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Assessment of Emission Reduction and Fuel Savings using Ship Speed Optimization in Realistic Weather Conditions

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ABSTRACT

In this work, our objective is to quantify emission reductions using speed optimization considering a realistic ship route and a broad range of weather conditions. Two representative bulk carriers have been selected for the analysis. An optimization algorithm has been used to minimize voyage fuel consumption while completing the voyage on or before the expected arrival time. A constraint on engine power has been used for realistic estimates of achievable ship speeds in different weather conditions considering the available engine power. Multiple voyages at different ship speeds and in different seasons have been simulated with and without speed optimization to observe the effect of these factors on emission reduction. The effect of wind and waves on engine power has been considered by calculating wind and wave resistance along with propeller efficiency as a function of advance coefficients.

Up to 11% reduction in fuel consumption was obtained by optimizing speed as compared to the constant speed profile. It was observed that a significant amount of fuel could be saved especially in seasons with a higher likelihood of heavy weather. Variation in fuel savings in different seasons has been discussed in the context of metocean conditions experienced in the selected months. Additionally, higher fuel savings were obtained for lower average ship speed which means speed reduction combined with speed optimization has greater potential to reduce emissions. Realistic estimates of fuel savings in a range of operating conditions presented in this paper would help ship owners, operators, and policymakers to assess the benefits of speed optimization among other technologies to decarbonize the shipping industry.

Keywords: Speed optimization; Weather Routing; Emission Reduction; Vessel Performance; Carbon Intensity Indicator (CII).

1. INTRODUCTION

The shipping industry is facing a challenge of transitioning towards zero emissions, with multiple solutions proposed that range from short-term to long-term and require varying levels of additional infrastructure. These measures include design improvements, operational measures, and the use of clean fuels. Operational measures such as speed optimization require relatively low additional infrastructure, but their emission reductions are also relatively low.

Several authors have studied speed and voyage optimization using different objectives and methods (Yu et al., 2021). Relevant parameters affecting speed optimization were discussed by Psaraftis and

Table 1: Principal dimensions of the case vessels (Taskar and Andersen, 2020a)

Ship Name	Panamax	Capesize
Capacity	75,000 dwt	175,000 dwt
Length	220 m	280 m
Breadth	32.25 m	45 m
Design draft	12.2 m	16.5 m
Design Speed	14.6 knots	15 knots
Block coefficient	0.855	0.85
Propeller Diameter	6.81 m	8.39 m
MCR Power	11904 kw	18657 kW

Kontovas (2009). The objective of this work is to quantify emission reductions using speed optimization by considering a realistic ship route and a broad range of weather conditions. Only ship speeds at multiple points along the route are changed during the optimization process, while the route is kept fixed. This approach assesses long-term fuel savings and emission reductions by speed optimization, rather than calculating gains in selected cases. The analysis focuses on two bulk carriers, and the effect of wind and wave conditions on power consumption is modeled to estimate increased fuel consumption and emissions in rough weather conditions. Multiple voyages at different ship speeds and in different seasons are simulated, both with and without speed optimization, to observe the effect of these factors on emission reduction. A similar analysis was conducted by Taskar et al. (2023) for a couple of container ships. Selecting different ship types aims to investigate whether fuel savings using speed optimization depend on ship type. Bulk carriers typically operate at lower speeds than container ships, and there is a marked difference in the pattern of their resistance curves. The behavior of added wave resistance and the contribution of wave resistance to total resistance is likely to be different for the two ship types. Therefore, it is interesting to investigate how these differences affect the optimization procedure and final results.

2. METHODOLOGY

This section provides details about the vessels selected for the study and describes the simulation methodology used to perform voyage simulations under different weather conditions, as well as the various resistance components considered in the simulations. Additionally, we present an optimization algorithm for speed optimization, along with the details of objective functions and constraints.

2.1 Case Vessels

For this study, we selected a 75,000,dwt Panamax bulk carrier and a 175,000,dwt Capsize bulk carrier provided by Taskar and Andersen (2020a). These ship types carry maximum deadweight and are responsible for significant CO_2 emissions among bulk carrier segment (Psaraftis and Kontovas, 2009; MAN Diesel & Turbo, 2014). Detailed data about these ships are available in Taskar and Andersen (2020b). Table 1 presents the principal dimensions of the ships.

2.2 Problem Setup

The aim of the optimization is to minimize fuel consumption on a given voyage, while also ensuring that the ship reaches its destination port on time. To achieve this, a constraint on voyage time is necessary, as ships must arrive at their destination on schedule. Without this constraint, the optimization would always prefer longer voyage times, as lower ship speeds can significantly reduce fuel consumption.

Additionally, for a realistic speed profile, available engine power must be considered. The required engine power at a given speed and weather conditions should be less than or equal to the available engine power. Therefore, the optimization problem is a minimization problem with fuel consumption as the objective function, where ship speeds at multiple points along a route are the optimization variables. The constraints include the voyage time, which must be less than or equal to the specified time, and engine power, which must be less than or equal to the available engine power at each waypoint. More details about the optimization method can be found in Taskar et al. (2023).

The calculation of fuel consumption, required power, and voyage time for computing the objective function and constraints using ship speeds as variables is discussed in the following section.

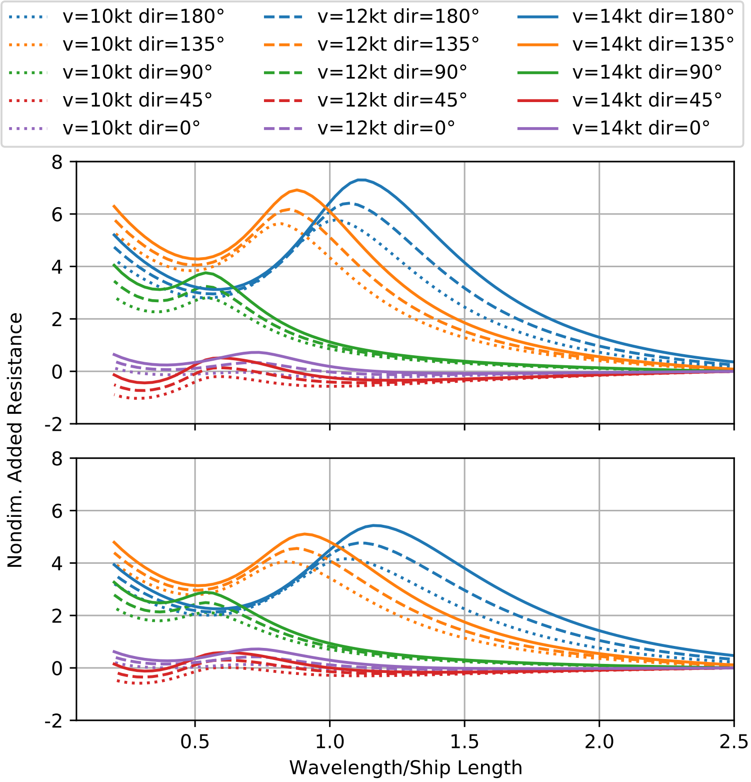

Figure 1: Added resistance RAOs for Capesize bulk carrier (top) and Panamax bulk carrier (bottom) at different speeds and wave headings.

2.3 Calculation of Fuel Consumption

To calculate the total resistance of the ships, three resistance components are considered: calm water resistance, wave added resistance, and wind resistance. Calm water resistance curves calculated by Taskar and Andersen (2020a) using Guldhammer and Harvald's method (Guldhammer and Harvald, 1974) updated by Kristensen and Bingham (2017) are used. The SNNM method (Liu et al., 2020) is used for the calculation of the frequency response of added resistance in different wave headings. The SNNM method computes added resistance transfer function for any ship speed and wave heading including stern quartering and following wave conditions. The frequency response of added resistance for both ships at different speeds and wave headings are presented in Figure 1. As reported by Taskar and Andersen (2021), frequency response function based methods can better predict added resistance.

The Bretschneider wave spectrum is used for the calculation of added wave resistance in irregular waves. Wind resistance coefficients for different wind directions obtained from Fujiwara et al. (2005) for fully loaded bulk carriers are used to compute wind resistance.

Using the ship speed and metocean conditions (wind and waves), the resistance components are obtained for all waypoints along the route. The corresponding propeller speed and shaft power are obtained using the open water curves for the respective propeller provided by Taskar and Andersen (2020a). The required power and travel time between different waypoints are used to estimate the total fuel consumption of the voyage, assuming a constant ship speed between the waypoints. The variation of engine fuel consumption at different loads is also taken into consideration using specific fuel consumption (SFOC) curves provided by Taskar and Andersen (2020b).

3. SIMULATIONS

This study aims to investigate possible fuel savings in a wide range of operating conditions. Therefore, simulations have been performed in four different months using hindcast metocean data for eastbound and westbound voyages at three average speeds. Simulations have been performed once for constant ship speed followed by optimized speed. Fuel consumption using constant ship speed is used as a benchmark to assess fuel savings using the optimization methodology.

3.1 Weather and Route

A transpacific route from the west coast of the United States to Japan has been chosen because metocean conditions vary significantly over a year in the Pacific ocean (Figure 2). Therefore, simulations could be performed on a realistic route in a wide variety of weather patterns. Moreover, this is also one of the busiest shipping lanes. Four different seasons have been selected for the simulations and metocean data from one respective month for each season is utilized. Here, wave reanalysis data has been derived from ERA5/ECMWF (Hersbach et al., 2020) for October 2021, January 2022, April 2022, and July 2022. The metocean data consists of wind speed, wind direction, significant wave height, mean wave period, and mean wave direction. In addition, we also analyzed wave spectral kurtosis which gives a statistical measure of extreme ocean waves (ECMWF-CY47R1, 2020).

Extreme metocean conditions are not uncommon in the North Pacific Ocean as it encounters a large number of tropical depressions and storms. Some of these storms lead to developing strong and violent typhoons in the Western North Pacific Ocean. The Eastern North Pacific Ocean also experiences tropical cyclones and hurricanes. According to the global climatology of tropical cyclones, the Western and Eastern North Pacific Oceans account for a total of 50% of all storms (Ramsay, 2017). In-situ and satellite altimeter-based observations of significant wave height reveal that storm-generated extreme waves can reach up to 20 m in the North Pacific Ocean. The shipping route selected here lies within this stormy region of the North Pacific where extreme sea states are common. As such, a ship operating on this route is expected to experience such extreme wave conditions. The spatial distributions of mean H_s, maximum H_s, and maximum kurtosis are shown here for October, January, April, and July (Figure 2). The mean $H_s > 4\,\mathrm{m}$ can be observed in the Eastern North Pacific during October (Figure 2a). The largest mean H_s in excess of 5 m is observed during January and most of the waypoints are located within the mean $H_s > 4\,\mathrm{m}$ (Figure 2b). The mean H_s remains smaller than 4 m during April, while it reduces further to below 3 m during April (Figure 2c,d). In order to demonstrate the severity of sea states in the North Pacific Ocean, the maximum of H_s is analyzed for different seasons (Figure 2e-h). The most important feature is the storm/typhoon generated extreme waves that reach almost 14 m. The storm tracks can be identified north and south of the shipping route

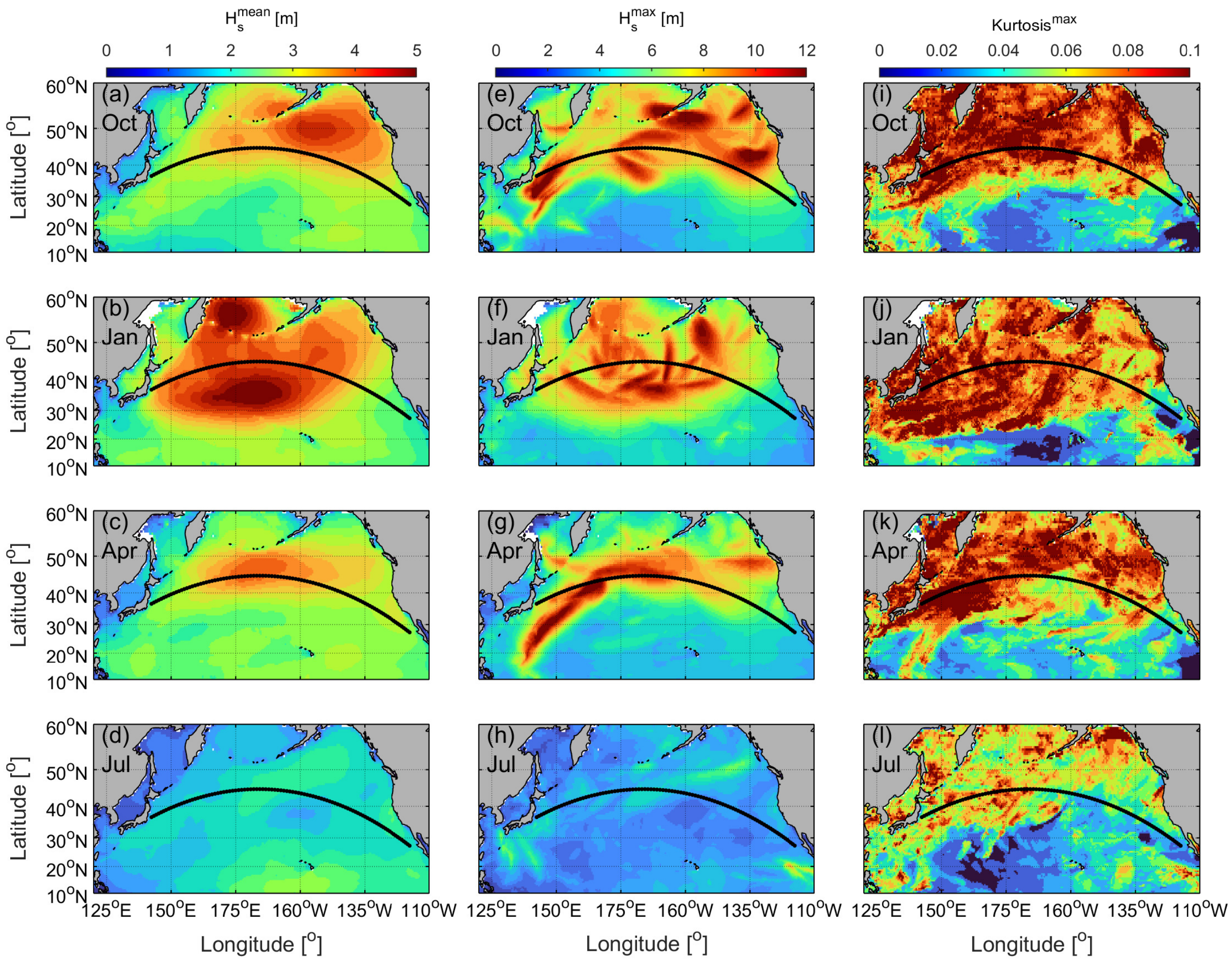

Figure 2: A shipping route between East Asia and North America is shown with the waypoints highlighted in black markers. Spatial distribution of H_s^{mean} (a-d), H_s^{max} (e-h), and kurtosis^{max} (i-l) are shown for four different seasons.

(e.g. Figure 2f). Most of the storm tracks are noted in January, whereas, no severe storm is identified in July (Figure 2f,h). Our analysis of the metocean data along the ship track reveals the strongest wind speed of 25 m/s and the highest wave height of 13 m H_s in April. However, in terms of the number of storm tracks, the month of January has experienced more storms across the shipping route compared to the other three months. In addition to maximum H_s, we also analyzed the maximum wave spectral kurtosis during four seasons (Figure 2i-l). A positive value of kurtosis indicates that extreme waves will occur more frequently. The spatial distribution of maximum kurtosis shows larger values in areas influenced by storms. For instance, the maximum kurtosis shows the largest values during January which also experienced more number of storms. A ship navigating along the selected route will encounter some of these storms and therefore storm-generated extreme waves (Figure 2f). The impacts of extreme metocean conditions on ship speed optimization and fuel saving are discussed.

Multiple voyages are simulated in each of the selected months. One voyage is started every day to obtain day-to-day variation in fuel-saving potential due to changing weather patterns. Note that the wind and wave conditions changes with location as well as time, therefore, the ship is likely to

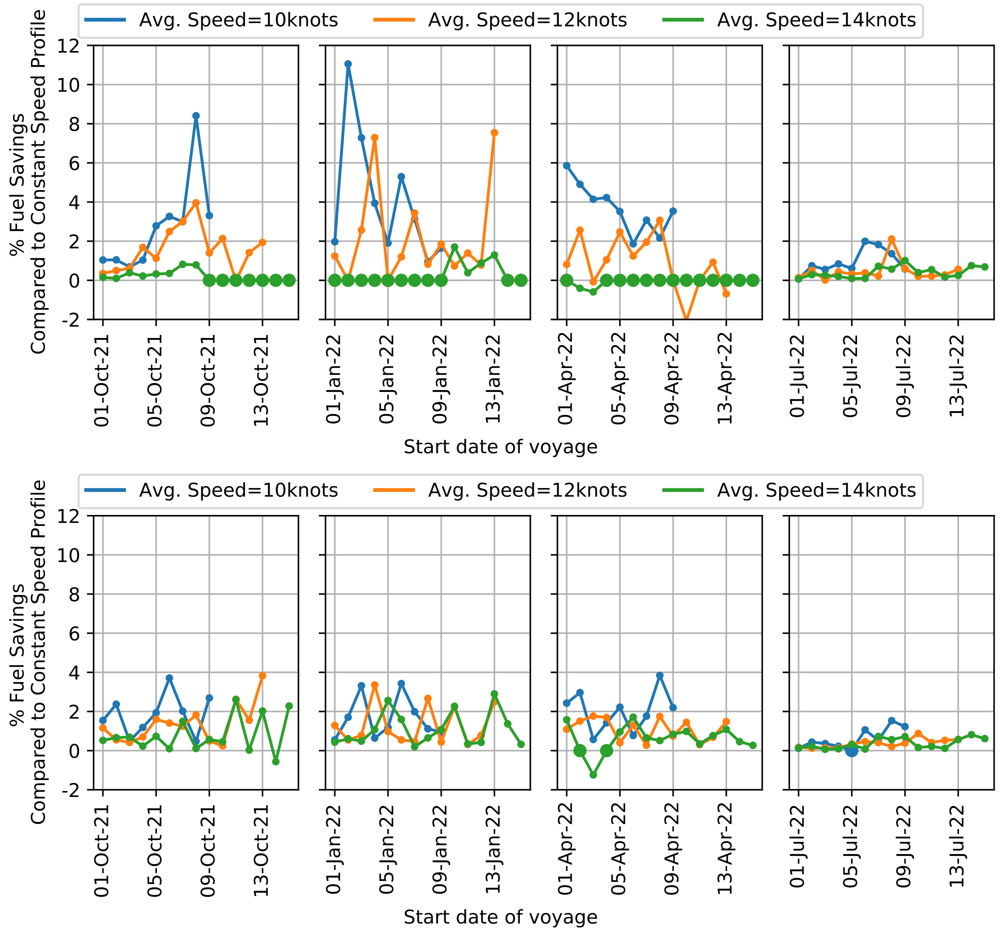

Figure 3: Fuel savings on westbound (top) and eastbound (bottom) voyages at different average speed and seasons for Capesize bulk carrier.

encounter different metocean conditions when the speed profile changes.

Simulations are performed with three average speeds, 10 knots, 12 knots, and 14 knots. Even though the speed can vary at different points along the route, the average speed is unaltered due to the constraint that voyage time should be less than or equal to the specified length of time. The voyage time used in the constraint is obtained considering these average speeds along the route. First, simulations are performed with constant speed along the route to calculate baseline fuel consumption for the voyage. The fuel consumption after the optimization is compared with the baseline to calculate fuel savings.

4. RESULTS AND DISCUSSION

Fuel consumption is affected by several factors, including ship speed, wind, and wave conditions. Ship speed has a significant impact on calm water resistance, wave added resistance, and wind resistance. Wind and wave resistance, in turn, are dependent on the prevailing wind and wave conditions. Furthermore, the speed profile of the ship indirectly affects wind and wave resistance. Changing the speed profile alters the encountered wind and wave conditions, resulting in changes in the corresponding resistance components. Therefore, reducing fuel consumption primarily involves minimizing wind and wave resistance by avoiding unfavorable metocean conditions through the selection of an appropriate

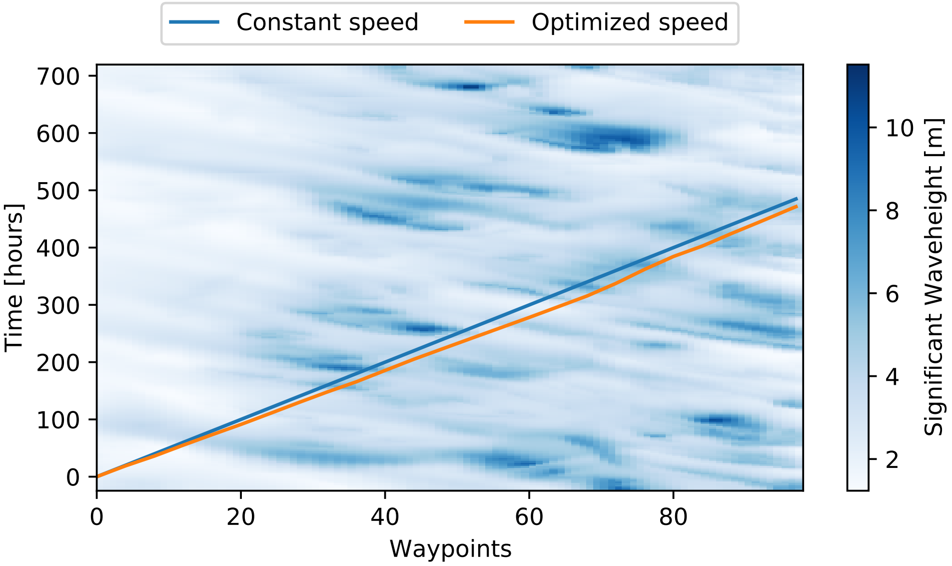

Figure 4: Evolving weather and route with fixed speed and optimized speed.

speed profile.

4.1 Capesize Bulk Carrier

Fuel savings by optimizing the ship speed profile for a range of operating conditions are plotted in Figure 3. The number of simulations in each month is dependent on the average ship speed. For simplicity of handling the data, one month of metocean data was used for each month, and only voyages which could be completed within a month were simulated. Since the voyages at a lower speed take longer time, fewer voyages could be considered. In some cases, the optimization algorithm is unable to find a speed profile that satisfies all the constraints i.e., engine limits and voyage time. These cases have been marked using larger dots on the x-axis. The likelihood of such cases is greater in heavy weather conditions because of higher power demand and limited onboard power. In a few cases like 10-Apr-22, a westbound voyage at 12 knots shows negative fuel savings. Here it is necessary to mention that constant speed profiles considered for the baseline may not satisfy the constraint of engine limits. Therefore, negative fuel saving means that the optimization algorithm is able to find a speed profile that satisfies all the constraints but the fuel consumption is greater than the baseline. The ship would have got delayed in the case of a fixed speed profile whereas the ship traveling at an optimized speed profile can reach the destination on time. Therefore, the optimization also helps to avoid delays due to rough weather conditions.

A significant seasonal variation can be observed in fuel savings using speed optimization. For westbound voyages, the maximum fuel savings of up to 11% are observed in January whereas savings are marginal in July. For eastbound voyages, savings are similar and relatively low throughout the year. It was found that fuel savings are likely to be higher in harsh weather conditions. Because fuel savings are obtained by avoiding rough weather. Whereas in relatively calm wind and wave conditions, calm water resistance is the most dominant resistance component hence there is limited scope to further reduce fuel consumption. It was observed that the ship encounters higher wind and waves from the head sea and bow quartering sea conditions on westbound voyages in Oct-21 and Jan-22, which are

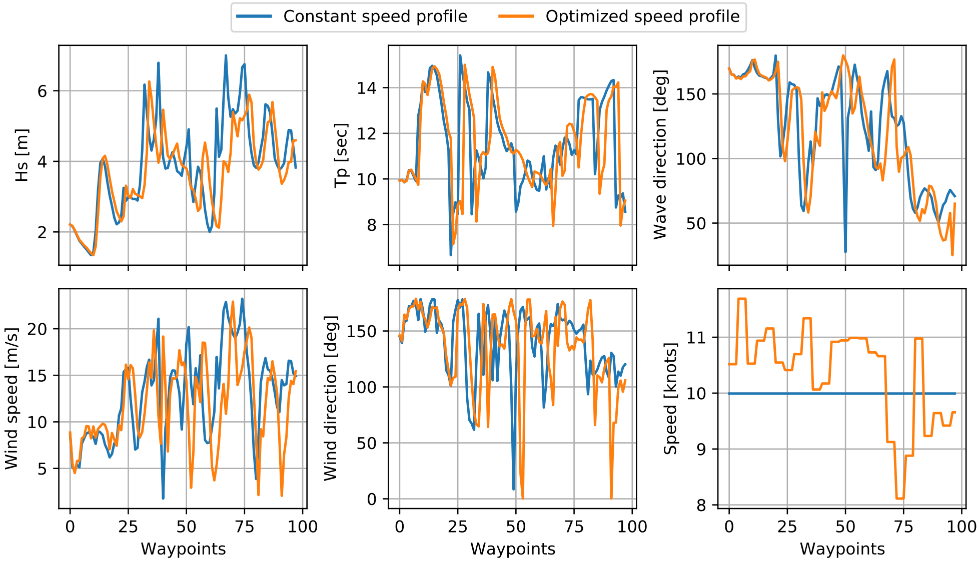

Figure 5: Encountered metocean conditions with fixed and optimized speed profile.

responsible for higher wind and wave resistance. Whereas for eastbound voyages wind and waves are mostly coming from directions other than head and bow quartering sea.

In addition to the seasonal trend, one can also observe that fuel savings are higher for lower average speeds both in eastbound and westbound voyages. Average savings are 2.2%, 1.3% and 0.7% for average speeds 10 knots, 12 knots and 14 knots respectively. At lower speeds, the required power is much lower than the available power resulting in a larger power reserve. This provides greater flexibility in speed profile. Moreover, at lower speeds, calm water resistance is lower therefore the contribution of wind and wave resistance in total resistance is larger. Hence, sailing through more favorable conditions has a higher impact on overall fuel consumption.

As the westbound voyage on 2-Jan-22 at 10 knots shows the highest fuel savings, that voyage has been investigated in more detail. As the metocean conditions evolve in space and time, the evolution of significant wave height along with constant and optimized speed profiles are presented in Figure 4. It is observed that the ship traveling on the optimized speed profile speeds up in the initial part of the voyage to avoid high significant wave heights. Especially around waypoint 70 and waypoint 37, the optimized speed profile passes through the waypoints before severe weather develops resulting in encountering lower wave heights. It is also observed that the optimized speed profile takes a shorter time to complete the voyage. To further illustrate the point, metocean conditions encountered along the route by both speed profiles are plotted in Figure 5. It is evident that the optimized speed profile encountered lower significant wave height, especially in the vicinity of waypoints 70 and 37. It must be noted that added wave resistance depends on peak period and wave direction in addition to significant wave height. Therefore, resistance components are shown in Figure 6 to observe the combined effect of different variables on resistance. Lower wind and wave resistance is observed close to waypoints 70 and 37 as expected.

4.2 Panamax Bulk Carrier

A similar analysis was performed using the Panamax bulk carrier. Fuel savings in different seasons at three average speeds on westbound and eastbound voyages are shown in Figure 7. In this case, a

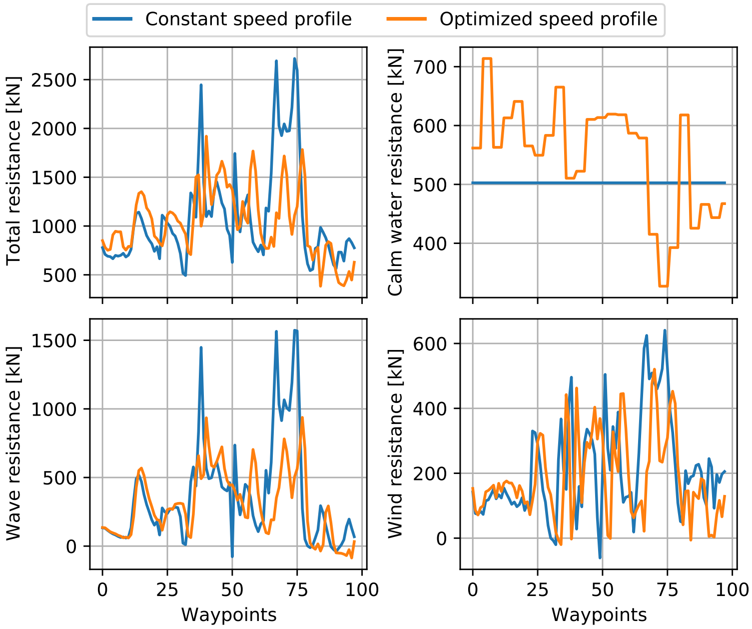

Figure 6: Resistance components for fixed and optimized speed profiles.

successful optimization was only possible with 10 knots and 12 knots speeds. This could be attributed to the smaller design speed of this vessel compared to the Capesize bulk carrier. Fuel savings at 10 and 12 knots are lower than those obtained for the Capesize bulk carrier. Seasonal trends are similar to the earlier results that optimization results in higher savings in rough weather. Considering the fuel savings at different speeds, it is also evident that higher savings are obtained for 10 knots average speed which is again in line with the earlier result.

5. LIMITATIONS AND FUTURE WORK

The safety of a ship is paramount when considering weather routing. Typically, safety is evaluated in terms of motions and accelerations at critical locations on the ship. However, this current work does not explicitly consider ship motions. Nonetheless, the algorithm minimizes added resistance, which is related to ship motions, particularly heave and pitch. (Added resistance comprises two components, one due to wave reflections and the other due to motions.) By minimizing added resistance, ship motions are also reduced to some extent, as observed in simulations through a decrease in encountered wave height. However, since roll is not directly linked to added resistance, roll motion might worsen as a result of optimization. In the future, it would be advisable to include motion limits when optimizing a route alongside speed, thereby providing enough degrees of freedom for optimization.

6. CONCLUSIONS

Two ships were studied to evaluate potential fuel consumption reduction through speed optimization without altering the route. The model considered engine limits for a realistic estimation of involuntary speed loss. It was observed that seasons with a higher likelihood of rough seas have a greater potential for fuel savings, as speed optimization helps avoid unfavorable metocean conditions. The study found that lower average speeds result in higher fuel savings, so concepts like slow steaming and just-in-time arrival can be combined with speed optimization to obtain even larger savings. Although the

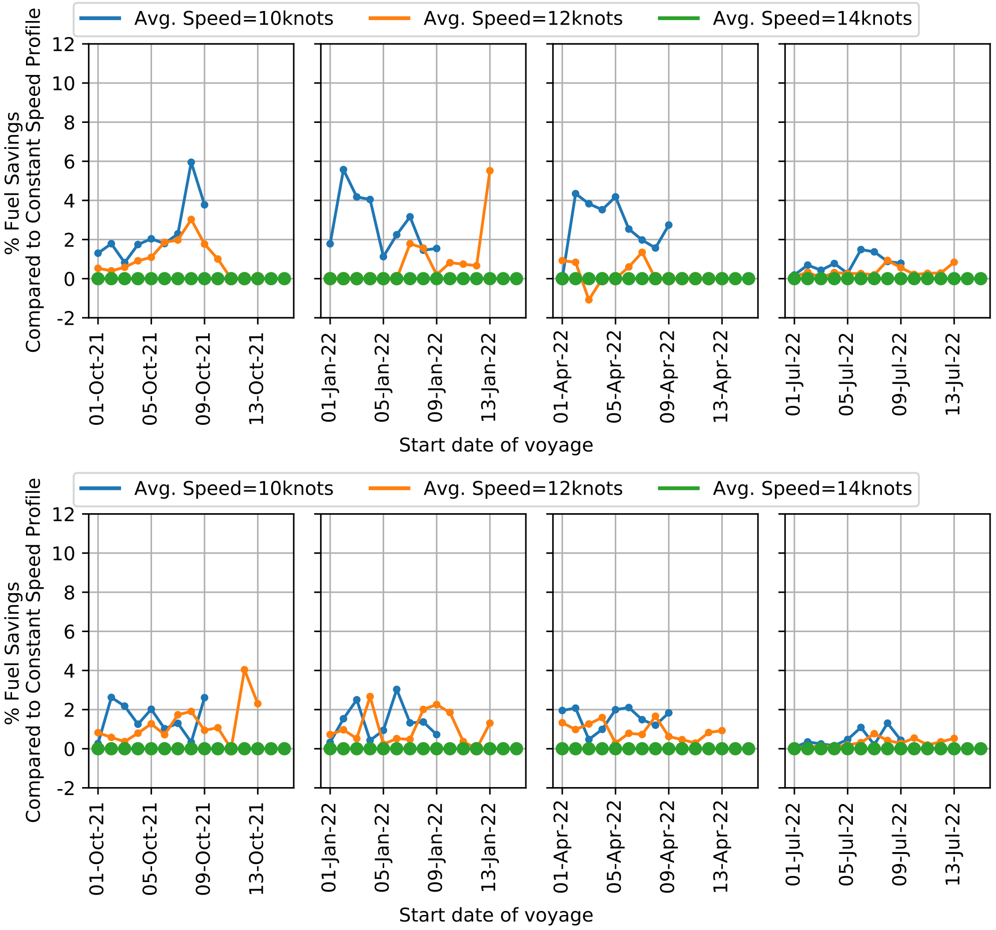

Figure 7: Fuel savings on westbound (top) and eastbound (bottom) voyages at different average speed and seasons for Capesize bulk carrier.

average fuel savings are around 1.4%, this method is easy to implement without requiring significant infrastructure. By keeping the route and voyage time fixed, the implementation of such a solution reduces the complexity without affecting other practical priorities. Speed optimization, in addition to saving fuel, can also help ensure timely arrival of the ship during heavy weather.

Ships were simulated in a wide range of operating conditions to provide an overview of day-to-day fuel savings. Therefore, the effect of daily changes in metocean conditions is captured across different seasons. Such a detailed analysis is essential, especially from a decarbonization standpoint, to study the costs and benefits associated with different solutions for reducing the carbon intensity of the shipping industry.

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