Revealing a Fuel-Saving Tip for Main Engine Operation in Rough Sea Conditions

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1. INTRODUCTION

The target of achieving net-zero GHG emissions from global shipping by around 2050 was set by the International Maritime Organization (IMO) in 2023. To reach this target, a range of solutions have been implemented or are under consideration by the shipping industry. These efforts include the adoption of alternative marine fuels and further improvements in energy efficiency. Among these measures, energy saving will remain essential, even after the adoption of carbon-free or carbon-neutral fuels, due to the forecasted significantly higher prices of these candidate fuels compared to current heavy fuel oil (HFO). Energy efficiency improvements can be achieved through the application of energy-saving devices and/or operational optimization. Operational optimization is easier to implement, as it typically does not require hardware changes.

This paper specifically focuses on how to operate the main engine to save fuel during severe weather conditions. Section 2 provides a general description of the main engine and ship behavior in various sea conditions. Section 3 explains the concept of MAMES (Maximum Attainable Main Engine Speed) in certain weather conditions. Section 4 estimates the amount of potential wasted fuel if the main engine is not properly operated. Section 5 outlines methods to save fuel. Finally, section 6 summarizes the conclusions.

2. MAIN ENGINE AND SHIP BEHAVIOR IN VARIOUS SEA CONDITIONS

When a ship encounters severe sea conditions, it requires more main engine power to maintain a certain speed. Fig. 1 conceptually illustrates the relationship between main engine power, ship speed, and engine speed for an imaginary Panamax bulk carrier with a main engine output of 10,000 kW at 80 rpm. On the left of Fig. 1, curves in different colors indicate the relationship between ship speed and required main engine power for various sea conditions, represented in terms of wave height. On the right of Fig. 1, curves in different colors show the relationship between engine speed and main engine power for different sea conditions. These curves were calculated based on the propeller characteristic curves for each sea condition. Normally, a ship operates with a setting main engine (propeller) speed. As sea conditions change from calm to rough, the ship's speed-power operating point shifts, as indicated by the dashed lines on the left for different setting engine speeds.

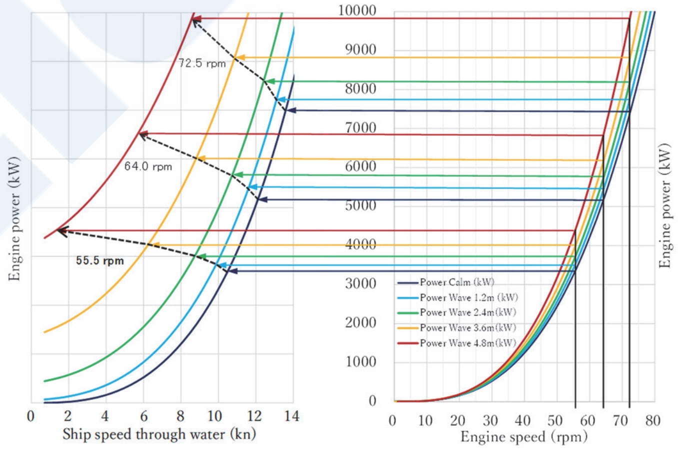

Fig. 1 Conceptual relationship between main engine power, ship speed, and engine speed for an imaginary Panamax bulk carrier

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This general behavior aligns closely with the measured data. Fig. 2 shows the measured data of a 200 m long general cargo ship over a period of 3 years by P. Gupta et al. [1] Each sample is obtained by averaging over a 15-minute period. The original data were pre-processed by removing samples during ship acceleration or deceleration to ensure the ship was in a quasi-steady state.

Although the samples in Fig. 2 appear to scatter over a wide area, some samples are concentrated and aligned along several lines slanting upward to the left. These lines suggest that certain engine speeds were more frequently chosen for the ship's operation, as explained in Fig. 1.

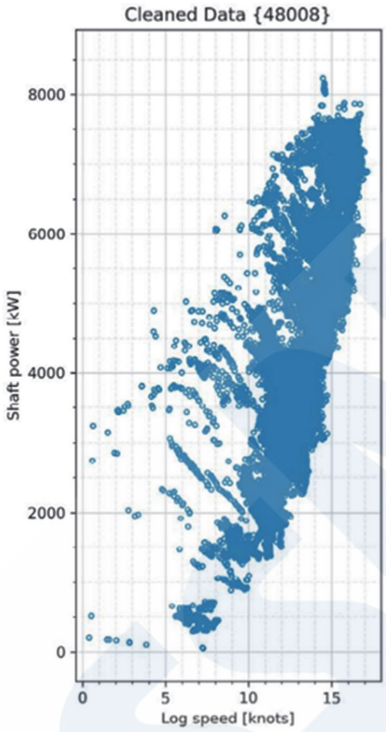

Fig. 2 Measured data of a 200 m long general cargo ship over a period of 3 years, reproduced from P. Gupta et al. [1]

3. MAXIMUM ATTAINABLE MAIN ENGINE SPEED (MAMES)

One might think that the main engine can deliver whatever torque is needed to maintain a commanded speed, but this is not always the case. There is a limit to the torque that the main engine can generate at a given speed to avoid overloading. This limit is enforced by restricting the amount of fuel injected into the cylinders per cycle. The fuel injection amount per cycle is the dominant factor that determines torque through the fuel's calorific value, combustion efficiency, mechanical linkage mechanisms, and other factors, and can be simplistically treated as being in proportion to the generated torque. Therefore, the fuel injection limit essentially corresponds to the torque limit for each rotational speed. Traditionally, the amount of fuel injected per cycle is controlled by a component called the fuel rack in the fuel injection pump, which is why it is commonly referred to as the fuel rack limiter. The fuel rack limiter is shown as a dashed red line on the right side of Fig. 3. If a propeller loading curve intersects with the limiter line, then, theoretically, the propeller (and the main engine) can never be accelerated beyond the intersection point due to insufficient driving torque from the engine to overcome the propeller loading torque. In other words, the intersection point represents the maximum attainable main engine speed (MAMES).

In terms of propeller loading, the most severe case is called bollard pull, which occurs when the hull is stationary, as shown by the dashed black line on the right side of Fig. 3. While determining the exact power required in a bollard pull condition is difficult, a heavy running factor of 15-20% relative to the light propeller curve is commonly used. In Fig. 3, a factor of 20% is adopted [2]. In the bollard pull situation, the MAMES will be significantly lower than for most normal propeller loadings, even in heavy weather, as shown on the right side of Fig. 3.

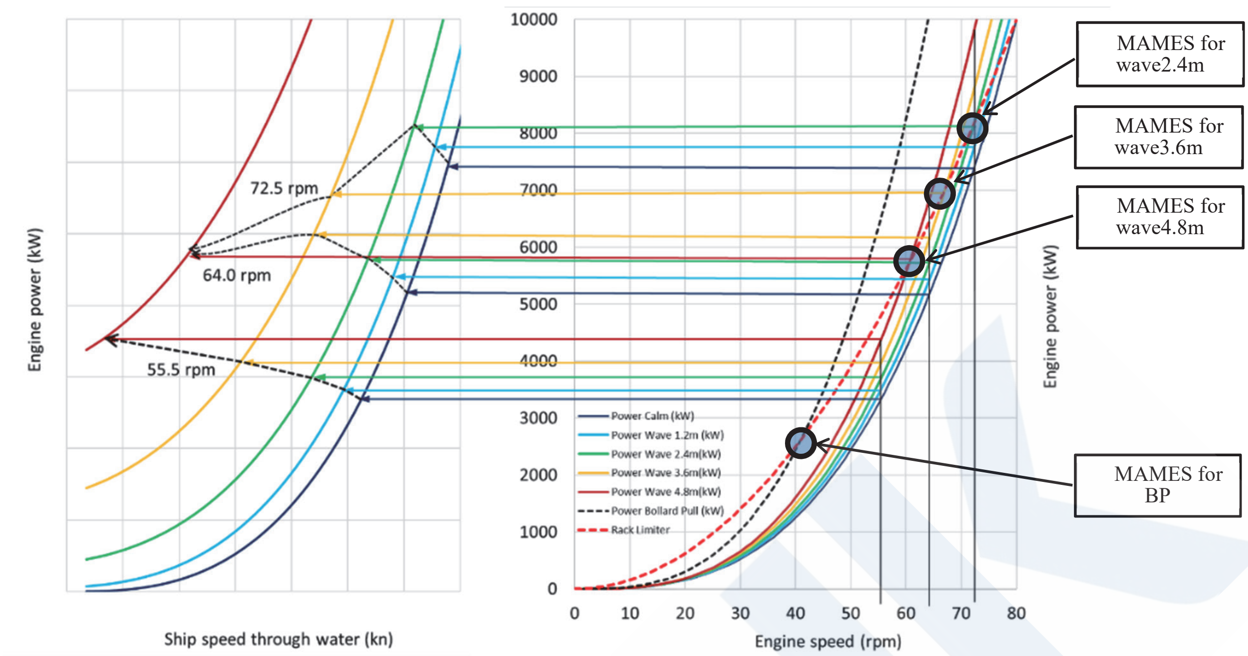

Fig. 3 Conceptual explanation of propulsion power limited by maximum attainable main engine speed

As the maximum available power is also limited by the torque limit for a given engine speed, the attainable ship speed will also be limited according to the available power. This is shown on the left side of Fig. 3 for the commanded engine speeds of 64.0 rpm and 72.5 rpm when encountering waves of significant heights greater than 3.6 m and 2.4 m, respectively. This phenomenon is also visible in Fig. 2. Samples that initially aligned with a nearly straight line slanting upward to the left began to turn downward to the left as they approached the left edges of the sampling area.

Measured data from a Panamax bulk carrier also shows the same trend, as shown in Fig. 4 [3]. For confidentiality reasons, the data were normalized by dividing them by the values at the maximum continuous rating (MCR). Additionally, the log speed was normalized by the service speed. Similar normalizations were also applied in Figs. 6, 7, and 8. The measured data were concentrated along a nearly straight line slanting upward to the left when the main engine output was between 0.2 and 0.3. This indicates that the ship was frequently operated at a specific commanded engine speed below the MAMES. As the main engine output increased to the range of 0.4 to 0.6, some operating points in the left area began to show flattened or downward slanting patterns. These patterns indicated that the main engine torque limit had been reached, as the left area corresponds to high wave conditions.

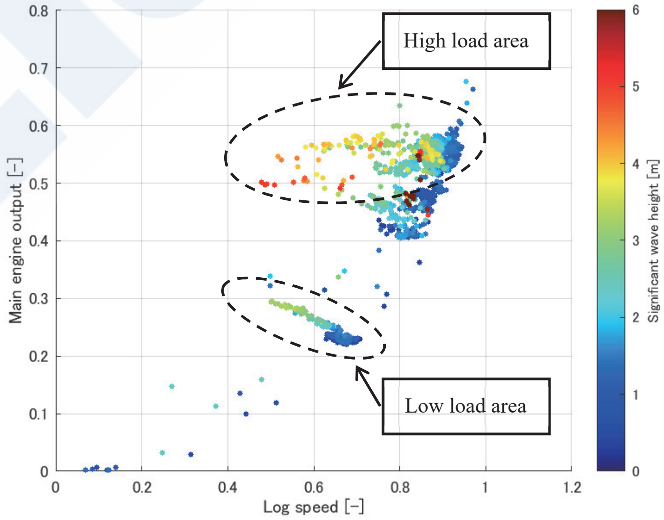

Fig. 4 Measured data showing the relationship between main engine power and ship speed of a Panamax bulk carrier

4. FUEL WASTE DUE TO ENGINE SPEED GAP

The commanded engine speed is used by the main engine governor to determine the target fuel rack position [4]. If the current engine speed is below the commanded engine speed, the governor will increase the fuel mass per cycle until the commanded engine speed is achieved. However, if the commanded engine speed exceeds the MAMES, it can never be reached due to the fuel rack limiter (torque limit). This means that the additional fuel corresponding to the difference between the MAMES and the commanded engine speed is wasted (see Fig. 5).

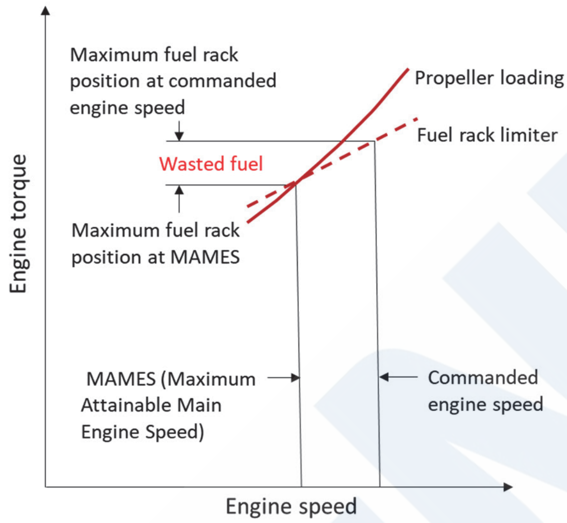

Fig. 5 Conceptual explanation of fuel waste due to engine speed gap

In real ship operation, ships are expected to encounter situations where the commanded engine speed cannot be achieved due to severe weather conditions. Fig. 6 illustrates the plot of engine speed against commanded engine speed for a Panamax bulk carrier over a 70-day voyage. The colors indicate the fuel rack position or significant wave height. In this case, the engine speed fell short of the commanded speed by up to just below 3 rpm. The speed gap was observed when the engine speed command ratio (relative to the speed at maximum continuous rating) was 0.79 and around 0.85.

An interesting observation from the left side of Fig. 6 is that whenever the engine speed falls short of the commanded speed, the injected fuel mass per cycle (fuel rack position) increases, regardless of how high the commanded speed is. This occurs because when the engine governor detects the speed gap, it increases the fuel mass flow to accelerate the engine and close the gap, as mentioned at the beginning of this section. When closing the speed gap becomes impossible, the fuel rack remains high, leading to fuel waste.

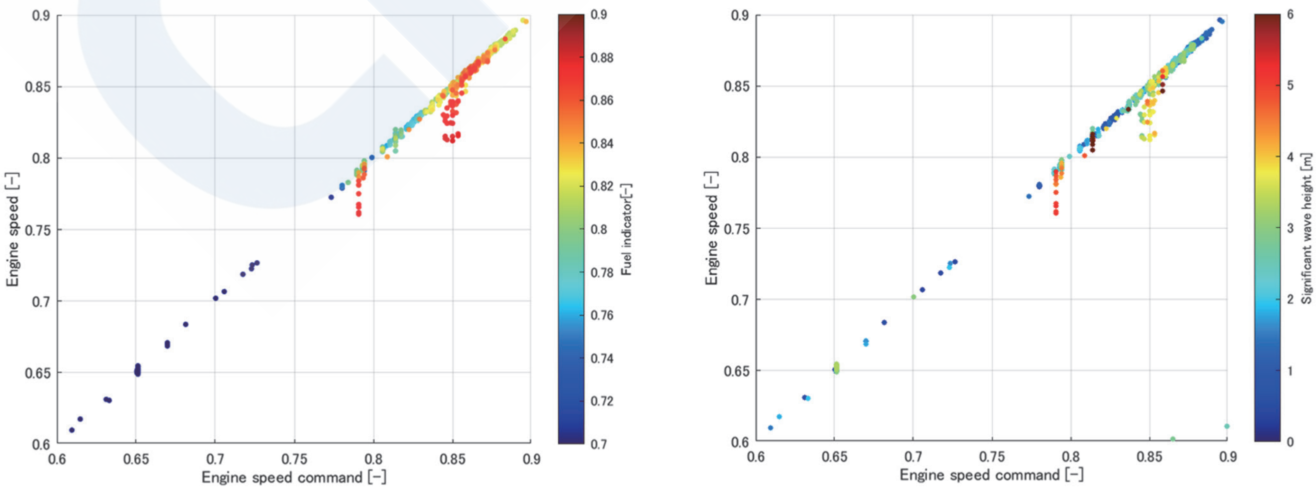

Fig. 6 Plot of obtained engine speed versus the commanded engine speed of a Panamax bulk carrier (left: fuel indicator; right: significant wave height)

Using the same voyage data as mentioned above, Fig. 7 shows the fuel indicator (fuel rack) against the commanded engine speed, with colors depicting the significant wave height. Fig. 7 demonstrates that when the engine speed command ratio is 0.79 and around 0.85, where speed gaps occur, the fuel indicator rises well beyond the values obtained in the main engine shop test.

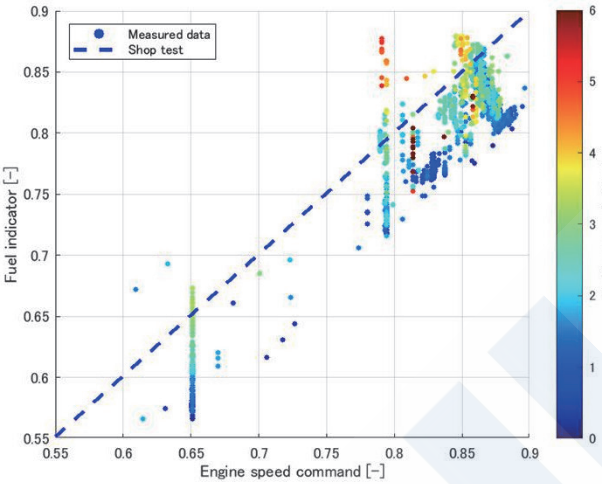

Fig. 7 Fuel indicator (fuel rack) versus commanded engine speed of a Panamax bulk carrier

The amount of fuel wasted depends on where the MAMES is located and how large the speed gap is. As ships age, the MAMES tends to shift to a lower position due to increased fouling on both the hull and propeller, as well as other factors that reduce propulsion efficiency. Therefore, a higher percentage of fuel waste would be expected due to higher probability of the speed gap existing as ships age.

Table 1 shows an estimation of wasted fuel for an imaginary main engine of 10,000 kW at 80 rpm, considering different MAMES and speed gaps. The leftmost column, N/NMCR, shows the MAMES relative to the speed at MCR. It is clear that as the speed gap grows, the wasted fuel increases. Similarly, as the MAMES increases, the wasted fuel increases in absolute terms but decreases in percentage terms. The rows highlighted in yellow indicate MAMES ratios of 0.79 and 0.85, where the real Panamax bulk carrier experienced a speed gap. At these MAMES ratios, if a speed gap of 3 rpm occurs, fuel waste of 9.8% and 9.0% is expected, which corresponds to a fuel waste of 1,943 and 2,260 kg per day, respectively.

Table 1 Potential fuel savings for an engine of 10,000 kW at 80 rpm

N/N_{MCR}	Load (%)	Speed gap (1 rpm)		Speed gap (2 rpm)		Speed gap (3 rpm)	
		Wasted fuel (kg/day)	Wasted fuel (%)	Wasted fuel (kg/day)	Wasted fuel (%)	Wasted fuel (kg/day)	Wasted fuel (%)
0.70	34	504	3.6	1,017	7.3	1,540	11.0
0.71	36	522	3.5	1,054	7.1	1,594	10.8
0.73	38	541	3.5	1,091	7.0	1,650	10.6
0.74	40	559	3.4	1,128	6.9	1,707	10.4
0.75	42	579	3.4	1,167	6.8	1,764	10.3
0.76	44	598	3.3	1,206	6.7	1,823	10.1
0.78	47	618	3.3	1,245	6.6	1,882	9.9
0.79	49	638	3.2	1,285	6.4	1,943	9.8
0.80	51	658	3.1	1,326	6.3	2,004	9.6
0.81	54	679	3.1	1,367	6.2	2,067	9.4
0.83	56	699	3.1	1,410	6.2	2,130	9.3
0.84	59	721	3.0	1,452	6.1	2,194	9.2
0.85	61	742	3.0	1,496	6.0	2,260	9.0
0.86	64	764	2.9	1,540	5.9	2,326	8.9
0.88	67	787	2.9	1,584	5.8	2,393	8.8
0.89	70	809	2.8	1,629	5.7	2,461	8.6
0.90	73	832	2.8	1,675	5.6	2,530	8.5

Fig. 8 shows time histories of measured data from a single voyage of a Panamax bulk carrier. The area framed in red indicates where the speed gap arose. The histories clearly show that the commanded engine speed was deliberately lowered, likely in response to worsening weather conditions, particularly after encountering beam seas with significant wave heights greater than 4 meters. However, even after lowering the commanded engine speed, a difference of approximately 2.5 rpm persisted for about 8 hours, with the maximum speed difference observed during this period.

The actual fuel loss for this Panamax bulk carrier was estimated using the fuel indicator shown in Fig. 8. The fuel loss was calculated based on the difference in the fuel indicator for two cases: when the difference between the commanded and actual engine speed was at its maximum (approximately 2.5 rpm) and when there was no difference, while maintaining a constant commanded engine speed. The estimated fuel loss is 2,286 kg/day, representing 12.2%.

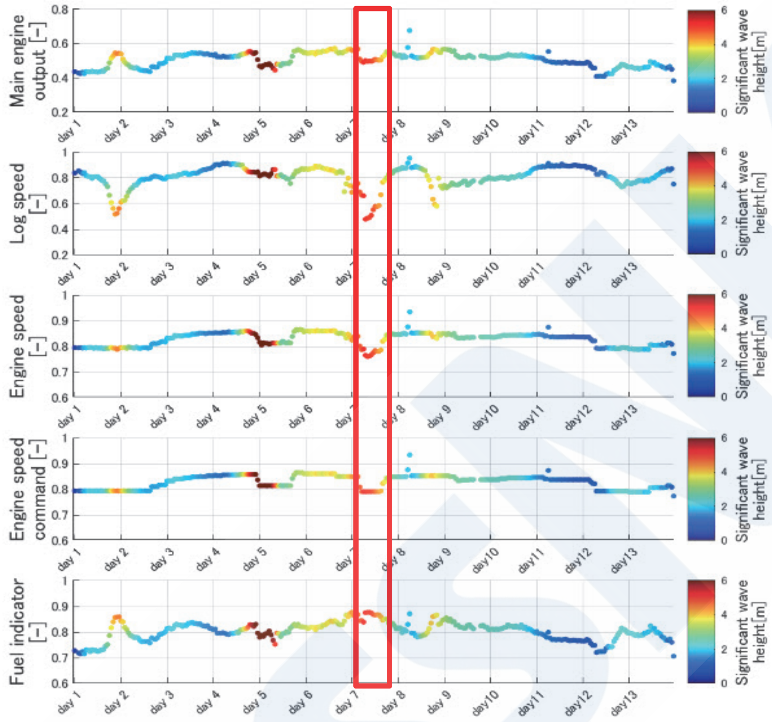

Fig. 8　Time histories of measured data from a Panamax bulk carrier

Fuel loss due to the speed gap over an extended period, such as one year or a ship's lifespan, significantly depends on the probability of encountering weather conditions severe enough to cause the engine speed gap. Table 2 presents the total hours and their ratio to the entire voyage time during which the significant wave height exceeds 4.5 m on each route over the course of a year. It also includes the estimated wasted fuel mass and cost, assuming a constant speed gap of 2.5 rpm during those periods.

Representative routes for a Panamax bulk carrier were selected based on past Automatic Identification System (AIS) data, shown in Fig. 9. In the analysis, the threshold wave height that causes the speed gap was set at 4.5 m, according to measured data from the Panamax bulk carrier. The wave data used for analyzing encountered sea conditions along each route is derived from the ERA5 wave hindcast, provided by ECMWF. The sea conditions encountered over a one-year period were estimated by considering the effect of weather routing to avoid heavy weather, based on statistical data regarding sea conditions along each route and past operational records [5), 6)]. Furthermore, the ship's operational rate was assumed to be 0.8, and the price of VLSFO (Very Low Sulphur Fuel Oil) was assumed to be 600 USD per metric ton.

Table 2 indicates that, over the course of a year, the probability of encountering waves exceeding the threshold is 81 hours on the Asia-Australia route, 901 hours on the Asia-US West Coast route, and 1,196 hours on the US East Coast-Europe route. Furthermore, if a speed gap of 2.5 rpm were continuously maintained during periods when the encountered wave height exceeded 4.5 m on each route, the estimated wasted fuel would range from 8 to 114 MT, with the corresponding cost ranging from 5,000 to 71,000 USD. However, it should be noted that the speed gap can vary depending on the operation of the main engine as well as the sea conditions. Thus, the actual values of the wasted fuel can also change accordingly.

Table 2 Estimated total hours and their ratio to total voyage time in which the significant wave height exceeds 4.5 m on each route over the course of a year, along with the estimated wasted fuel and its cost assuming a constant speed gap of 2.5 rpm during those periods

Route	Time (h)	Time ratio (%)	Wasted Fuel (MT)	Wasted Fuel cost (USD)
Asia-Australia	81	0.9	8	5,000
Asia-US West Coast	901	10.3	86	54,000
US East Coast-Europe	1,196	13.7	114	71,000

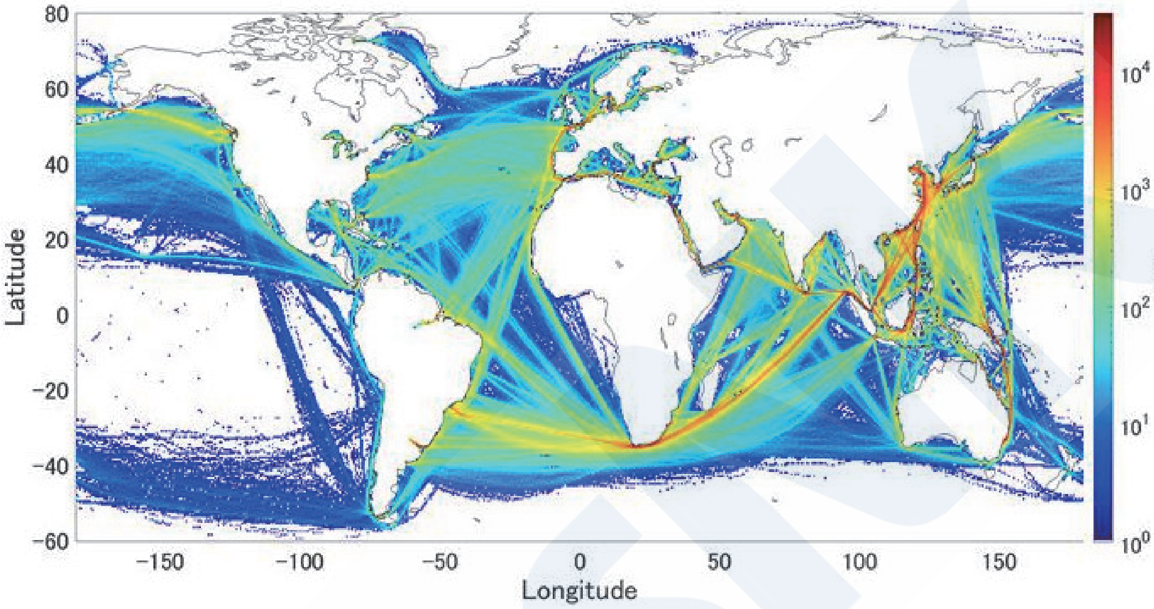

Fig. 9 Routes of Panamax bulk carriers based on AIS Data (2022-2023)

Apart from the economic perspective, safety implications are also important. As the engine continuously tries to fill the speed gap, it is forced to remain in a constant state of acceleration. In this acceleration state, due to the inertia of the turbocharger rotor, the air-fuel ratio tends to be lower than in steady-state conditions. A low air-fuel ratio can cause incomplete combustion and may momentarily result in a high density of smoke. Incomplete combustion particles (soot) in the exhaust gas will adhere to the turbine blades. This, in turn, can cause an imbalance, leading to vibration and rapid wear of the rotor and bearings (see Fig. 10) [7), 8)].

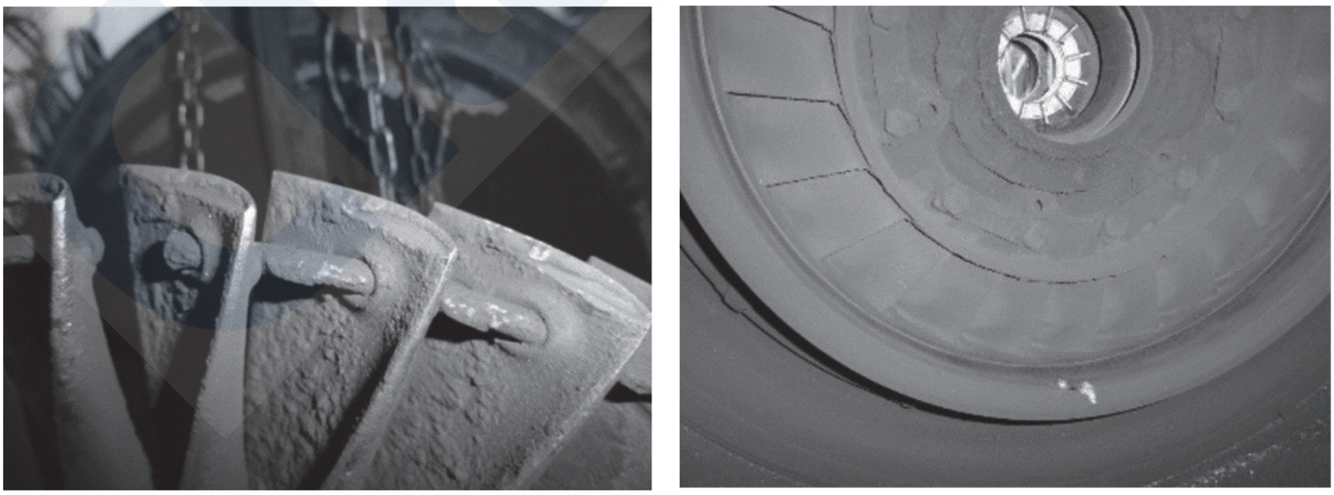

Fig. 10 Turbocharger components fouling with soot - Turbine blades (left) and turbine nozzles (right)

5. TIP FOR FUEL-SAVING MAIN ENGINE OPERATION IN ROUGH SEA CONDITIONS

There seems to be a common practice in the shipping industry to lower the main engine speed when encountering rough seas [9]. However, how much the speed of the main engine should be reduced is usually left to the individual ship crew's experience. In some cases, although the engine speed has been lowered by several rpm, the actual speed remained below the commanded speed for hours. These facts suggest that the speed gaps may have gone unnoticed by the crew. Thus, it is desirable to monitor the difference between the actual engine speed and the commanded speed. If the speed gap persists, the commanded speed should be gradually lowered until the gap disappears. Shipping companies are highly encouraged to review their fleet's past voyage data, if available. If main engine speed gaps are found in the past data, the crew should be instructed to check for any speed gaps onboard their ships and take appropriate action.

6. CONCLUSIONS

When ships encounter rough sea conditions, a main engine speed gap can occur between the obtained speed and the commanded speed, which may last for hours until the weather improves sufficiently for the main engine to close the gap. This phenomenon was confirmed by onboard measurements of a Panamax bulk carrier, and the mechanism behind it was theoretically analyzed and explained. A prolonged speed gap leads to waste of fuel. Depending on the main engine running speed and the size of the gap, the wasted fuel can be as high as 10% of the fuel consumed under normal conditions without the speed gap. The speed gap can also cause incomplete combustion, leading to turbine blades and nozzles fouling with soot. Fouling of the turbine components, in turn, causes rotor imbalance, which leads to vibration and rapid wear of the rotor and bearings.

By properly adjusting the main engine speed order in heavy weather conditions, a significant amount of fuel can be saved. In addition to the economic benefits, eliminating the speed gap reduces the likelihood of turbocharger failures and damage to other components exposed to exhaust gases.

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