Optimizing Fuel Management for Halifax Class Frigates: Leveraging Sensor Data for Enhanced Efficiency.

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Synopsis

This article explores how operational data from sensors integrated with Royal Canadian Navy (RCN) Halifax Class Frigates onboard Integrated Platform Management System (IPMS) can be leveraged to minimize fuel consumption. The idea is to use IPMS data logged by the Equipment Health Monitoring (EHM) software tool. This, along with data collected from temporary fuel meters installed on several Halifax Class Frigates, aids in the development of fuel consumption models for onboard power generating and propulsion equipment. The study aims to identify the most fuel-efficient driving mode among the options available for specific operational conditions, leveraging the Combined Diesel or Gas (Turbine) Propulsion System (CODOG) and twin shaft arrangement of the Halifax Class Frigates. Building upon this, the developed fuel consumption models are employed to implement various fuel optimization methods on a specific ship platform. This entails the adaptation and integration of these methods into dashboards for enhanced accessibility, with the fuel consumption models providing essential input data.

In the course of the study, several fuel optimization techniques were examined, revealing valuable information about their applicability in specific cases, taking into account factors such as data availability and reliability. The development process of equipment fuel consumption models showcased how sensors designed for operational support could enhance fuel consumption optimization efforts.

Fuel Management Dashboard (FMD) application prototype was developed to facilitate user access to current operational data, fuel consumption-related information as well as fuel consumption optimization tools.

Enhanced value could be realized with the installation of high-quality fuel flow meters during ship construction or the prolonged use of temporary fuel flow meters to capture data across the ship's speed and load ranges.

The IPMS emerged as a valuable information source supporting fuel optimization initiatives.

Validation of the FMD performance in the field and its value to end-users is pending; however, the progress achieved thus far shows promising potential.

Keywords: Navy; Fuel Consumption; Fuel Efficiency; Data Analysis; Simulation and Modelling.

1. Introduction

While in naval operations, mission success takes precedence over fuel consumption concerns, there are still many opportunities to optimize fuel usage, improve endurance, and reduce associated costs (Brown, 2007). Fuel cost constitutes a significant portion of overall ship operating expenses (Schreiner, 2021). Continuous monitoring of fuel usage efficiency, based on reliable equipment fuel consumption models, is essential to ensure efficient operation, enhance endurance, and enable prompt corrective action when deviations occur. (Mandler, 2000, Schreiner, 2021)

The Halifax-class propulsion system operates in a CODOG configuration. Main propulsion is provided by two General Electric LM2500 Gas Turbines (GTs), each rated 17.7MW, one SEMPT Pielstick Propulsion Diesel Engine (PDE) rated to deliver 6.47MW at rated speed, the main reduction gear is Royal Schelde cross connect gear box, that connects the gas turbines and diesel engine to port and starboard shaft lines driving two Escher Wyss controllable, reversible-pitch propellers (see Figure 1). This propulsion system configuration offers various driving modes. Refer to Table 1. These different modes influence propulsion fuel consumption, with multiple options often available for achieving the same speed (Schreiner, 2021).

The potential sources of data required to build fuel consumption models include engine shop trials, ship sea trials, and historical data collected by the onboard Integrated Platform Management System (IPMS) also known as Supervisory Control and Data Acquisition (SCADA) System (Brown, 2007, Mandler, 2000).

The shop trial data, carried out by the Original Equipment Manufacturer (OEM) may not perfectly reflect the fuel efficiency of the engine when operated on a specific ship in real-world circumstances. This discrepancy can

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Author's Biography
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arise due to differences in operating conditions, ship-specific factors, and limited representation inherent in the testing program.

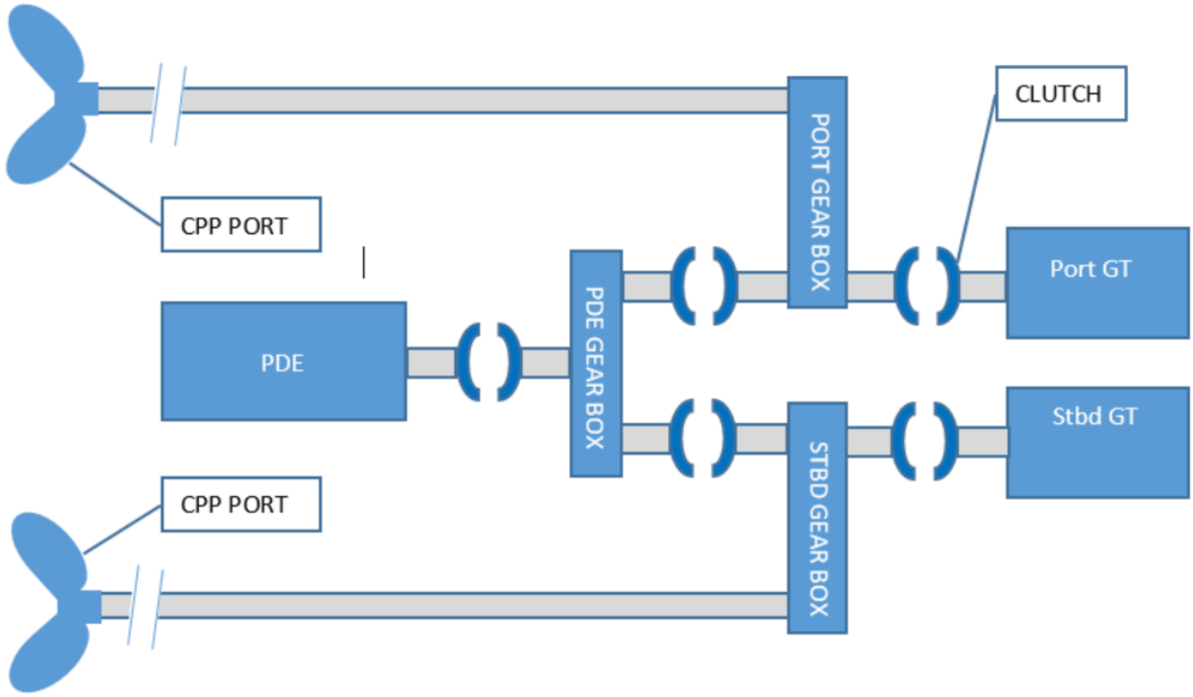


Figure 1 Halifax Class Frigate principal drivetrain diagram

Table 1 Halifax Class Frigates CODOG driving modes

Driving mode	**Name**	**Description**
PDE XCON	Propulsion diesel engine cross connected	PDE connected to both propeller shafts
PDE PORT	Propulsion diesel engine unitized (Port side)	PDE connected to Port side propeller shaft, Stbd propeller shaft either locked or trailing
PDE STBD	Propulsion diesel engine unitized (Stbd side)	PDE connected to Stbd side propeller shaft, Port propeller shaft either locked or trailing
PGT UNI	Ports Gas Turbine unitized (Port side)	PGT connected to Port side propeller shaft, Stbd propeller shaft either locked or trailing
SGT UNI	Stbd Gas Turbine unitized (Stbd side)	SGT connected to Stbd side propeller shaft, Port propeller shaft either locked or trailing
PGT XCON	Ports Gas Turbine cross connected	PGT connected to both propeller shafts
SGT XCON	Stbd Gas Turbine cross connected	SGT connected to both propeller shafts
TWO GT XCON	Two gas turbines cross connected	Both gas turbines connected to both propeller shafts. Both drive both shafts
TWO GT UNI	Two gas turbines cross connected	Both gas turbines connected to both propeller shafts. Each drives its shaft

While sea trial data can provide a rough estimate of fuel consumption, the actual fuel usage of a ship may deviate from predictions based on such data. Normal wear and tear on the ship and its equipment, which sometimes cannot be fully restored to "as new" condition through repair and maintenance, can affect actual fuel consumption, making sea trial data less reliable for estimating actual fuel usage.

More up to date fuel consumption models for each driving mode can be developed using data collected by IPMS integrated sensors while the ship is sailing. Ideally, data collection should commence immediately after the ship leaves dry-dock, where hull cleaning, painting, propeller blade repair, and propulsion equipment overhaul typically occur. These models reflect the optimal fuel efficiency achievable under ideal conditions and serve as benchmarks for comparing actual fuel efficiency in the future.

This paper pertains to a study initiated in 2020 with the objective of assessing the feasibility of utilizing the equipment operational data generated by the IPMS to construct fuel consumption models for power generating and propulsion equipment. The study also incorporates data from temporary fuel flow meters installed on the related equipment on board of several Halifax Class frigates. The aim was to develop fuel efficiency models for selected equipment, which will subsequently be utilized in FMD.

For this purpose, the data from both sources was consolidated, cleaned and analyzed using Machine Learning (ML) methods.

Fuel consumption models were built for diesel generators and all driving modes that were represented in consolidated data. For driving modes that were not adequately represented in the available flow meter data, the models were generated using the IPMS Onboard Training System (OBTS) simulator.

Based on the fuel consumption models, it was possible to pinpoint the most fuel-efficient driving mode depending on the ship speed order. Related recommendations along with supporting information were shown in the FMD. Along with displaying actual fuel consumption information, obtained from IPMS integrated sensors, several fuel consumption optimization features and techniques that analyze fuel consumption reduction from various perspectives have been designed.

The FMD with fuel consumption models at their core will be deployed on board of one of the Halifax Class Frigates in the year 2024. Upon completion of the trial period, FMD generated data will be analyzed and the performance of fuel consumption models will be accessed against recognized quality metrics.

2. Problem analysis

Fuel cost and ship's endurance are critical factors in naval ship operations. Efficient fuel management is essential not only to minimize operational expenses but also to enhance endurance, which directly translates into a strategic military advantage. Optimizing fuel efficiency can extend a ship’s operational range and duration, providing greater tactical flexibility and effectiveness during missions.

However, achieving optimal fuel efficiency presents several challenges. Diverse mission requirements often restrict flexibility in adjusting factors such as ship speed. Monitoring tools for fuel efficiency are typically basic and lack comprehensive consideration of all influencing factors. Additionally, fuel usage data is often fragmented and requires integration from disparate sources, such as fuel flow meters and IPMS systems.

3. Objectives

The long-term goal is to facilitate an effective continuous ship fuel efficiency monitoring.

The main objectives of the study were to:

1. Examine the factors affecting ship fuel consumption, such as speed, driving mode, weather, draft, trim, hull, and propeller condition, and assess their availability within Halifax Class frigates’ IPMS data.
2. Develop fuel consumption models for onboard power generating and propulsion equipment for each driving mode.
3. Identify the most fuel-efficient driving mode among the options available for specific operational conditions.
4. Develop tools for continuous fuel efficiency monitoring, implemented through interactive dashboards
5. Develop fuel consumption optimization algorithms that account for multifaceted factors influencing fuel consumption.

A derived objective was to provide various stakeholders, ashore and onboard, information about the fuel efficiency via adapted fuel management dashboards.

4. Hypotheses

Integration of fuel flow meter data with IPMS data enables the development of accurate fuel consumption prediction models for various ship driving modes. Furthermore, implementing fuel consumption optimization techniques based on these models can lead to significant improvements in fuel efficiency, increased endurance and cost savings for navy operations.

5. Limitations

Given that the permanent fuel flow sensors are unavailable, the fuel consumption models will need to utilize data from temporarily installed isolated fuel flow meters. The flow meter data (collected from four frigates) may not necessarily correspond to occasions when the selected ships had just left dry-dock. Consequently, the resulting models may not accurately represent the best achievable performance in terms of fuel efficiency.

It was noted that some equipment was not used during the data collection period. Furthermore, only one of the ships that participated in the study was equipped with the newer diesel generators at the time of data collection. Other ships in the study were still operating with the original engines. Diesel generator flow meter data was mostly limited to loads ranging from 300-650 kilowatts (kW) in spite of a 950 kW rating (see Figure 2).

The analysis of power plant load structure and methods to reduce it is beyond the scope of this study. The total DG load is used to calculate the related fuel consumption, which is then added to the total ship fuel consumption for endurance and range calculations.

Additionally, certain driving modes (PGT UNI, TWO GT UNI, and PDE UNI) were not adequately represented, which means that related models may lack accuracy.

Sufficient data representing PDE is available for only one ship. It is worth noting a phenomenon of lower-than-OEM-declared specific fuel consumption that was observed at partial PDE loads across all PDE data.

To standardize models across the fleet, navigational sensor data reflecting weather conditions was excluded from the analysis. Instead, indirect indicators reflecting sea state were used as substitutes during this phase.

6. Methods

6.1. Data collection and processing methods.

In this work, the following equipment was selected for fuel efficiency study: Diesel Generators (DG), Propulsion Diesel Engine (PDE) and Gas Turbines (GT).

There are two major sources of data utilized in the study. The data related to above equipment produced by IPMS integrated instrumentation and recorded by its EHM module is the first major source. The on-board EHM monitors and records any data or processed information pertaining to the on-board machinery equipment monitored/controlled by the IPMS. EHM data contains the following information: time stamp, sensor Identification Number (ID), sensor status, sensor value.

The second large source of data came from fuel flow meters that were temporarily installed onboard selected ships to gather fuel flow information from the equipment identified above. The fuel flow meter data consists of the fuel flow history recorded on the local sensors and collected at periodic intervals. Depending on the ship, the dataset covers the data from several months to several years of ship operations.

The fuel flow meter data contains the following fields: time stamp, fuel temperature, fuel supply and fuel return flow meter values. The data update frequency is equal to one minute.

The data from both sources was merged based on time stamp and resampled by one minute.

The operational modes that were underrepresented in the dataset were appended to ensure they are not mistakenly treated as outliers during the outliers' removal process.

The resulted data was cleaned from outliers using One Class SVM (Support Vector Machine) method, which is a ML technique for detecting outliers by learning the normal behavior of a dataset and identifying instances that deviate significantly.

The following filters were used for process transients' removal: limiting the difference between targeted and achieved values of the propellers pitch, propeller shafts speed, gas turbine load (PLA) level of fluctuations, change of driving mode and ship speed order.

6.2. Diesel generators (DG)

The following ML algorithms were used to build DG fuel consumption models: Least Absolute Shrinkage and Selection Operator (LASSO), k-Nearest Neighbors (kNN), Random Forest and Linear Regression as initial approach to the problem. The following model features were selected for preliminary analysis:

1. Engine power, (kW)
2. Sea water temperature
3. Intake Manifold Temperature
4. Engine Speed
5. Power Factor
6. Engine Running Hours
7. Exhaust Manifolds Temperature
8. Crankcase Pressure
9. Ambient Air Temperature
10. Engine power, kW.

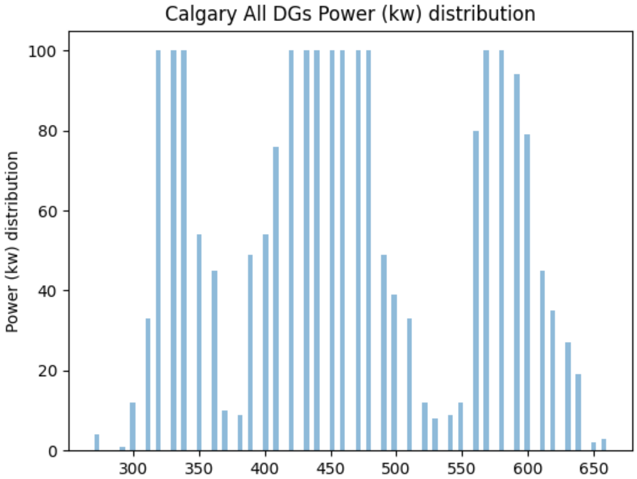


Figure 2 DG load distribution

To estimate the accuracy of the model, its R^2 (R- Squared) measure was used. R^2 is a statistical measure that represents the proportion of the variance of the dependent variable that is predictable from the independent variables.

The model R^2 results under testing are as follows:

1. LASSO: 0.9
2. kNN: 0.98
3. Random Forest: 0.97
4. Linear regression based solely on kW power input: 0.94

A simplified Linear Regression model based solely on kW power as the input was explored. This simpler approach maintained a high R-squared value (0.94), indicating only a minimal unexplained variance when compared to the best but more complex model utilizing multiple inputs (kNN: 0.98). The robust R-squared test results validate the accuracy of the model, justifying its selection as the final choice.

6.3 Gas Turbines (GT)

Flow meter data was available for the following driving modes: SGT XCON, PGT XCON, and TWO XCON. For TWO UNI driving mode the data set is sparse and noisy, especially when the ship speed is above 20 knots and as a result, the prediction may have a low accuracy. The SGT/PGT UNI dataset covers a narrow span of speeds.

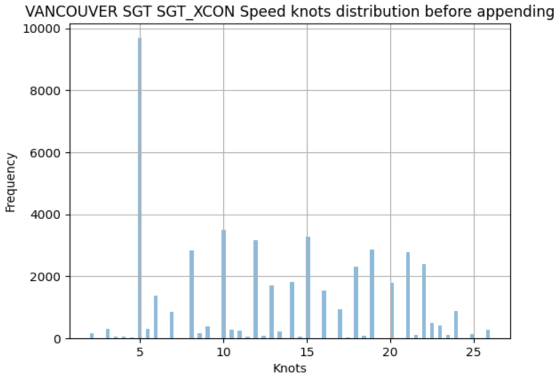


Figure 3 SGT XCON speed distribution

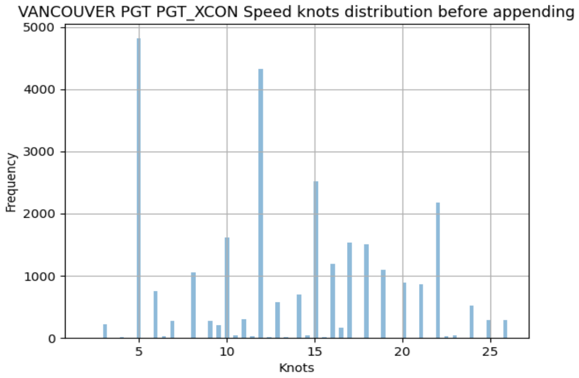


Figure 4 PGT XCON speed distribution

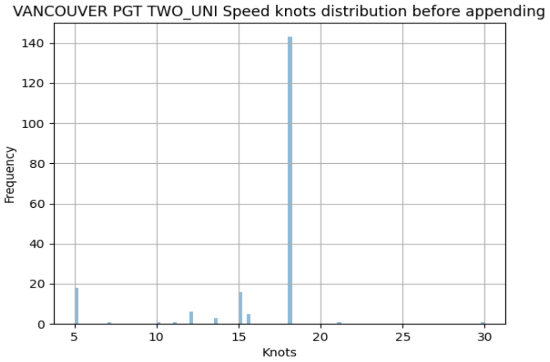


Figure 5 TWO UNI speed distribution

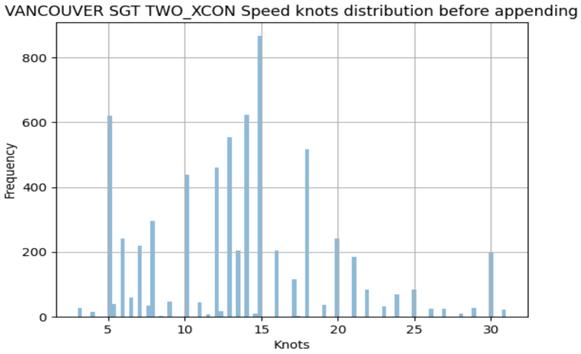


Figure 6 TWO XCON speed distribution

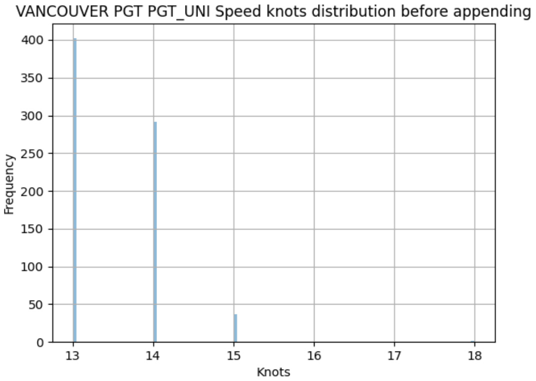


Figure 7 PGT UNI speed distribution

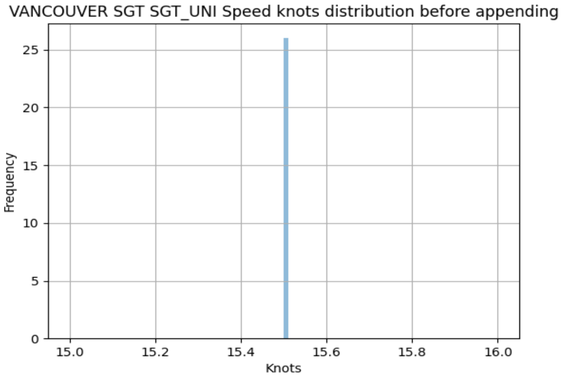


Figure 8 SGT UNI speed distribution

Figures 3 to 8 show the distribution of GT data depending on the driving mode and selected speed and provide an insight for the most frequently used speeds.

The following model features were selected for preliminary analysis:

1. Ship speed
2. Sea water temperature
3. Sea state (engineered feature, combining steering gear rudder angle dynamics and propeller shaft speed fluctuations)

The analysis highlighted inconsistencies of the impact of sea state feature and sea temperature on fuel consumption across different GT and operational modes. Consequently, the final model opts for ship speed as the independent variable, ensuring greater reliability and consistency in predictions. Polynomial Regression was used to build GTs fuel consumption models due to its easier interpretability for the engineers onboard.

PGT UNI and SGT UNI driving modes are represented just by three and one unique speed values accordingly. The method using adjustment of outliers' removal filter and following OBTS simulation was used to generate the model for these modes.

6.4 PDE (Propulsion Diesel Engine)

Flow meter data is available for PDE XCON driving mode (see Figure 9). EHM and flow meter data covering PDE UNI (Port or Stbd) driving mode is not available. SVM and Polynomial regression ML algorithms were initially used for this study. Similarly to GTs, there was no clear evidence confirming a strong correlation between sea states (indirectly derived), sea temperature and fuel consumption in the observed data. Consequently, these features were discarded.

Since both SVM and Polynomial Regression algorithms demonstrated relatively similar performance, Polynomial Regression was chosen for further study and ship speed was selected as the only input model parameter. Upon analyzing the fuel consumption predictions at lower ship speed settings, it was observed that for two out of three ships that participated in the study, the predicted Specific Fuel Consumption (SFC) values were significantly lower than that documented by OEM in the engine shop trial report. This discrepancy is highly improbable, as the fuel efficiency typically peaks when the engine is new and gradually diminishes when accumulating running hours.

Considering the lower-than-expected predicted PDE fuel consumption at lower ship speeds for the majority of participating ships, an OEM-based fuel consumption model with ship speed as the input signal was selected as the final model.

Due to the lack of available data for the PDE unitized driving modes, the model was generated by combining capabilities of the IPMS OBTS simulation module and PDE XCON fuel consumption model.

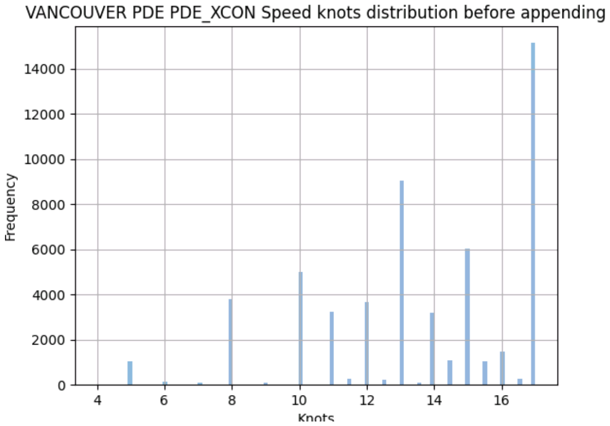


Figure 9 PDE XCON speed distribution

7. Results

Using the methods described above, it was found that the information provided by the IPMS sensors and temporary fuel flow meters was sufficient for building the fuel consumption models for the most frequently used driving modes.

Less frequent driving modes such as unitized modes were not appropriately represented in the data. In order to build their fuel consumption models, the capabilities of OBTS and its physics-based models were utilized.

The most fuel-efficient mode depends on the selected equipment and speed.

TWO UNI and TWO XCON GT modes are similar. The differences may be attributed to different losses in the main gearboxes. The difference between PGT XCON and SGT XCON modes may reflect the actual state of GTs onboard of a selected ship and different losses in the gearbox. In addition, the noise in the data could be a contributing factor. PGT UNI and SGT UNI models are identical since they were both built based on data produced by HMCS Vancouver with help of OBTS. PDE PORT and PDE STBD models are identical as well, as they were also based on the OBTS simulator.

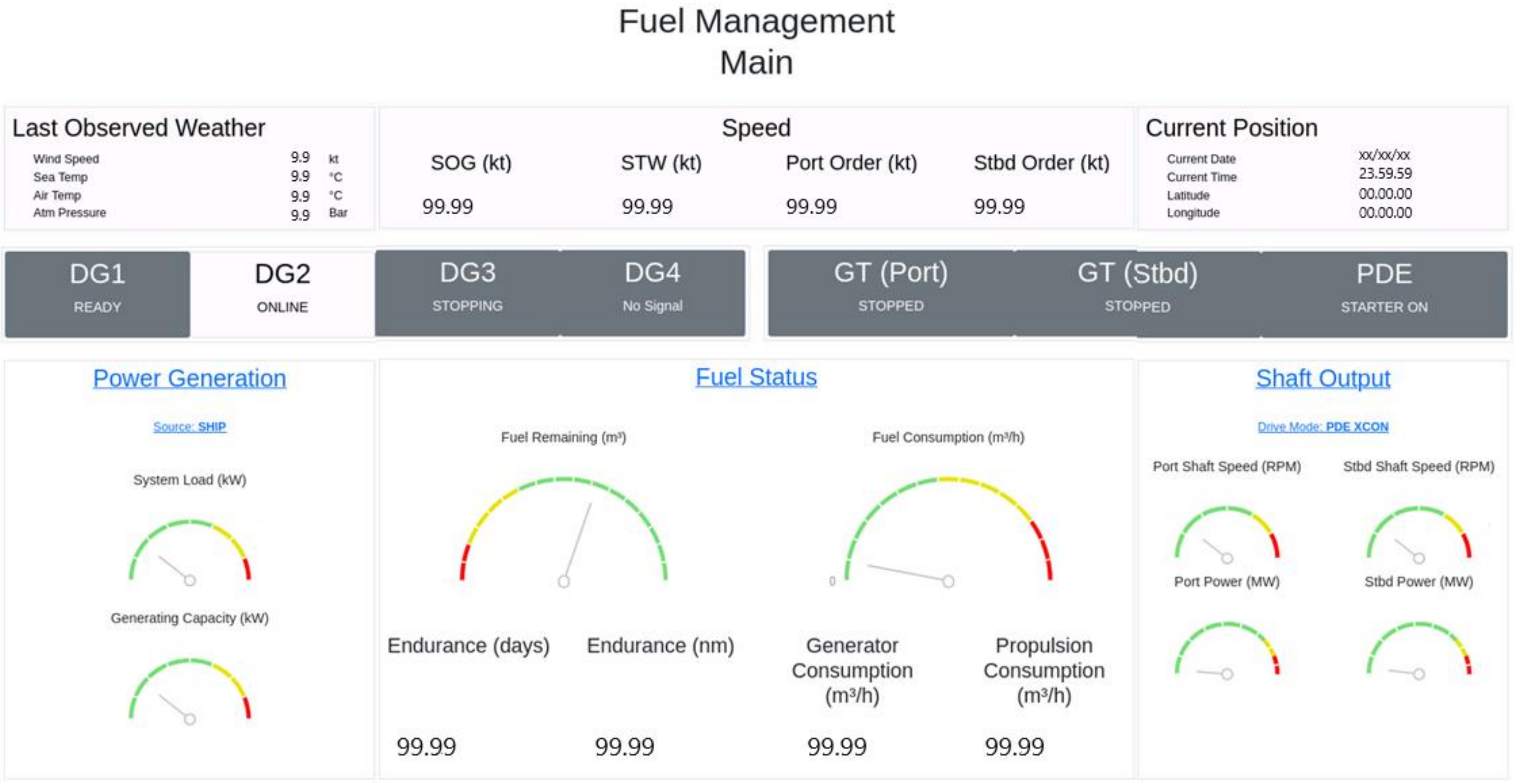
Using the fuel consumption models described above, the following methods of ship fuel efficiency monitoring and optimization have been developed and integrated into Fuel Management Dashboards.

7.1. Ship Endurance and Range

The endurance estimation feature allows calculating the maximum time at sea given the sequence of driving modes, corresponding speeds and fuel safety margin as well as the estimated diesel generators load defined by the user. A ship's range value is derived from the endurance calculations (see Figure 10).

7.2. Voyage Planning

This feature enables the calculation of the Fuel Remaining Onboard (ROB) upon arrival from a specific voyage. Users can define the ports of departure and arrival, precise ship route, expected speed at different route segments, as well as specifying different modes of operation. This feature assists in estimating when the ship needs to be refueled (see Figure 11).



Fuel Management
Main

Last Observed Weather

Wind Speed	9.9	kt
Sea Temp	9.9	°C
Air Temp	9.9	°C
Atm Pressure	9.9	Bar

Speed

SOG (kt)	STW (kt)	Port Order (kt)	Stbd Order (kt)
99.99	99.99	99.99	99.99

Current Position

Current Date	xx/xx/xx
Current Time	23.59.59
Latitude	00.00.00
Longitude	00.00.00

DG1	DG2	DG3	DG4	GT (Port)	GT (Stbd)	PDE
READY	ONLINE	STOPPING	No Signal	STOPPED	STOPPED	STARTER ON

Power Generation

Source: **SHIP**

Fuel Status

Shaft Output

Drive Mode: **PDE XCON**

Endurance (days)	Endurance (nm)	Generator Consumption (m³/h)	Propulsion Consumption (m³/h)
99.99	99.99	99.99	99.99

Figure 10 Fuel Management Dashboard Endurance

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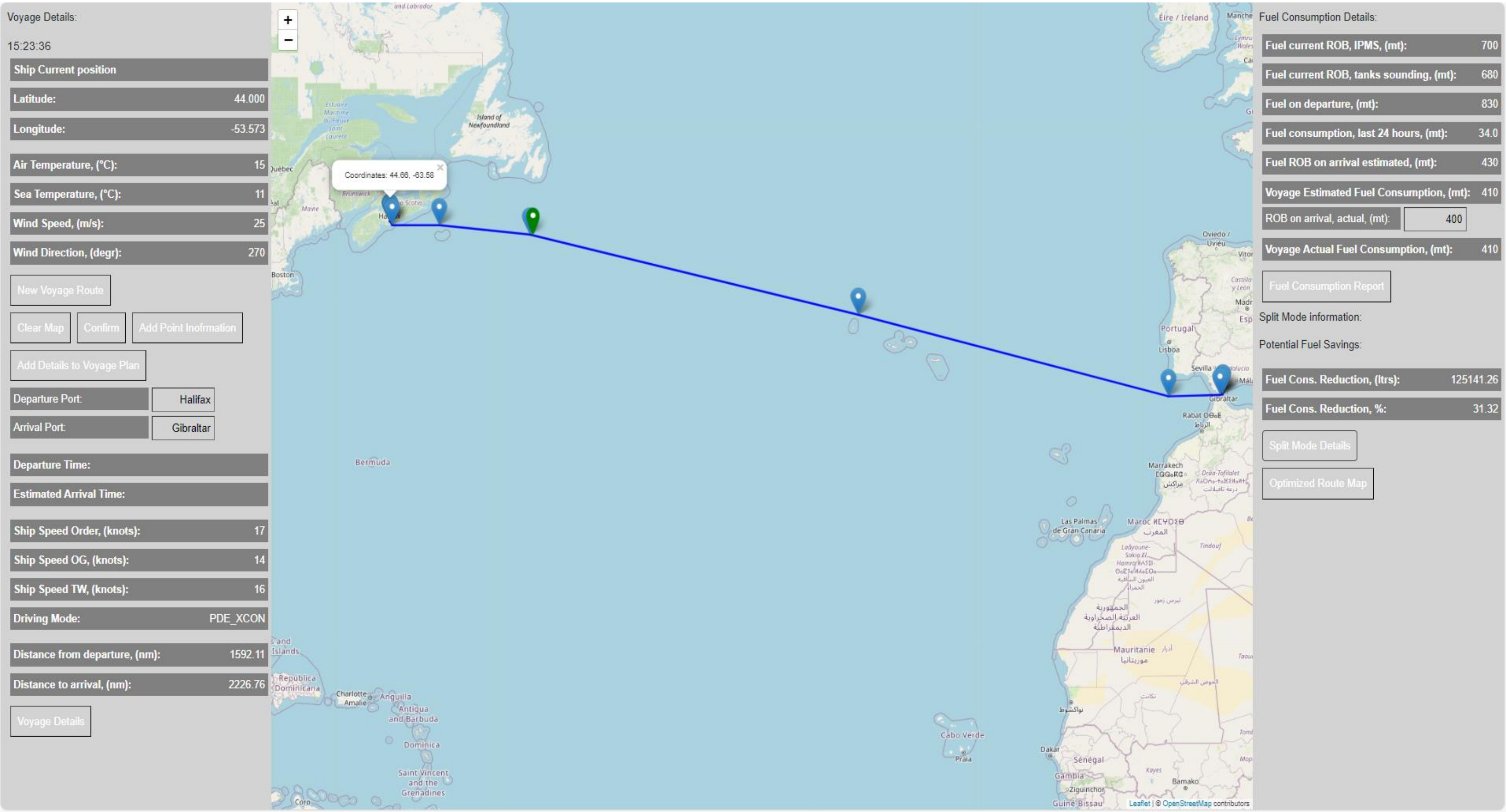

Voyage Details:

15:23:36

Ship Current position

Latitude:	44.000
Longitude:	-53.573
Air Temperature, (°C):	15
Sea Temperature, (°C):	11
Wind Speed, (m/s):	25
Wind Direction, (degr):	270
Departure Port:	Halifax
Arrival Port:	Gibraltar
Departure Time:	
Estimated Arrival Time:	
Ship Speed Order, (knots):	17
Ship Speed OG, (knots):	14
Ship Speed TW, (knots):	16
Driving Mode:	PDE_XCON
Distance from departure, (nm):	1592.11
Distance to arrival, (nm):	2226.76

Fuel Consumption Details:

Fuel current ROB, IPMS, (mt):	700
Fuel current ROB, tanks sounding, (mt):	680
Fuel on departure, (mt):	830
Fuel consumption, last 24 hours, (mt):	34.0
Fuel ROB on arrival estimated, (mt):	430
Voyage Estimated Fuel Consumption, (mt):	410
ROB on arrival, actual, (mt):	400
Voyage Actual Fuel Consumption, (mt):	410

Split Mode information:

Potential Fuel Savings:

Fuel Cons. Reduction, (ltrs):	125141.26
Fuel Cons. Reduction, %:	31.32

Figure 11 Voyage Planning page view

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7.3. Sea Passage Time optimization

This technique allows minimizing the overall operating costs of the ship by optimizing its speed while underway, with fuel consumption models developed in this study at its core. This adjustment effectively manages the time taken to reach the port of destination. This optimization method can use various inputs, including selected driving mode and initial speed, fuel cost, crew cost underway and in port, port charges, etc.

Sea Passage Time Optimization Case

Conditions

- Ship is underway to port of destination with PDE driving @ **17 knots** on PDE XCON
- Distance to destination - 400 nautical miles
- Dock availability window - 7 days
- Fuel Cost - 940 $/metric ton
- Crew details: 180 persons is on board.
- Average annual salary - 75 k$.
- Time required to complete planned port tasks - 4 days
- The latest time of arrival is 24 hour after initial ETA.

Cost of ship underway is defined in this calculation by the following factors:

- Fuel cost
- Crew cost (head count, salary, load factor)
- Maintenance – 2 k$/day

Cost of ship in port is defined by the following factors:

- Fuel cost
- Crew cost (head count, salary, load factor)
- Port charges – 50 k$/day
- Maintenance – 1.5 k$/day

Optimization results:

- Recommended Speed: **16 knots**
- Recommended driving mode: PDE XCON
- The new Estimated Time of Arrival (ETA) is **1.47** hours later than the initial.
- Potential savings: **5.2 k$**

Figure 12 Sea Passage Time Optimization

The outputs of this algorithm are the new recommended speed underway, the driving mode, and the updated Estimated Time of Arrival (ETA), which correspond to the minimal ship running cost and potential cost savings if these recommendations are followed.

Figure 12 shows the application of this method using a representation with hypothetical ship technical details and cost data. The optimization task is to find the best balance between the time underway and the duration of stay in port, which is affected by the difference in hourly ship costs underway and in port. As can be seen, the optimization algorithm recommended reducing sea passage speed to 16 knots. The amount of potential savings depends on the input variables, such as the number of crew onboard. The list of input variables can be further refined, and actual data will be used once this dashboard function is deployed.

7.4. Mixed Mode Plant Operation

The objective of this feature is to reduce the fuel consumption by selecting an optimal sequence of driving modes and speeds. Mixed Mode Plant Operation optimizes fuel consumption by blending different driving modes and speeds while maintaining the scheduled arrival time (Brown, 2007). It leverages varying fuel consumption rates across different driving modes. The output of this method is the sequence of driving modes and speeds that guarantee a minimum fuel consumption during the sea passage. Figure 13 (not based on actual data) illustrates the concept of Mixed Mode Plant.

Figure 14 displays the results of Mixed Mode Plant Operation optimization for a ship trip from Halifax to Gibraltar. Time of arrival dictates a sea passage speed of 19 knots. Preliminary selected drive mode is PGT XCON.

As the result, the algorithm recommended splitting the sea passage between two driving modes:

1. PDE XCON with speed of 17 knots and
2. PGT XCON with speed of 23.35 knots.

In this case, resulting fuel consumption reduction would correspond to a 13.3% of fuel economy. Time underway and estimated time of arrival (ETA) remain unaffected.

The software automatically adds the new waypoint, indicating the location where the transition from the first driving mode to the second one should occur (see Figure 15).

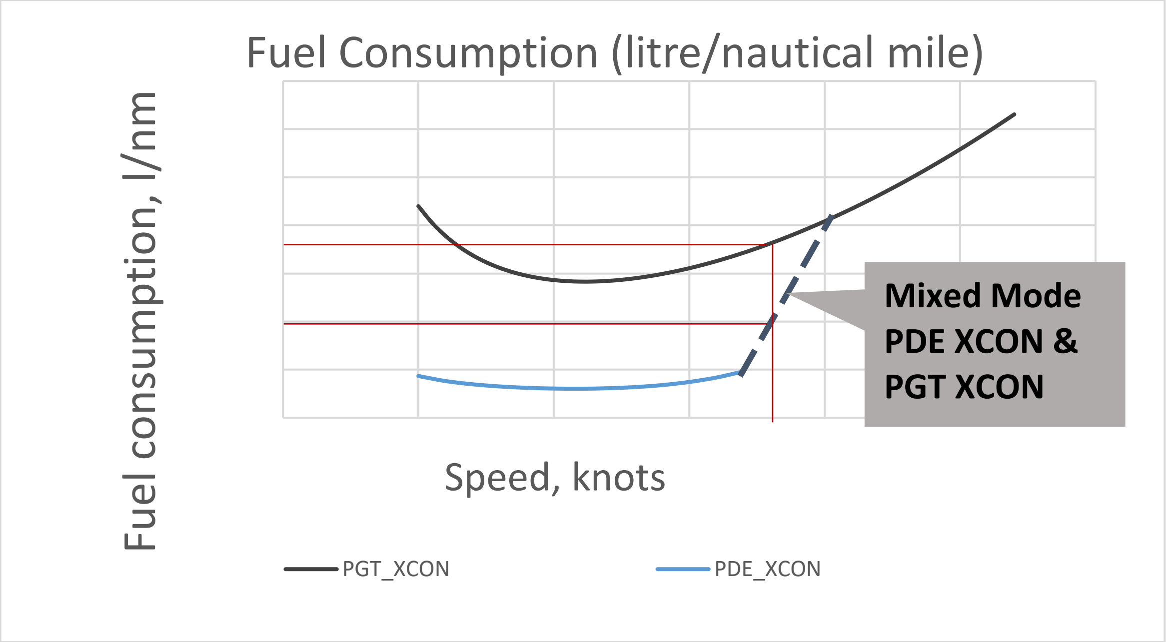


Figure 13 Mixed Mode Plant

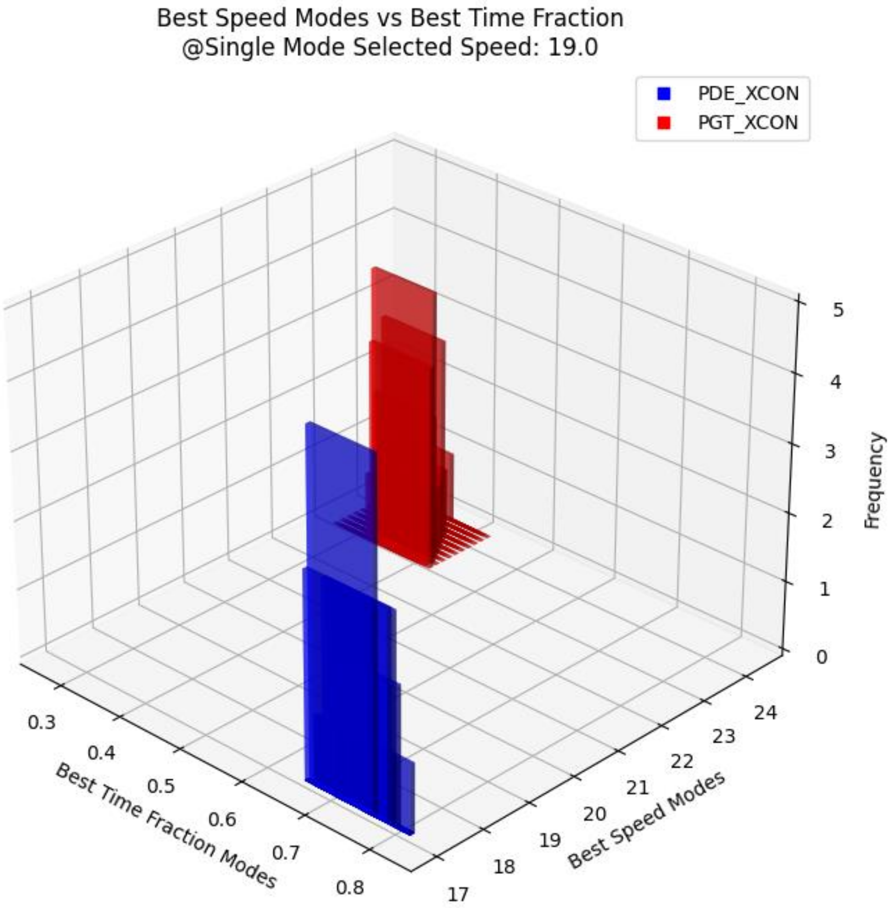
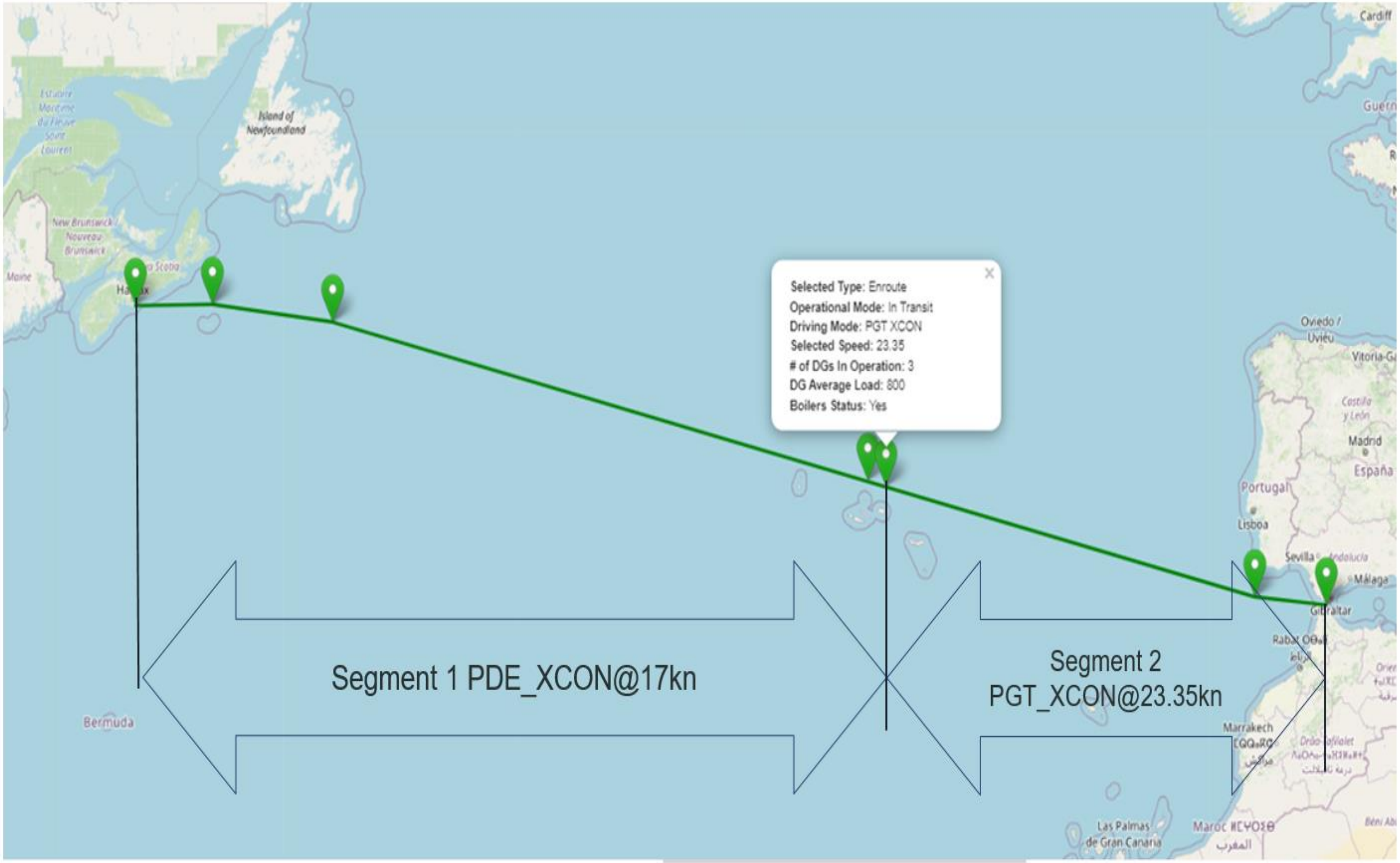


Figure 14 Recommended Mixed Mode Plant configuration



Selected Type: Enroute
Operational Mode: In Transit
Driving Mode: PGT XCON
Selected Speed: 23.35
# of DGs In Operation: 3
DG Average Load: 800
Boilers Status: Yes

Figure 15 Mixed Mode Plant page view

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7.5. *Propeller Slip Monitoring Feature*

The Propeller Slip Monitoring dashboard feature provides frequent automatic propeller slip measurements and compares them with the slip baseline model built using historical data collected by IPMS/EHM versus traditional propeller slip calculations based on the ship and propeller design data. Figure 16 illustrates the propeller slip concept.

A large amount of historical data captured by EHM allows building propeller slip baselines based on the actual data rather than the design data. A baseline of propeller slip can be built by analyzing related EHM data obtained immediately after the ship left dry-dock, or following underwater hull clean up, or propeller repair or blades polishing.

High propeller slip suggests deterioration of hull or propeller conditions, which can impact fuel consumption, and decrease propulsion efficiency (Schreiner, 2021). This feature offers advantages such as reduced fuel costs due to propeller condition monitoring, fewer diving inspections, and enhanced timing for underwater propeller/hull cleaning. Figure 17 visualizes ship speed with respect to propeller shaft speed and propeller pitch.

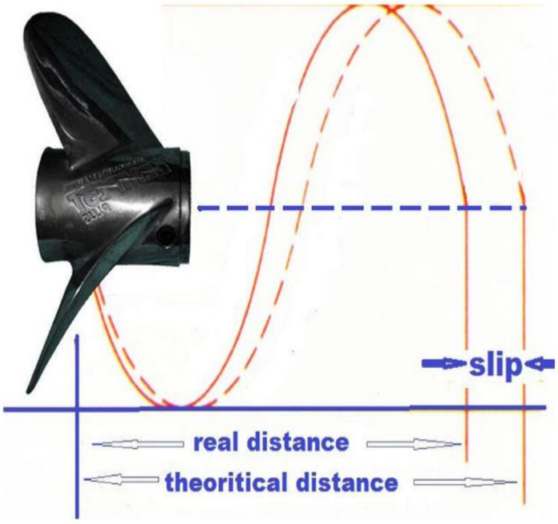

Figure 16 Propeller Slip concept

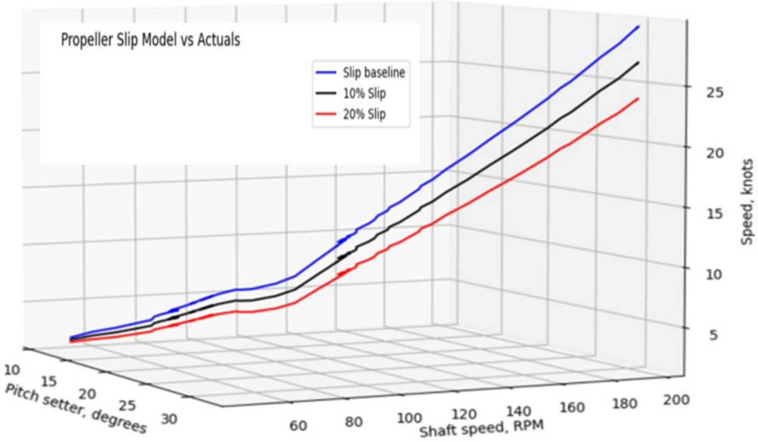

Figure 17 Speed as a function of Propeller Shaft Speed and Propeller Pitch

8. Discussion

The result of this study indicates that IPMS and fuel flow meter data contain the necessary information to construct models for the most commonly used driving modes for targeted power generation and propulsion equipment. The most fuel-efficient mode for every speed was determined.

As expected PDE in cross-connected mode facilitates the most fuel-efficient operation when the ship speed is in the range of 8 to 18 knots, whereas as observed in the simulations, PDE in unitized mode provides the best fuel efficiency when the speed is below 8 knots (although this needs to be substantiated with data, when it becomes available). If the speed exceeds 18 knots, using mixed modes (Refer to **Error! Reference source not found.**) over the transit, meaning different speeds at different time involving PDE XCON and either turbine in cross-connected mode or two turbines will facilitate an optimal fuel consumption. For the speeds in the range of 26-31 knots, the combination of single cross-connected GT and double gas turbines running in unitized or cross-connected mode may be the best scenario.

PDE fuel flow meter data related to mid to high PDE loads demonstrates similarity with OEM provided sea trial report. At the same time, fuel flow meter data related to partial loads was lower than declared by OEM for the same load. Therefore, the model based on flow meters was substituted by an OEM-based model.

The fuel consumption models developed in this project enabled the creation of features for estimating and optimizing fuel consumption from various perspectives. They also support voyage planning, refueling scheduling, and maintenance and inspection planning. Paired with live operational data, and a user-friendly interface of the fuel dashboard, these features enhance situational awareness and provide valuable assistance to the crew onboard.

9. Conclusion

In general, the objectives of this study were achieved. During the course of this study, the data was analyzed and fuel prediction models for all driving modes were developed. As a result, the most efficient driving modes and corresponding speeds were identified. This information is presented in the Fuel Management Dashboards and can be used to help selecting the best driving mode while taking into consideration operational requirements and constraints. It also helps to estimate the potential fuel savings when comparing the actual and optimal driving modes. From the data science point of view, this study has helped to streamline the process of consolidating data from diverse sources such as IPMS and isolated fuel flow meters. It has also facilitated research work aimed to apply various fuel optimization techniques to a specific ship platform.

Fuel Management Dashboards developed in this phase of the project provide a clear and informative snapshot of the ship's operational status with just a single glance. They lay the foundation for developing additional dashboard pages that can target specific aspects of fuel management and efficiency, both onboard and ashore.

To further develop and refine researchers' efforts, focus should be directed towards analyzing additional fuel flow meter data and enhancing existing fuel consumption models, particularly targeting modes that are underrepresented in the data available in this study.

Analyzing the power plant load structure and exploring methods to reduce it will be a valuable focus for the next phase of the research, offering potential improvements in overall fuel efficiency and operational effectiveness.

Following the deployment of the Halifax Class Fuel Management Dashboards, the subsequent step involves assessing the effectiveness and user-friendliness of the dashboards for the intended users. Potential enhancements of the fuel consumption models include incorporating environmental factors such as sea state and water temperature. As the indirect method employed to account for weather conditions proved unsatisfactory, exploring alternative methods could improve the accuracy of the consumption models.

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