 00:03:00	45.3
3300	12	47.6	76.4	0.7	53	00 00:12:00	47.4
3500	9	48.9	76.4	1.3	54	00 00:09:00	48.7
3700	4	53.8	79.5	0.3	60	00 00:04:00	53.6
3900	1	54.7	78.0	#DIV/0!	60	00 00:01:00	54.5
4300	2	60.8	81.7	0.5	68	00 00:02:00	60.6
4700	42	68.1	83.8	0.6	74	00 00:42:00	67.8
4900	74	69.5	83.7	1.1	75	00 01:14:00	69.2
5100	812	73.0	85.6	1.9	80	00 13:32:00	72.7
5300	833	74.9	85.4	2.2	81	00 13:53:00	74.6
5500	94	78.8	84.9	0.6	86	00 01:34:00	78.4
5700	31	80.7	85.8	0.9	88	00 00:31:00	80.3

8.2.6 Power vs. Speed Before and After Polishing

The same analysis methodology and figures (see Figure 40, Figure 41, Figure 42 and Figure 43) are presented for the Conveyor, to analyse the effect of the propeller polishing on the power consumption. The difference of power absorption prior to and after the propeller polishing is minimal.

The results presented in Figure 43 suggest that the power absorption increased after propeller polishing, however the average power absorption curves lie within the error bands. Future studies could consider dedicated trials to improve confidence in predicted performance for key power bands.

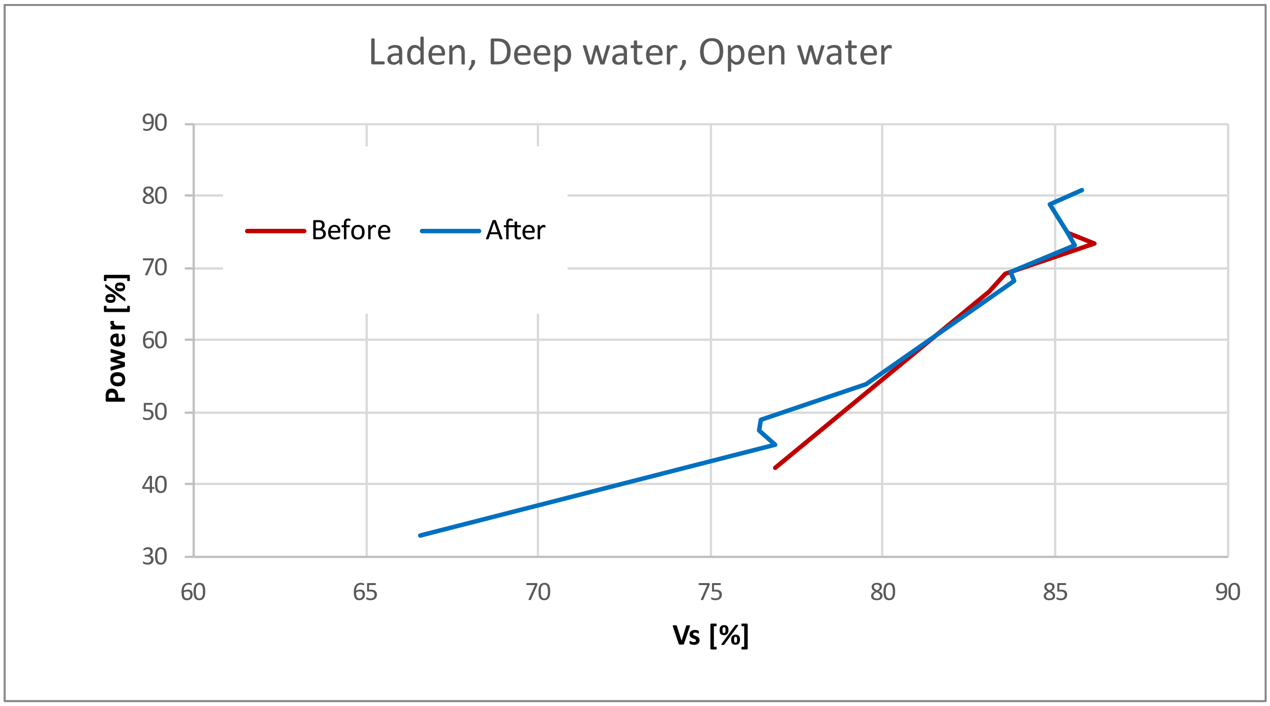

Figure 40: Power versus SOG for Conveyor prior and after propeller polishing

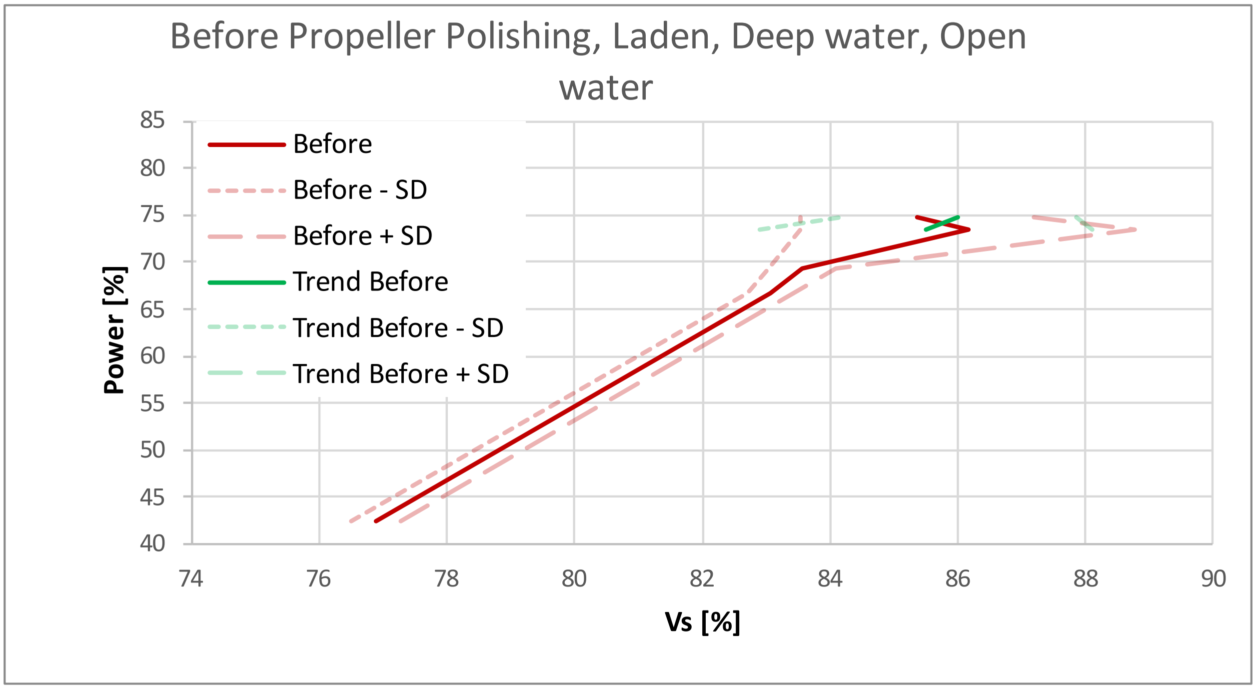

Figure 41: Power versus SOG for Conveyor prior propeller polishing

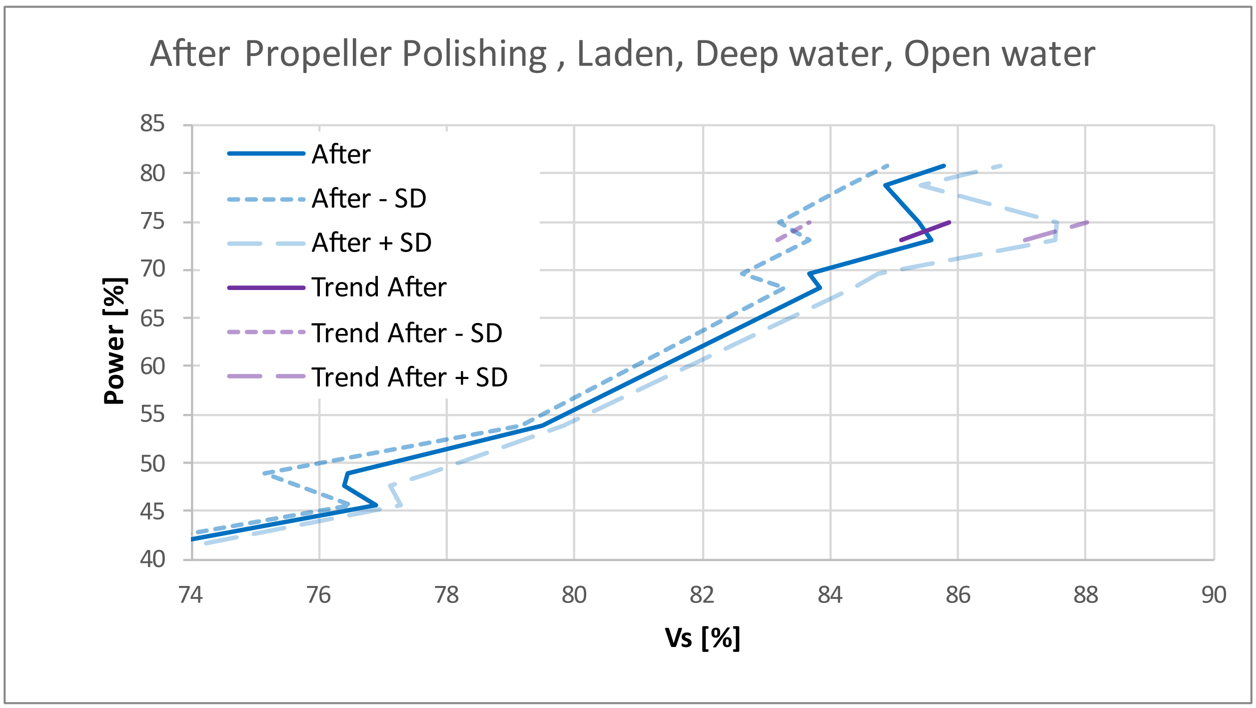

Figure 42: Power versus SOG for Conveyor after propeller polishing

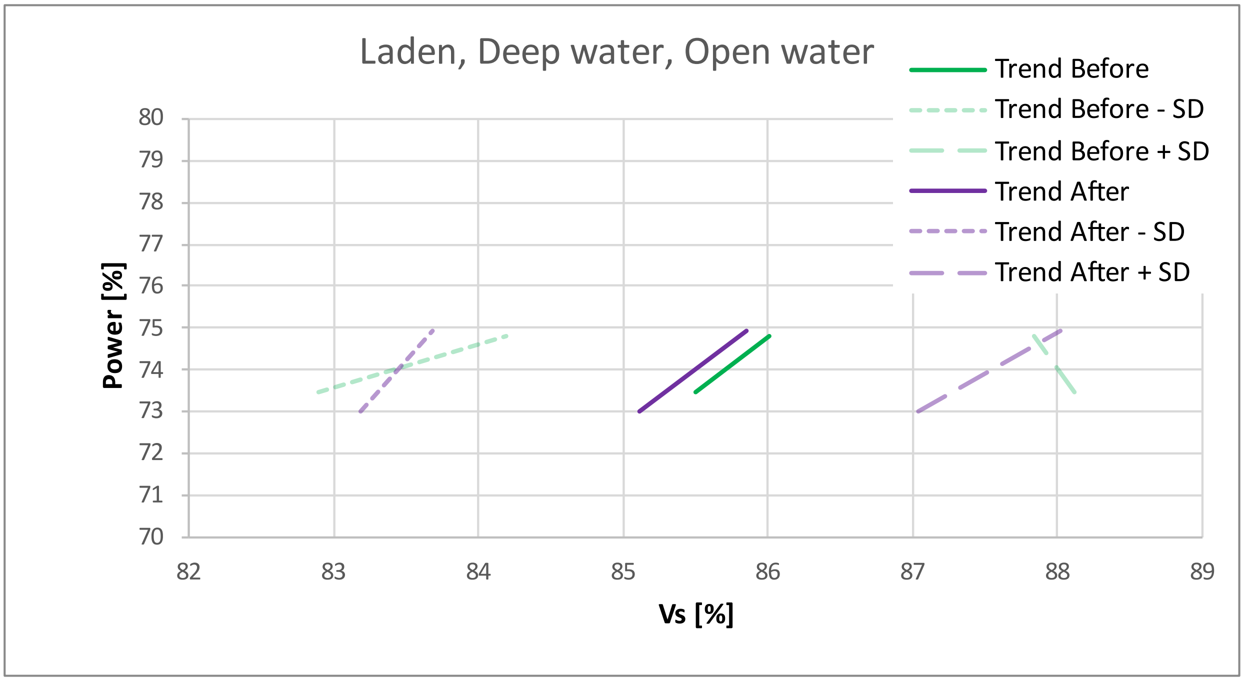

Figure 43: Power versus SOG trendline for Conveyor prior and after propeller polishing

8.2.7 Fuel Consumption vs. Speed Before and After Polishing

Figure 44 presents the measured fuel consumption of the Conveyor prior and after propeller polishing.

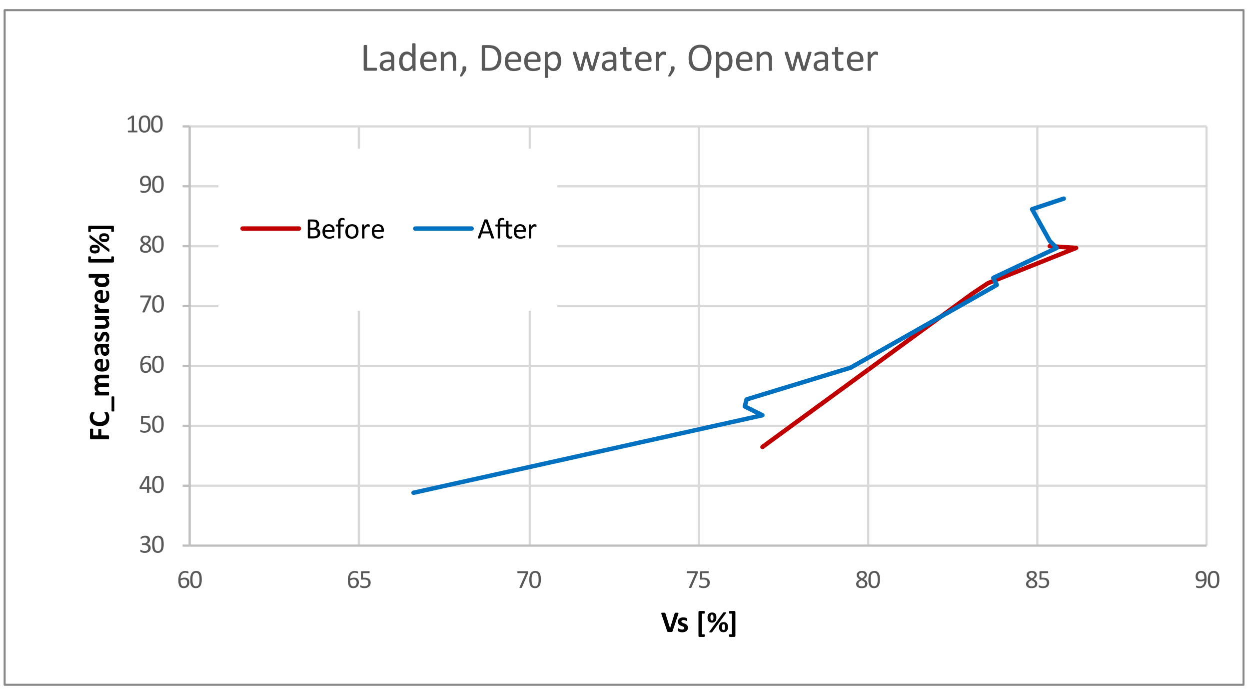

Figure 44: Fuel Consumption (measured) vs SOG trendline for Conveyor before and after propeller polishing

The fuel consumption measurements of the Algoma Conveyor show a linear relationship between fuel consumption and power as seen for the Algoma Mariner. Data from the Algoma Conveyor is shown in

Figure 45. The data from the Algoma Conveyor would suggest a trendline that gives unrealistic high fuel consumption in the lower power ranges, and it would give too low fuel consumption values in the higher (around 6000 kW) range. Further analysis was performed using the linear relationship of fuel consumption versus power from the Algoma Mariner (see Figure 36) which gives more reliable fuel consumption values throughout to whole power range. Furthermore, the Conveyor uses a similar propulsion plant as the Mariner and has adequately equivalent fuel consumption expectations. All the measured fuel consumption values (as presented in Table 21 and Table 22) are substituted by calculated values based on the trendline presented in Figure 36.

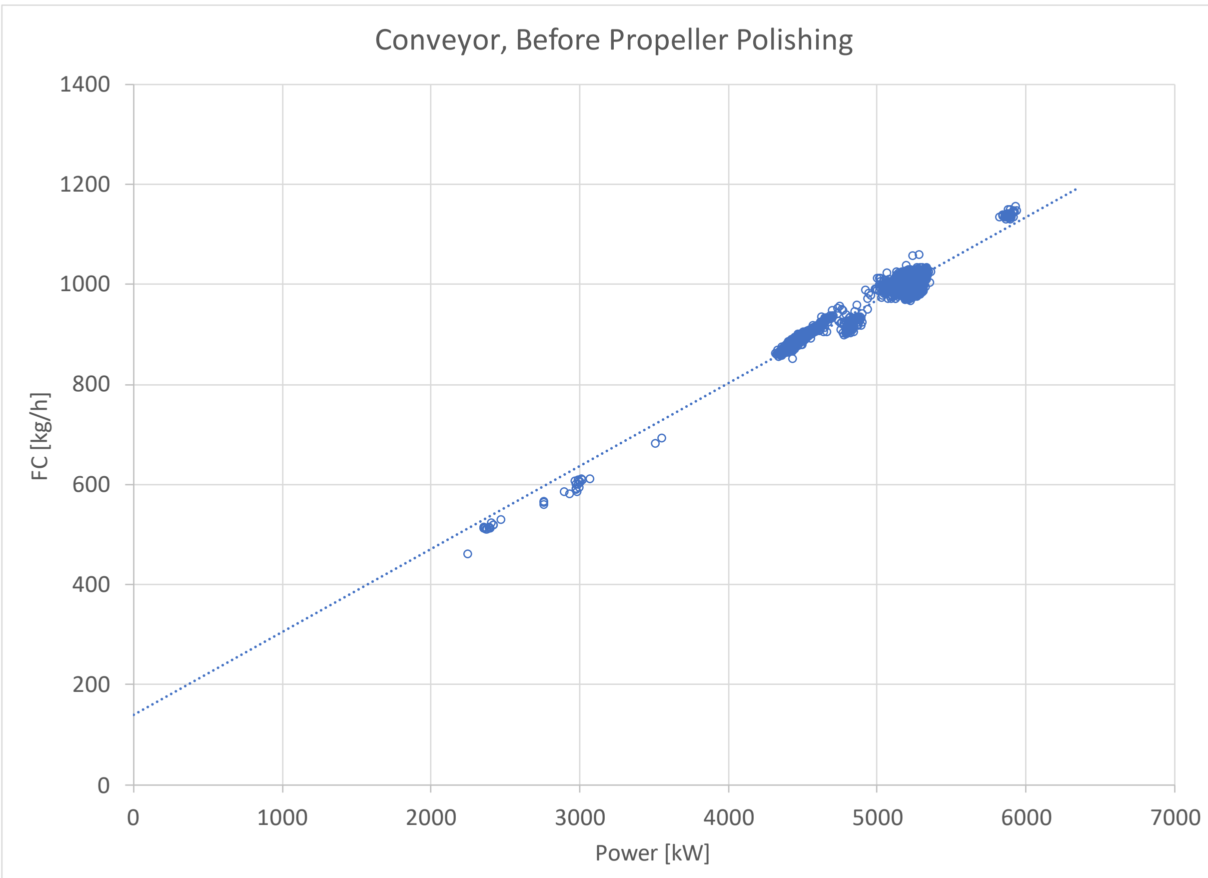

Figure 45: Measured Fuel Consumption vs Power trendline for Conveyor prior to propeller polishing

Based on the found relationship between fuel consumption and power, the trendlines of the fuel consumption versus vessel speed (and the error bands) could be analysed (see Figure 46).

As with hull coating, future work or detailed analysis that requires a high level of statistical confidence could consider supplementing operational data with additional trials data for the most important power bands.

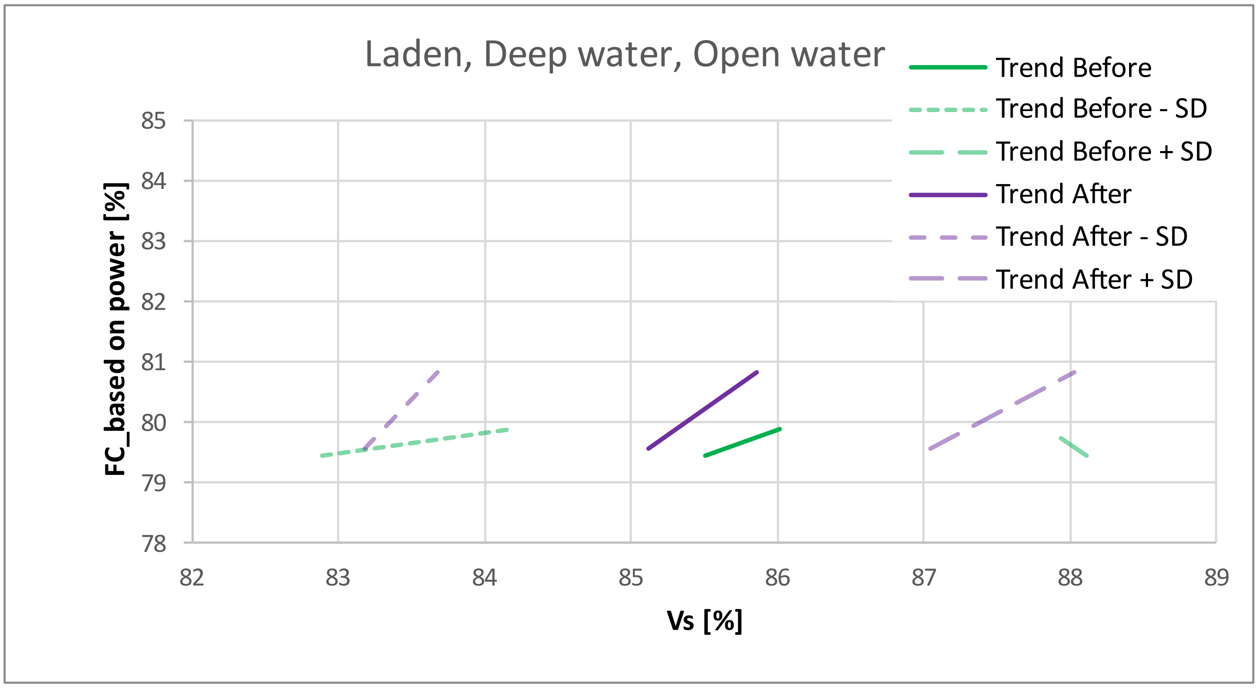

Figure 46: Fuel Consumption versus SOG trendline for Conveyor prior and after propeller polishing

8.2.8 Efficiency Before and After Propeller Polishing

Figure 47 and Figure 48 present the efficiency analysis of the Conveyor prior and after propeller polishing. As with the other analyses presented in this report an estimate of the change in efficiency can be made by comparing the trendlines for the data before and after propeller polishing.

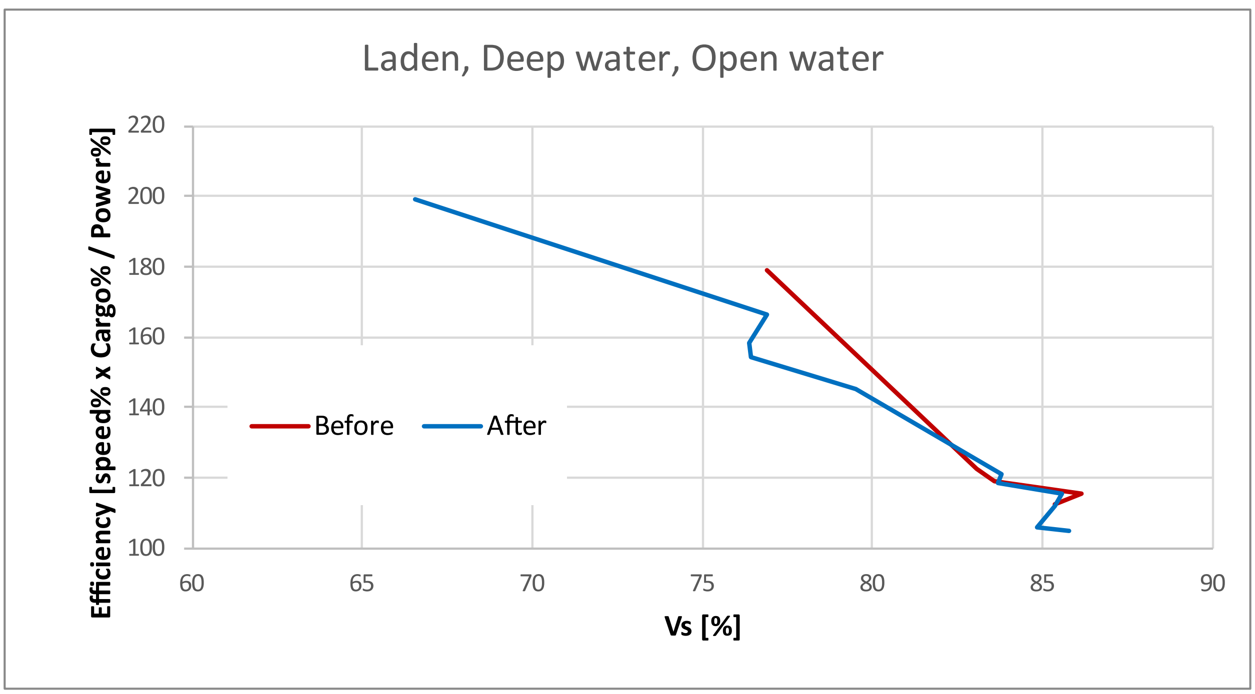

Figure 47: Efficiency versus SOG for Conveyor prior and after propeller polishing

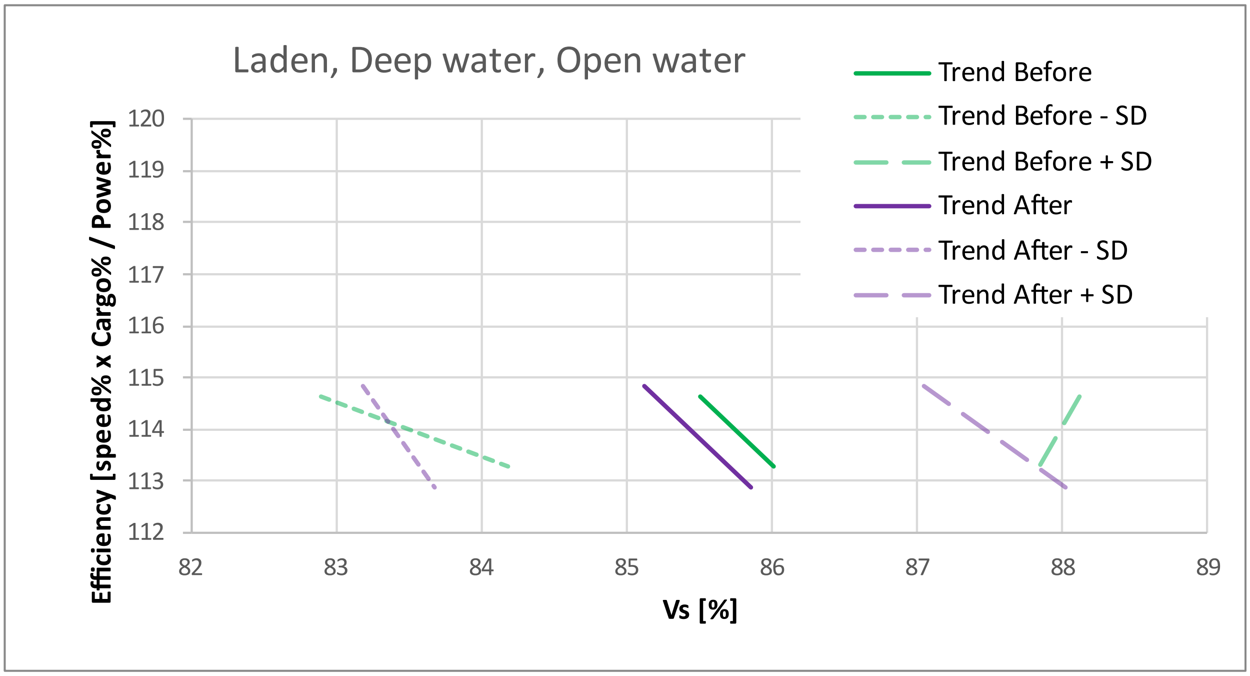

Figure 48: Efficiency versus SOG trendline for Conveyor prior and after propeller polishing

8.2.9 Propeller Efficiency

The propeller thrust (T in kN), revolution rate (n in rpm), torque (Q in kNm) and ship speed (Vs in m/s) are measured. Based on those measured particulars and the additional estimate for the water density (ρ = 1000 kg/m^3) and the propeller diameter (D_P in m) a quasi propeller efficiency can be determined. The pitch setting (P in %) of the propeller is logged as well (see Table 23 for an overview of the most used pitch settings). The pitch setting of 95 % has been set most for the after condition and has sufficient data points in the before condition as well, hence this pitch setting will be further presented in Figure 49. In Figure 49 the non dimensional propeller speed ($Js = Vs/(n * D_P)$) is presented versus the quasi propeller efficiency for the prior and after condition for the Conveyor for a pitch of 95 %. The same error bands are presented in Figure 49 as well. Propeller pitches that contained more than 1000 datapoints have been presented in this section. It appears that the quasi propeller efficiency has not significantly changed. The found minor differences might be due to the limited amount of data points (so that a true average condition could not yet be obtained), might be due to the propeller polishing, or might be due to other (yet) unknown reasons. The information for the 94, 95 and 96 % pitch is presented in tabular format in Table 24, the standard deviation of the quasi propeller efficiency is presented in the same table as well. For the three analysed pitch settings, the quasi propeller efficiency has practically not changed after propeller polishing.

Table 23: Propeller Pitch Count

Pitch [%]	Prior Count [-]	After Count [-]
92	191	696
93	593	2251
94	1903	2737

Pitch [%]	Prior Count [-]	After Count [-]
95	4182	3228
96	11168	1854
97	4687	440

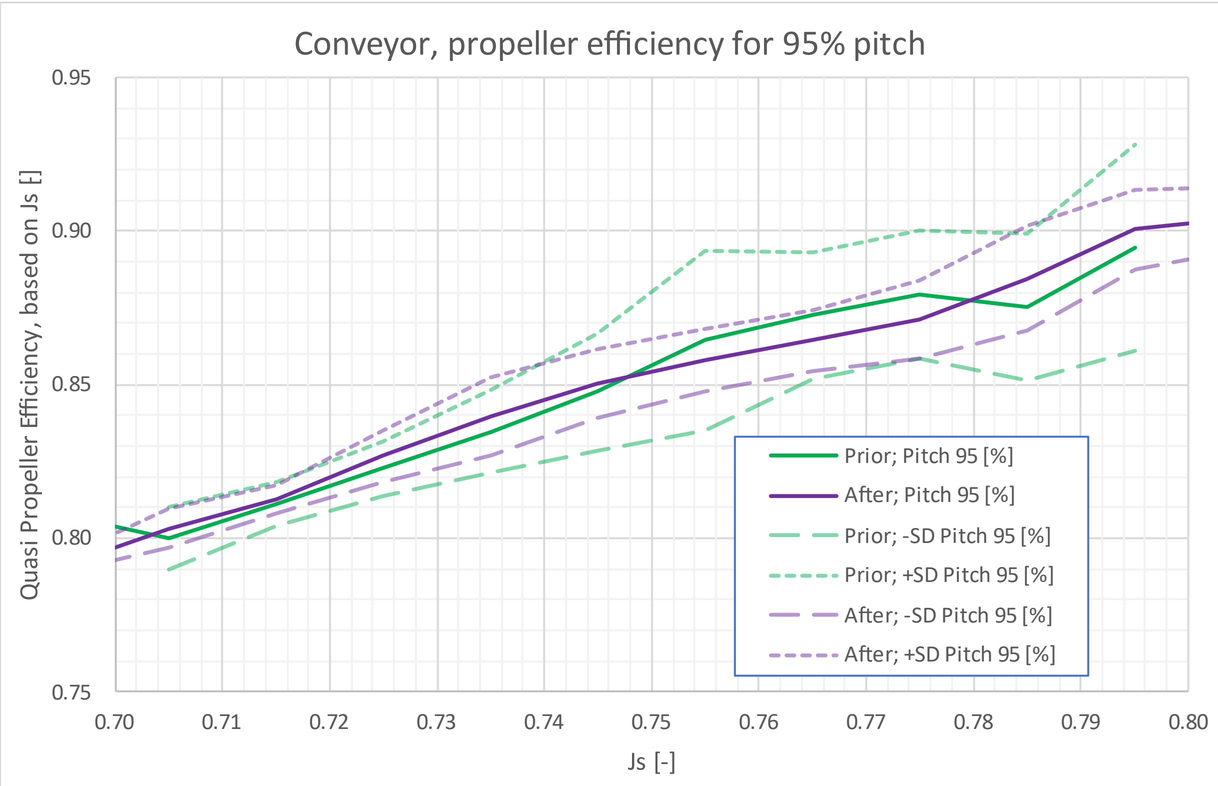

Figure 49: Quasi Propeller Efficiency versus Js

Table 24: Quasi Propeller Efficiency and SD versus Js

Condition [-]	**Prior;**	**After;**	**Prior;**	**After;**	**Prior;**	**After;**	**Prior;**	**After;**	**Prior;**	**After;**	**Prior;**	**After;**
Pitch [%]	94	94	95	95	96	96	94	94	95	95	96	96
Js-bin [-]	Efficiency [-]						SD of Efficiency [-]					
0.68-0.69	0.803	#N/A	#N/A	#N/A	#N/A	#N/A	0.008	#N/A	#N/A	#N/A	#N/A	#N/A
0.69-0.7	0.806	0.811	0.808	0.791	#N/A	0.794	0.007	0.004	#N/A	0.002	#N/A	0.000
0.7-0.71	0.809	0.817	0.800	0.803	0.787	0.802	0.008	0.003	0.010	0.006	0.007	0.003
0.71-0.72	0.819	0.830	0.811	0.813	0.807	0.811	0.009	0.005	0.007	0.005	0.009	0.004
0.72-0.73	0.832	0.834	0.823	0.827	0.821	0.821	0.010	0.010	0.009	0.008	0.008	0.005
0.73-0.74	0.842	0.845	0.835	0.840	0.834	0.832	0.008	0.013	0.013	0.013	0.019	0.011

Condition [-]	Prior;	After;	Prior;	After;	Prior;	After;	Prior;	After;	Prior;	After;	Prior;	After;
Pitch [%]	94	94	95	95	96	96	94	94	95	95	96	96
Js-bin [-]	Efficiency [-]						SD of Efficiency [-]					
0.74-0.75	0.854	0.850	0.848	0.850	0.841	0.841	0.016	0.017	0.019	0.011	0.027	0.016
0.75-0.76	0.871	0.855	0.864	0.858	0.841	0.845	0.024	0.019	0.029	0.010	0.024	0.017
0.76-0.77	0.880	0.871	0.873	0.864	0.858	0.855	0.020	0.020	0.021	0.010	0.024	0.015
0.77-0.78	0.872	0.878	0.879	0.871	0.866	0.861	0.014	0.021	0.021	0.013	0.021	0.017
0.78-0.79	0.901	0.870	0.875	0.885	0.864	0.871	0.028	0.017	0.024	0.017	0.017	0.017
0.79-0.8	0.921	0.880	0.894	0.900	0.869	0.878	0.040	0.017	0.034	0.013	0.019	0.015
0.8-0.81	#N/A	0.880	#N/A	0.904	0.871	0.887	#N/A	#N/A	#N/A	0.010	0.011	0.008
0.81-0.82	#N/A	#N/A	#N/A	0.923	0.885	0.901	#N/A	#N/A	#N/A	0.003	0.015	0.017
0.82-0.83	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
0.83-0.84	#N/A	#N/A	#N/A	#N/A	0.890	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Average (Js 0.70-0.79)	0.860	0.853	0.850	0.851	0.839	0.842						
Delta (Js 0.70-0.79)	-0.007		0.001		0.003							

8.3 COMPARATIVE ANALYSIS

This section presents a summary of the filtered data (filtered per the data filtering methodology described in Sections 6 and 8.1), comparing before and after vessel performance for the Algoma Mariner and Algoma Conveyor. The summary tables in this section are derived from the results from Section 8.2.1 and 8.2.5. The results are from the following steps:

1. The Algoma Mariner and Algoma Conveyor results before condition improvement were plotted and the resulting distribution was used to create trendlines for speed, fuel consumption, and average power within the bin increment.
2. The same trendlines were created for the data collected after condition improvement.
3. These trendlines were compared at the points matching each average power bin, yielding an efficiency difference.

As noted in Section 8.2, results based on comparing trendlines are subject to the caveat that a certain amount of statistical uncertainty exists because the overall estimated change in efficiency lies within the standard deviation of the overall dataset. Empirical analysis can also be subject to bias because the operational conditions before and after the coating/polishing differ, and some of these aspects (e.g. cargo load) have a significant impact on propulsive performance.

However, for the purposes of summarizing real world data they provide a reasonable estimate of the observed results from the data collection program.

8.3.1 Hull Coating Results

The results suggest that for open and deep-water operations in laden condition the coating renewal has consistently improved performance over the whole speed range, with a duration-weighted average overall power improvement of approximately 5 % (which is inline with the theoretical analysis presented in Section 4, since for the theoretical analysis the whole underwater body of the ship was assumed to be re-coated and in reality just over half of the underwater body was re-coated).

Table 25 below presents the estimated change in power, fuel consumption and transport efficiency for the Algoma Mariner after hull coating. The presented data covers 90 % of the time of the operational profile of the Mariner (for the operational profile see Section 10.1).

Table 25: Summary of Mariner Speed Vs. Fuel Consumption Prior and After Hull Coating

Vs [%]	Power Difference [%]	FC Difference [%]	Efficiency Difference [%]
83.9	-5.4	-5.3	5.8
85.4	-5.4	-5.3	5.8
86.6	-5.4	-5.3	5.8
Duration Weighted Average:	-5	-5	6

8.3.2 Propeller Polishing Results

Table 26 below presents the estimated change in power, fuel consumption, and transport efficiency for the Algoma Conveyor after propeller polishing for several vessel speeds.

The results show a duration weighted power decrease of 0 % (which is not inline with the theoretically analysed propeller efficiency in Section 8.2.9, but the results are inline with the data presented in Section 8.2.9). The presented data covers 97 % of the time of the operational profile of the Conveyor (for the operational profile see Section 10.1). The expectations (as mentioned in Sections 1.1 and 4.3.2) were more optimistic. This result may be due to various factors, such as (but not limited to):

- How the Controllable Pitch Propeller (CPP) was being operated, however the results of Section 8.2.9 suggest that for identical propeller pitch the efficiency of the propeller has not changed.
- The current configuration of the ship's combinator curve noted in Section 7.2.3
- A relatively small dataset for performance after propeller polishing (particularly after filtering the data) which could cause the unexpected result in multiple ways:
    - Too few data points to allow the expected more efficient mode of operation to be prominent within the overall dataset
    - Too few data points to allow differentiation between operations where outside environmental factors introduce variability in the propeller performance versus operations in relatively stable conditions where a change in performance would be more pronounced

Due to the limited time available after propeller polishing to collect data compared to the full season for hull coating on the Algoma Mariner the performance difference from propeller polishing is statistically less significant than the improvement from hull coating renewal.

As shown in Section 7.2.1 and 7.2.2 (for the Algoma Conveyor) the data collected before propeller polishing had only 4 power bin increments with 1000 or more datapoints, and only 2 power bin increments with 1000 or more data points for data collected after propeller polishing.

In contrast, the data for the Algoma Mariner (see Section 7.1.1 and 7.1.2) has 7 power bin increments with 1000 or more datapoints for data collected prior to hull coating renewal, and 7 power bin increments with 1000 or more data points for data collected after hull coating renewal.

This does not mean that the data collected after propeller polishing is problematic. It does suggest that more data should be collected so that the dataset can eventually cover more operational power ratings, types of operation, and outside environmental factors. Future work could consider more signals than currently collected.

It is recommended that more data be collected to represent a full season of operations with a polished propeller, and/or multiple shorter before and after periods for multiple propeller polishings be collected. This additional data, potentially supplemented with a planned set of guidance for the configuration of the CPP and related equipment, should yield more useful results.

Table 26: Summary of Conveyor Speed Vs. Fuel Consumption Prior and After Propeller Polishing

Average Power Bin [kW]	Vs [%]	Power Difference [%]	FC Difference [%]	Efficiency Difference [%]
5100	85.5	0.3	0.3	-0.3
5300	86.0	0.3	0.3	-0.3
Duration Weighted Average:		0	0	0

9 ENVIRONMENTAL CONSIDERATIONS

The real-world propulsive performance of a vessel can be strongly influenced by a variety of environmental factors. While attempts have been made in the preceding sections to filter out these effects, it is difficult to fully capture all of these. This section provides an overview of the environmental effects expected to be the most important, including, shallow water, temperature, and wind.

Current is implicitly filtered out of the dataset by only using data from the Great Lakes. Waves are not discussed explicitly, as they are typically considered to be correlated with wind in fetch-limited waters, such as the great lakes.

9.1 ICEBREAKING AND ICE INFESTED WATERS

VARD utilizes open-source Geographical Information System (GIS) software to analyze ice conditions in areas around the globe to provide operational analysis and information to clients on their vessel operations or plans. VARD currently uses the GIS software from the QGIS project[29] and updates our software suite as new versions are available.

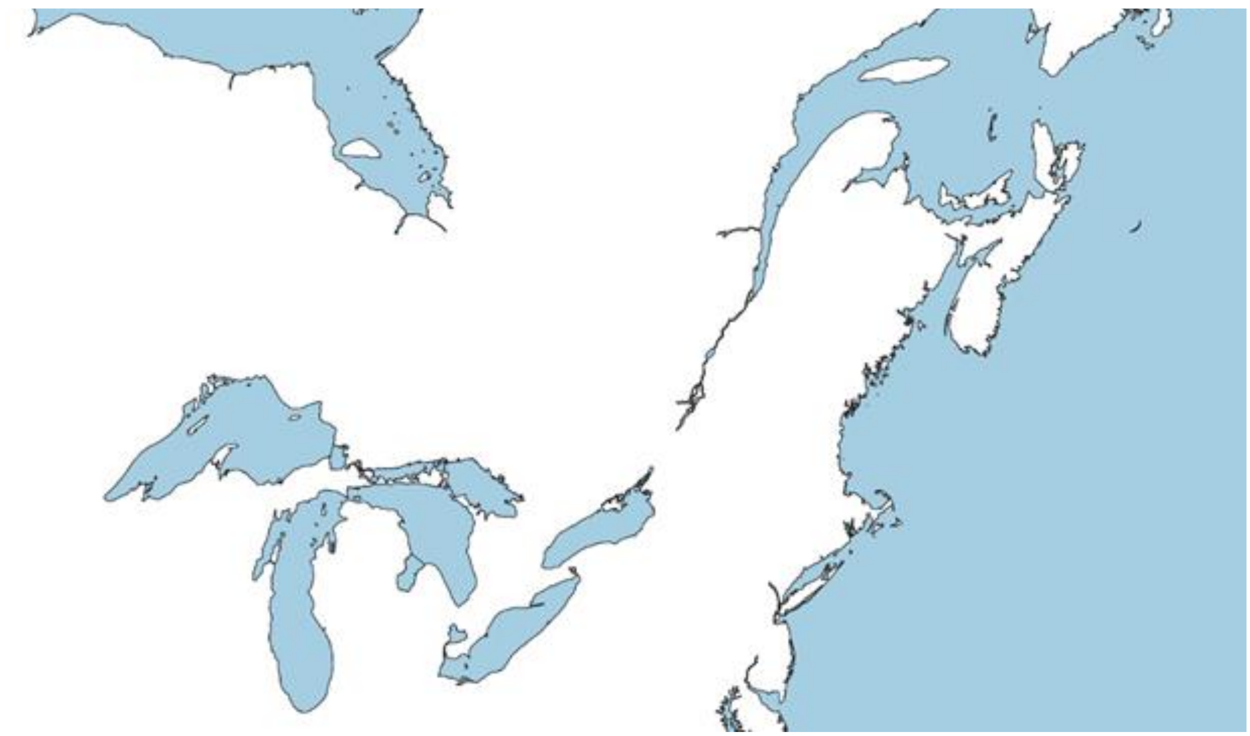

Figure 50: QGIS Map of Great Lakes and East Coast Areas

Other data sources used are ice charts provided by the National Snow and Ice Data Center (NSIDC)[30], geographic shapefiles from Natural Earth[31], and Bathymetry files provided by National Oceanic and Atmospheric Administration (NOAA)[32].

[29] QGIS Project, Available at: https://www.qgis.org/en/site/
[30] National Snow and Ice Data Center (NSIDC), Available at: https://nsidc.org/data
[31] Natural Earth, Available at: https://www.naturalearthdata.com
[32] National Oceanic and Atmospheric Administration (NOAA), Available at: https://www.noaa.gov

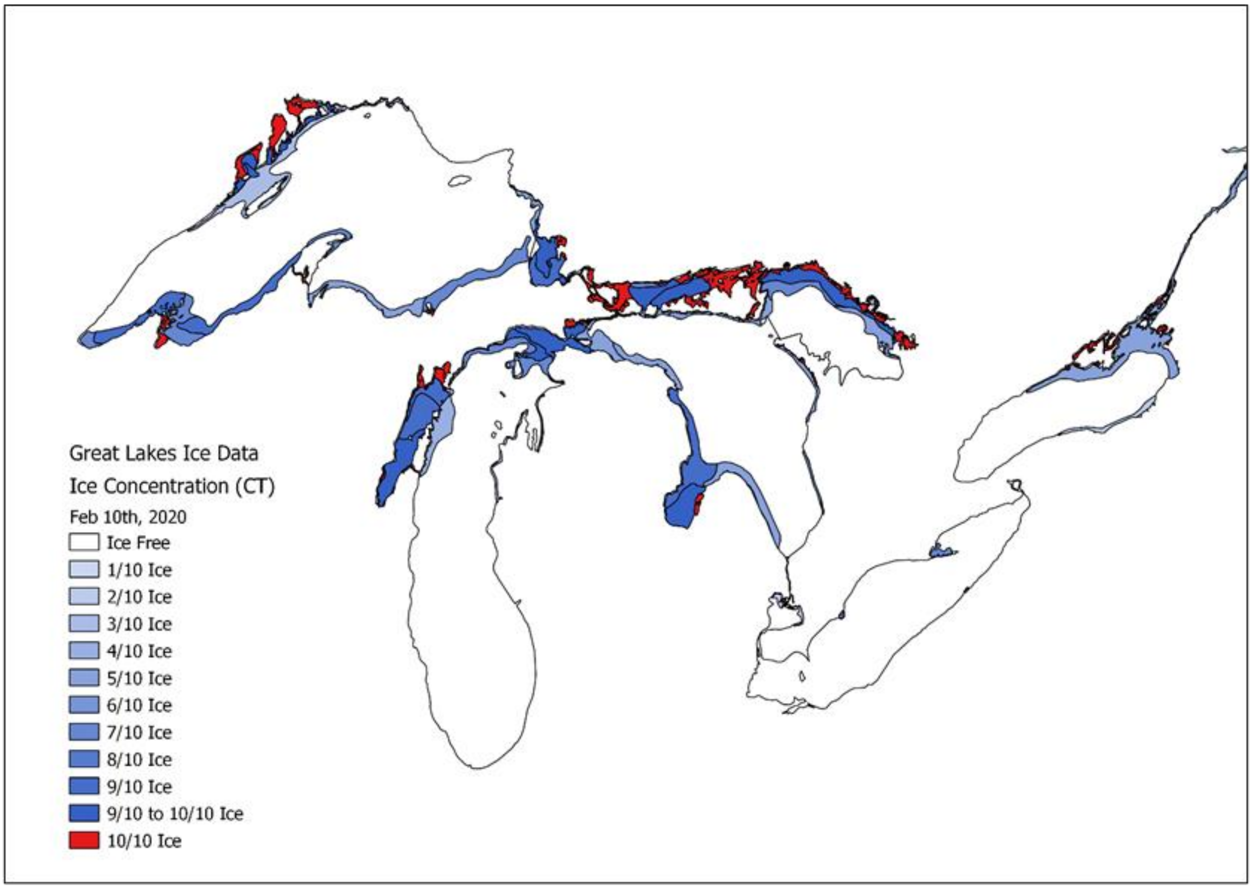

Figure 51: Ice Data on the Great Lakes Feb 10th, 2020

All ice charts were collected for the 2019, 2020 and 2021 periods up to June 2021. These ice charts are typically captured every week and available to download directly from the National Snow and Ice Data Center. All voyages for the vessel were split into separate data sheets, then these voyages imported directly into the QGIS program. This allowed for visually filtering the data points where the vessel was potentially in ice according to the chart as shown above.

The ice charts downloaded from NSIDC are presented in the SIGRID-3[33] format, allowing VARD to understand the concentration, stage of development, and floe sizes of the ice.

The project originally planned to consider operations in ice conditions, however, the Algoma Mariner completed hull coating in mid-February 2021 and the Algoma Conveyor completed propeller polishing in August 2021, so neither vessel's dataset includes a complete ice season since their condition upgrades. The ice season on the great lakes is typically starting around Dec 15th, and the last areas of ice fully melting by the second week of April the following spring. Future studies could consider further investigating the performance implications of operating in ice.

[33] Canadian Ice Service, 2009. Canadian Ice Service Arctic Regional Sea Ice Charts in SIGRID-3 Format, Version 1. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. https://doi.org/10.7265/N51V5BW9.

9.2 SHALLOW DRAFT AREAS

For this analysis, it has been determined that all water depths smaller than 12 m are considered shallow (see Section 6). Vessels that operate in shallow draft areas, meaning areas that have very little to almost zero clearance between the vessel's hull and bottom of the water way, have a drastic change in their hydrodynamics in two different ways.

The first is that the shallow water depth will change the wave period and height acting on the vessel. The wave period is the time it takes for two successive crests to pass a specified point. The shallow water depth can affect the wave period and wave height of the waves caused by the vessel and in turn changing the hydrodynamic resistance of the vessel as the waves are acting on the hull in different places compared to the design's intent.

The second way that shallow draft areas can affect the vessel performance is the hydrodynamic squat effect. When a vessel is moving through an area of shallow water a low-pressure zone is formed under the hull, which in turn causes the vessel to be pulled down towards the bottom of the waterway. This suction increases the resistance of the hull passing through the water. The squat effect can also change the trim of the vessel, causing the bow or stern to rise or sink. [34]

Shallow water has a different effect on the vessel based on the loading condition, the water depth and the vessel speed. In sufficiently deep water, the hydrodynamic behaviour of the vessel becomes insensitive to water depth.

VARD has utilized the data analysis platform Kibana, alongside the Algoma PRISM website to collect all data for the project. The built-in geofencing tool was used to draw a shape on the live fleet map to disregard all shallow water areas (e.g. Figure 52 shows no data is retained in the Welland Canal) and obtain all datapoints within the deep water area for the periods required on the two vessels. This single system collects all the vessel data used for the project data for the time period and region of interest, this data set was directly used as part of the master data set.

[34] Society of Naval Architects and Marine Engineers (SNAME), "Principles of Naval Architecture", 1989, Vol. II "Resistance and Propulsion"

Figure 52: Geofencing Tool Used for Filtering Data Based off Area

Taking the GPS co-ordinates for the boundaries on the above shape and similar ones for other shallow areas, Kibana was used to download all the data points for both vessels when they were operating in deep water.

Over the course of a season the ships do not have long periods of relatively consistent operational parameters in shallow water. Shallow operating conditions could therefore be a good candidate for a basic sea trial – unlike deep water sailing at cruising speed which will naturally yield a large number of data points over a season due to the nature of how the vessels are operated, establishing hundreds or thousands of datapoints for shallow water operations at consistent speed, power, and FC levels could take much longer. A sea trial could yield results over a few days which might be more useful than attempting to interpret real world data collected during operations that naturally have highly variable speeds and power demands.

9.3 TEMPERATURE ANALYSIS

As the temperature of air decreases the density of the air increases as well as the oxygen levels increase. Both the Algoma Mariner and Conveyor utilize turbocharged diesel engines as their sole propulsion engines. Having colder air being drawn into the intakes on the engines, will allow the engines to increase the amount of fuel being injected into the cylinders. Therefore, when operating in colder ambient air temperature the engines will theoretically receive a small increase in the power output compared to summer operations.

For example, the density for air at 1 atm, and 0 degrees Celsius is 1.292 kg/m3, where as the density of air at 25 degrees Celsius is 1.184 kg/m3.[35]

[35] Engineering ToolBox, (2003). Air - Density, Specific Weight and Thermal Expansion Coefficient vs. Temperature and Pressure. Available at: https://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html.

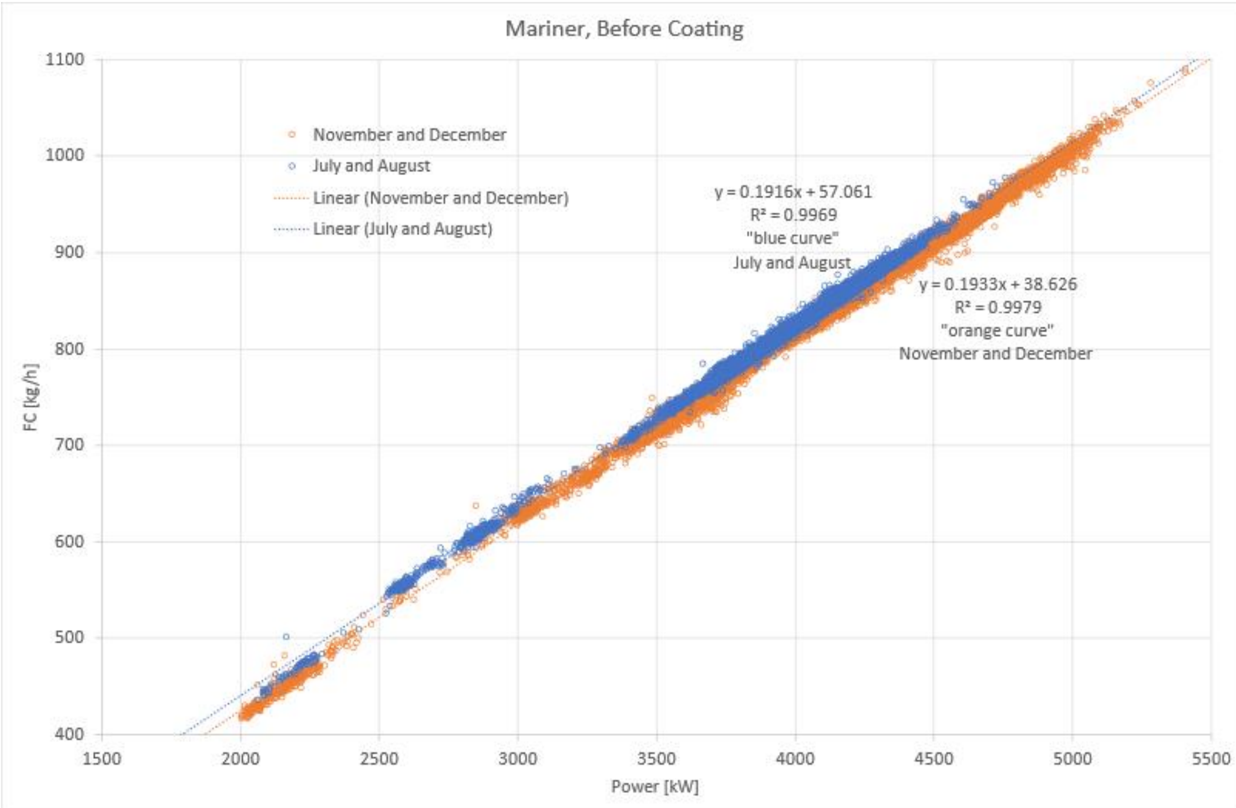

Figure 53: Temperature Influence Fuel Consumption versus Power

As shown in the figure above, there is a slight fuel consumption decrease on the Mariner for the same power bins when operating in colder months, November and December, versus operating in warmer months, July and August. This slight difference is within the spread of the data shown on Figure 18: Power versus SOG for Mariner before Coating, and as such no statistical certainty can be given.

An estimate based on the difference between the two trendlines is calculated to be 1.8% at a power level of 3,300 kW.

9.4 WIND SPEED AND RELATIVE ANGLE SUMMARY

Wind speed and wind angle data was collected for both vessels (see Section 7.1.1, 7.1.2, 7.2.1 and 7.2.2). This was completed through the Kibana dashboard via selecting the two fields to filter the data: *Relative Wind Speed* (in knots) between 0 and 100 knots, and *Relative Wind Angle* (in degrees) between 0 to 360 degrees. These two filters allowed for capturing all the available data where any wind speed or angle was reported. The relative term refers to the vessel as being the point of reference of where the values are measured from. The relative wind direction can be transferred into the absolute wind direction, where the absolute wind direction is analysed from an earthbound location. For the Mariner (before the coating), the 3700 kW power bin is sailed most (out of all the measured power bins). In Table 27 the average vessel speed and the absolute wind segment from the Mariner (after hull coating) for the 3700 kW power bin is provided. The amount of data is insufficient to determine the influence of wind on the vessel speed.

Table 27: Vessel speed per Wind Segment for Power Bin of 3700 kW, MarinerAfter Coating

Wind Segment [deg]	Count of data points [-]	Vessel speed [kn]
0 - 45	104	12.8
45 - 90	0	#N/A
90 - 135	0	#N/A
135 - 180	0	#N/A
180 - 225	0	#N/A
225 - 270	0	#N/A
270 - 315	0	#N/A
315 - 360	51	12.9

10 ECONOMIC ANALYSIS

10.1 PAYBACK PERIOD

The payback period can be viewed as the amount of time between the date of initial investment, in this exercise this is the hull coating and propeller polishing work, and the date when the break-even point has been reached, which is when the decrease in expenses is equal to the cost of the investment.

For this study, VARD has used the following formula to calculate the payback period.

$$Payback\ Period\ (Years) = \frac{\text{Initial Investment}}{Yr\ \text{Fuel Cost (Before)} - Yr\ Fuel\ Cost\ (After)} \quad (1)$$

Degradation of the hull coating or the propeller polishing has been taken into account by using the fuel consumption improvements as determined in Section 8.3. This payback period calculation has been kept extremely simple. Factors such as interest, inflation, rising fuel costs, or any other performance degradations have not been considered.

The degradation period of 8 years has been used as it is the typical drydocking schedule for the Algoma fleet. The Mariner previously had hull cleaning and new coating reapplied in 2015. For the Mariner the degradation of the hull will assume an efficiency loss of 0.875% per year.

Furthermore, the average values for fuel consumption have been used in this analysis. As noted in Section 8.2 and Section 8.3 these average values are derived from a comparison of trendlines for the observed real world data this study has collected. For a predictive analysis these averages should be understood to be estimates, and as such the presented fuel consumption, fuel costs and payback period are an indication of what could be achieved.

A basic operational profile for each vessel was created based on the measurements for the period before the condition renewal. Note that the values in the lower speed ranges have been extrapolated as explained in Section 8.2.3 Figure 36. VARD calculated the percentage of time travelled in the Laden condition, in deep water, in open water (no ice) and multiplied the percentage of time with the total travelled distance of the vessel to determine the distance travelled per power bin (and per vessel speed).

The distance per year (nm/year) is derived from the vessel speed and the distance per year. Based on the available data for the Mariner an average distance travelled of 95430 nm per year is used in the analysis.

See Table 28 for the Algoma Mariner assumed operational profiles. The applicable trend for the vessel speed of the Mariner covers 90 % of the operational time (for the filtered steady state conditions).

Table 28: Operational Profile – Algoma Mariner

Average Power Bin [kW]	Duration [dd hh:mm:ss]	Trend Vs [% of design speed]	Duration [%]	Distance [nm/year]
3100	00 00:03:00	-	**-**	**603**
3300	00 00:01:00	-	**-**	**201**
3500	00 00:04:00	-	**-**	**804**
3700	00 00:07:00	-	-	1406
3900	00 03:25:00	83.9	43.2	41186
4100	00 02:16:00	85.4	28.6	27323
4300	00 01:27:00	86.6	18.3	17479
4500	00 00:09:00	-	-	1808

Average Power Bin [kW]	Duration [dd hh:mm:ss]	Trend Vs [% of design speed]	Duration [%]	Distance [nm/year]
4700	00 00:23:00	-	-	4621

10.1.1 Hull coating

These calculations are based on data for when the vessel is in deep water, open water, and laden conditions. An operational profile for the vessel based on power bins and their associated speed was used to determine the tonnes per year of fuel burned.

The following payback figures have been calculated using this operational profile. The efficiency improvements used are the maximum values presented in Section 8.3.

Before the hull coating work was completed, the vessel burned roughly 5,602 tonnes of fuel per year. This figure then equals to $5,041,399 CAD over the year when using the average fuel cost of $900 CAD/tonne.

After the work was completed, the ship will burn an estimated 5,304 tonnes of fuel per year based on the average performance improvement from the operational profile shown in Table 28. This equates to $4,773,716 CAD over the year when using the same average fuel cost of $900 CAD/tonne.

The approximate total cost for getting the hull coating work performed was $1,500,000 CAD. This expense only covers the cost of having the hull coating work completed, no other costs such as lost or revenue due to dry docking time is taken into account.

The increase in fuel consumption, and therefore increase in fuel cost, is based on the hull coating degradation over the 8-year period, which is the typical docking schedule for the Algoma fleet. This is calculated by dividing the difference between the total fuel costs by the 8 year drydocking interval. This degradation cost is calculated out to $33,460 CAD per year for the Mariner. This has been captured in the annual fuel cost for the vessel after coating work was performed, and as further deterioration in the baseline case in which the hull is not re-coated.

These figures care summarized in the table below.

Table 29: Payback Period Calculation – Algoma Mariner

	Baseline		With Coating Renewal		
Year	Annual Cost [$CAD]	Total Spent [$CAD]	Annual Cost[$CAD]	Total Spent [$CAD]	Net Difference [$CAD]
0		0		$1,500,000	$1,500,00
1	$5,041,399	$5,041,399	$4,773,716	$6,273,716	$1,232,317
2	$5,074,859	$10,116,258	$4,807,176	$11,080,892	$964,634
3	$5,108,319	$15,224,577	$4,840,636	$15,921,528	$696,951
4	$5,141,779	$20,366,356	$4,874,096	$20,795,624	$429,268
5	$5,175,239	$25,541,595	$4,907,556	$25,703,180	$161,585
6	$5,208,699	$30,750,294	$4,941,016	$30,644,196	-$106,098

7	$5,242,159	$35,992,453	$4,974,476	$35,618,672	-$373,781

Therefore, the payback period can be interpolated from the point where the rightmost column of Table 29 passes through zero, or (equivalently) calculated as:

$$Payback\ Period\ (Years) = \frac{1{,}500{,}000}{(5{,}041{,}399) - (4{,}773{,}716)} \qquad (2)$$

$$Payback\ Period\ (Years) = \frac{1{,}500{,}000}{(267{,}683)} \qquad (3)$$

$$\text{Payback Period (Years)} = 5.60\ \text{Years} \qquad (4)$$

The resulting payback period of the hull coating for this approximate operational profile is just over 5 years 7 months.

Based on the information in Table 3, as well as the weighted average in Section 4.3, and specifically Figure 16: Average hull roughness (AHR) increase over the years in service, the increase in roughness on the hull coating is roughly linear after the 8 year point. Due to lack of hull roughness measurements being taken before the hull coating work began in 2021, VARD is not able to determine the real-world degradation of the hull coating.

These figures shown in Section 4.3 is the hull roughness that was used in the assessment of performance impact of hull roughness increase after 8 years in service. As the hull coating work is estimated to pay back just under 5 years 7 months of operations and combined with the other cost-benefits as described in Section 10.2, VARD recommends Algoma continues with the current 8 year dry docking schedule for the vessel.

10.1.2 Propeller polishing

Due to the limited time available after propeller polishing to collect data compared to the full season for hull coating on the Algoma Mariner the performance difference from propeller polishing is statistically less significant than the improvement from hull coating renewal.

Additionally, no economic analysis can be completed to determine if the $10,000 CAD cost of having the work will pay back during the typical 8 year dry docking period.

These concerns are expanded on in detail in Sections 8 and 8.3.

This does not mean that the data collected after propeller polishing is problematic. It does suggest that more data should be collected so that the dataset can eventually cover more operational power ratings, types of operation, and outside environmental factors. Future work could consider more signals than currently collected. The results of this work can be used to determine the payback period and figures for the propeller polishing.

10.2 COST-BENEFITS

10.2.1 Hull coating

The previous results suggest the power, fuel consumption, and associated costs can be minimized by keeping the hull surface as smooth as possible. However, drydocking ships to clear the hull of fouling organisms and/or reduce the roughness by applying new coating is costly and must be balanced by the cost savings and additional benefits that may be harder to quantify.

A very high-level benefits list of a new hull coating is as follows:

- Reduced operational costs compared to a ship with higher hull roughness
  - Either due to higher speed at the same power,
  - Or due to reduced fuel consumption at the same speed
- Potentially increased revenue compared to a ship with higher hull roughness due to increased speed at the same power (more distance travelled)
- Reduced loss of steel to corrosion
- Reduced cavitation on the propeller since the propeller is less loaded and works near ideal propulsive efficiency
- More uniform water flow to the propeller
- Reduced stress on the propulsion components due to less resistance and better propulsive efficiency
- Reduced wear & tear and associated maintenance on propulsion components including the propeller itself due to reduced cavitation, vibration, loads and stress
- Increased comfort due to reduced vibration and reduced turbulence but most importantly due to propeller loads and cavitation
- More visually appealing vessels and associated customer admiration of vessels

10.2.2 Propeller polishing

As investigated in the hydrodynamic analysis in Section 4, the impact of propeller roughness increase only affects the power requirement to reach the same thrust to propel the ship. As a result, there are no additional benefits as with hull coating maintenance.

The data analysed in this study does not yield a meaningful result for the improvement to efficiency from propeller polishing as explained in Section 8.3.2. Considering that it is a low-cost process, the following high-level benefits must be considered seriously in the light of hydrodynamic analysis results:

- Reduced operational costs compared to a ship with higher propeller roughness
  - Either due to higher speed at the same power,
  - Or due to reduced fuel consumption at the same speed

- Potentially increased revenue compared to a ship with higher propeller roughness due to increased speed at the same power (more distance travelled)
- More available power and thrust when needed in emergency situations (instead of wasted on roughness)
- Reduced stress on the propulsion components due to better propulsive efficiency
- Identifying any blade damage during polishing process (Note that none was found during this project)
- Reduced risk of unpredictable cavitation inception due to roughness buildup that can adversely change the foil shape and therefore pressure distribution
- Reduced risk of unpredictable cavitation related performance reduction, wear & tear, maintenance, and crew discomfort due to cavitation induced vibration

10.3 EMISSIONS REDUCTION

The operational profile created in Section 10.1 has been used to calculate the approximate CO_2 emissions for the vessel before and after the work was completed. The CO_2 emission output figures used to calculate the vessel total output has been calculated using the emission factors as presented in Green Marine Self Evaluation Guide from 2017[36] and is summarized in the table below. The underlying figures in the table are determined from the 4th IMO Greenhouse Gas (GHG) Study from 2020[37].

Table 30: Greenhouse Gas Emission Factors

FUEL TYPE	EMISSON FACTOR (KG-EMISSION / TONNE-FUEL BURNED)	SOURCE
	CO_2	
Heavy Fuel Oil (HFO)	3114	4th IMO GHG Study
Diesel, USLD and Marine Gas Oil (MDO / MGO)	3206	4th IMO GHG Study
Intermediate Fuel Oil (IFO380)	3123	Interpolation (10% MDO)

Using the above figures for the CO_2 emissions factors, VARD was able to calculate the total CO_2 output for the Mariner with the operational profile in Section 10.1, as well as the total tonnes of fuel consumed for the before hull coating and after hull coating. This calculation is summarized in the table below.

Table 31: Mariner Emissions Outputs

	Before Hull Coating	After Hull Coating	
Fuel Consumed/ Year	5602	5304	MT
CO_2 Output/ Year	17445	16517	MT
CO_2 Output Change	-928		MT

No emissions analysis has been performed for the Algoma Conveyor, since the propeller polishing did not have any effect on the power consumption of the vessel (neither of the propeller efficiency).

[36] Green Marine Self Evaluation Guide - https://green-marine.org/2018/01/20/2017-self-evaluation/
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11 RECOMMENDATIONS

Analysis of the project's data and development of economic analyses has led to two categories of recommendations – recommendations for treatment of data and planning for data collection in future studies, and operational recommendations which would support and enhance future studies.

In general, the most important recommendation is that more data could lead to greater confidence in the results. In the case of this study, the data collection effort yielded approximately 850,000 timestamped data points. After filtering the data for analysis this total was reduced to approximately 4,000 data points. This is not unexpected, and while reducing the available data points may not have a significant impact on stable operations with long periods such as open water sailing, it can pose challenges to deriving meaningful results for operations which occur infrequently and/or with less stable speed, power, or fuel consumption metrics.

11.1 FUTURE STUDIES – DATA AND ANALYSIS

- Data collection for key metrics such as fuel consumption, speed, and power should be measured through multiple channels (as some are now) to avoid occasional spurious data points and also to allow results to be baselined/validated against multiple datasets in the event that there is an issue with any single measurement source.

- Additional data collection for differentiating the power output and fuel consumption results for when the vessels are consuming different fuels, such as switching from HFO to MDO/MGO, as well as difference in results for consuming different blends of MDO/MGO. I.e. IFO380.
- More data signals should be collected in more ways before and after both propeller polishing and hull coating – in the case of propeller polishing this could mean more than one polish per season depending on how quickly the condition of the blades deteriorates. The difficulty in drawing meaningful conclusions for the effect of propeller polishing in this study might be mitigated by collecting more data to allow more time for visible trends to occur.
- More hull coating data should focus on long-term data with hull roughness measurements to capture the gradual decline in the coating and its effect. This could eventually feed into a data-based analysis of how frequently to recoat the hull.
- More signals to yield closer data distributions could help remove bias from data filtering. Bias removal is important, considering that the present data includes some significant bias in loading condition, and fails to show any change in performance for the propeller polishing. Also, the theoretical hydrodynamic work (based on NavCad) suggests the propeller improvements can't be expected to be as great as the hull coating improvements, which means that accuracy and good interpretation of the full-scale data is all the more important.
- Alternative strategies for data processing and analysis may prove useful in refining the precision of the data presently captured. For example, a method that includes means of correcting for the environmental effects, vessel draft, water depth, acceleration, etc. may be more effective than the present approach of filtering out data where these effects are suspected to be important. This may offer the potential to correct for bias between the "before" and "after" conditions (e.g. generally windier conditions before/after). If successful, this may enable the more subtle performance differences associated with propeller polishing to be observed more clearly.

11.2 FUTURE STUDIES – OPERATIONAL AND PLANNING CONSIDERATIONS

- Future work could include trials for collecting more data with more signals for sailing at relatively consistent speeds in deep water. Specifically, plan for a set of trials before the next coating renewal, and a following set of trials immediately after renewal according to ITTC recommendations[38]. Trials can be targeted for operational conditions where the vessel is believed to gain the most benefit from hull coating to support and numerically validate observed efficiency improvements.
- Any ship trials should focus on providing value by sailing in the most frequently encountered conditions at consisted, higher speeds because this is where a vessel stands to see the most significant improvement in fuel consumption.
- Similarly, low speeds may or may not benefit from condition upgrades due to their highly variable nature in terms of engine load demand and environmental conditions a dedicated trials program may not be good value.
- Hull roughness measurements should be included in any coating program to better characterize (and numerically validate) the efficiency gains from coating renewal.
- The guidance followed by the ship's master for operating the CPP and the combinator curve should be considered when collecting data and planning to analyse propeller performance.
- In the interest of achieving the full greenhouse gas reductions enabled by hull coating and propeller polishing, it is recommended that the operational procedures going forward aim to retain the same sailing speeds. Using the increased efficiency to sail at a higher speed with the same power is expected to negatively affect fuel efficiency and reduce the greenhouse gas reductions.
- Based on the data collected in this study as shown in Section 8, the improved transport efficiency could translate into higher sailing speeds if the operating philosophy is to retain same power. This can be estimated as as follows:

  Assuming a relationship of the form below between power consumption and vessel speed:

  $$P = c \cdot v^3$$

  Where c is a constant depending on the vessel performance. Noting the overall power improvement of approximately 5 %, the improved and old constants in the relationship would therefore be related as follows:

  $$c_i = 0.95 \cdot c_o$$

  Assuming operation at the same power:

  $$P = c_o \cdot v_o^3 = c_i \cdot v_i^3$$

  Therefore, by the definition of transport efficiency, the following yields the effect on transport efficiency for the same amount of cargo being transported at the same power level:

[38] ITTC – Recommended Procedures and Guidelines, Preparation, Conduct and Analysis of Speed/Power Trials, 7.5-04-01-01.1, 2017, revision 05

$$\frac{v_i \cdot Cargo/P}{v_o \cdot Cargo/P} = \frac{v_i}{v_o} = \sqrt[3]{\frac{c_o}{c_i}} = \sqrt[3]{\frac{1}{0.95}} = 1.017$$

This means a 1.7 % increase in transport efficiency can be achieved at the same power consumption level for the same amount of cargo transported.

This is substantially less than the 5% improvement in transport efficiency that could be achieved if the operational philosophy were to sail at the same speed. Sailing at the same power after hull coating thereby undermines much of the benefit of the hull coating. It is therefore recommended that following hull coating, the operational philosophy be to continue sailing at the same (or lower) speed as previously.

12 CONCLUSIONS

Two different Great Lakes vessels have been instrumented to collect propulsive performance data both before and after making changes intended to improve their fuel efficiency, and thereby reduce their greenhouse gas emissions. These changes included re-coating the hull, and propeller polishing, with one change applied to each ship. The data were analyzed to quantify the performance changes.

The data analysis yielded interesting results. When treated empirically (comparing trends for performance before and after condition improvement as described in Section 8.3) the data for the Algoma Mariner allowed for analysis of change in power, fuel consumption, and transport efficiency after hull coating.

- As expected, a third power curve (between power and vessel speed) can clearly be recognized in the dataset.
- As expected, a third power curve (between fuel consumption and vessel speed) can clearly be recognized in the dataset.
- At lower speeds the data is more scattered than at higher vessel speeds. This is expected since the environmental factors play a larger role on the resistance of the vessel at low vessel speeds than at higher vessel speeds.
- Trendlines for the power, fuel consumption and efficiency versus vessel speed could be created and compared between roughly 12 and 13 knots. These speeds are representative of open water sailing and stands to benefit the most from the efficiency increase after hull coating.
- Interestingly, there is a slight fuel consumption decrease on the Algoma Mariner (prior to the hull coating) for the same power bins when operating in colder months, November and December, versus operating in warmer months, July and August.
- Overall performance will decrease gradually with the degradation of the hull coating; while this was assumed to be linear, the data analysis does not support any conclusions on the degradation rate.

The observed efficiency results for the hull coating (Algoma Mariner) are particularly promising. The empirical analysis for the ship's data before and after hull coating yields an estimate of approximately a 5 % improvement. Specifically, the results suggest that for open and deep-water operations in laden condition the coating renewal have consistently improved performance, with a duration weighted average overall power improvement of approximately 5 %.

This is supported by the ITTC analysis which calculates upgrading (for a complete coated underwater hull) from a rough hull (580 µm AHR) to a smooth (freshly painted hull (150 µm AHR) reduces the power consumption (in the speed range of 7.5 to 15.5 knots) by roughly 11%. With roughly half of the underwater hull being recoated, ITTC would predict a performance increase of approximately 6 %, which is in line with the empirical (long term) data analysis.

Data from polishing the propeller of the Algoma Conveyor did not yield the same clear results; however this could likely be resolved through additional data collection and bias removal. The empirical (long term data) analysis has shown that the improvements are in the order of approximately 0%. An ITTC analysis as shown in Section 4.3.2 suggests that polishing the propeller and upgrading from an unpolished propeller (Rubert's scale D) to a polished propeller (Rubert's scale A) reduces the power consumption (in the speed range of 7.5 to 15.5 knots) by roughly 6%.

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