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Impact of Sailing Speed on a Container Ship's Fuel Consumption and Emissions Under Different Weather Conditions

Abstract

Approximately 80% of goods in global trade are transported by sea. In most cases, maritime transport is the most suitable form of transport according to economic criteria. Increasing efficiency and reducing negative environmental impact are particularly important for the sustainability of modern maritime transport. The International Maritime Organization (IMO) issues regulations aimed at improving energy efficiency and reducing emissions from ship propulsion systems. Requirements related to the energy efficiency of new ships are evaluated using the EEDI, while the EEXI index is applied to existing ships. Reducing ship speed can significantly decrease fuel consumption per mile travelled and lower emissions of carbon dioxide, nitrogen oxides, and particulate matter, all without additional investment. Since this effect is especially pronounced for faster ships, this study analyses the impact of sailing at reduced speed using a container ship with a capacity of 4,200 TEU as an example. The research used the Kongsberg Maritime ERS Sulzer RTA84C simulator. Data from the engine manufacturer Sulzer were used to validate the model for fuel consumption. The analysis was conducted for several different sailing speeds under various weather conditions. The results show that by reducing sailing speed, significant savings in fuel consumption and emissions from existing container ships can be achieved.

Keywords: energy efficiency, reduction of emissions, reduction of sailing speed

1. Introduction

Maritime transport is highly important for global trade, as 80% to 90% of the total volume of goods is transported by sea. The volume of goods transported by sea generally increases each year, with decreases occurring only during extraordinary events that disrupt global trade. According to data from the United Nations Conference on Trade And Development (UNCTAD) [1], from 2003 to 2023, global trade by sea routes grew at an average rate of 2.9% per year. The same source reports that the total volume of goods transported by sea increased by 2.2% in 2024, reaching 12,720 million tons. When considering both the volume of goods in tons and the distance traveled, maritime transport in 2024 increased by 5.9%, totaling 66,781 trillion ton-miles. These data on the volume of cargo transported by sea confirm the importance and efficiency of maritime transport for the development of global trade.

Although maritime transport is generally the most economically and ecologically acceptable form of transport, it requires constant adaptation to meet increasing energy efficiency standards and to reduce emissions of carbon dioxide and other harmful substances into the environment. The International Maritime Organization (IMO) and the Kyoto Protocol play important roles in setting goals for improving energy efficiency and minimizing negative environmental impacts. To advance efficiency and reduce greenhouse gas emissions, the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) have been in use since January 1, 2013. The EEDI applies to new ships, while the Energy Efficiency Existing Ship Index (EEXI) applies to all existing ships of 400 GT and above. For all ships of 5,000 GT and above using conventional fuels, the Carbon Intensity Indicator (CII) is also mandatory as a measure of energy efficiency when using carbon-containing fuels [2]. Additional measures requiring at least a 40% reduction in CO₂ emissions from maritime transport by 2030 compared to 2008 were adopted by IMO member states in 2021.

Despite various efforts and measures, the ultimate goal of reducing CO₂ emissions from ships has not been achieved. Between 2012 and 2025, a significant increase in carbon dioxide emissions was recorded, with a monthly rise of approximately 200 million tons. Due to increased ship speeds and rerouting, CO₂ emissions in 2024 increased by 5% compared to 2023. However, operational improvements, replacing existing ships with new ones, and reducing sailing speeds are likely responsible for the reduction in emissions during the first six months of 2025 [1].

For a shipping company to operate successfully and sustainably, continuous adaptation to regulatory requirements and market conditions is necessary, and the energy efficiency and environmental performance of the propulsion system play a significant role. Increasing energy efficiency and reducing emissions can be achieved by:

- improving the design and ensuring efficient, regular maintenance of the ship's hull;
- increasing the efficiency of the ship's propeller;
- utilizing waste heat;

- using alternative fuels;
- reducing electricity consumption for auxiliary systems;
- optimizing ship speed;
- ...

Reducing sailing speed is an effective and widely accepted measure among shipowners because it does not require additional investment and is applicable to both existing and new ships, regardless of the technical and technological solutions used in the propulsion system. The power required for ship propulsion increases exponentially with sailing speed, with an exponent of 3 to 4. This means that doubling the sailing speed requires at least eight times more power. Reducing sailing speed to increase energy efficiency and reduce CO₂ emissions is applicable to all ships; however, the best results are achieved with ships designed for higher speeds, such as container ships. One of the main disadvantages of slow steaming is the increased time required to cover the same distance. Besides sailing speed, the effectiveness of this measure is also greatly affected by the interaction between fuel prices, freight rates, and delivery schedules. In addition to energy and environmental reasons, sailing at reduced speed is also necessary in case of adverse weather conditions.

This paper analyzes the impact of slow steaming on fuel consumption and emissions at different sailing speeds and under various weather conditions, using a container ship propulsion system as an example. The research employed an advanced simulation model of the Kongsberg Maritime Engine Room Simulator (ERS) Sulzer RTA84C propulsion system. The Sulzer RTA84C engine room simulator is a complex model that enables the adjustment and monitoring of all relevant parameters for the operation of the ship's propulsion system.

In the paper by Zenna, M. et al. [3], it was pointed out that slow steaming is not the only method to reduce fuel consumption and consequently emissions from ships, but it is favored by shipowners because it requires no additional investment and is simple to implement.

Tezdogan, T. et al. [4] investigated the impact of reducing the speed of a container ship S-175, with a service speed of 24 knots, to 19 knots under three different sea states. The analysis was performed using the VERES software package, and the results were validated by comparison with available experimental data. The findings show that slow steaming positively affects the reduction of ship motion, fuel consumption, and CO₂ emissions. Compared to a sailing speed of 24 knots, fuel consumption is reduced by up to 53% at 19 knots.

According to Jasper, F. et al. [5], slow steaming significantly reduces carbon dioxide emissions, with a 10% speed reduction resulting in a 19% emission reduction, and generally leads to cost savings, except in scenarios with low fuel prices.

In the case study [6], the impact of reduced speed on CO₂ emissions and energy efficiency of a RO-RO cargo ship was investigated. A 10% speed reduction led to a 27% reduction in CO₂ emissions, while a 40% speed reduction resulted in a 78% reduction.

The impact of reducing sailing speed on CO₂, CH₄, N₂O, and BC emissions, as well as fuel consumption, was analyzed in [7] using real-world data from a general cargo ship. Emission reduction potential was analyzed at different main engine loads. Emissions at 38% engine load were 31.5% lower than at 75%. Emission reductions of 40.6% and 50.1% were achieved at 27% and 19% main engine loads, respectively. At the same time, the results of the economic analysis showed that slow steaming effectively reduces emissions and fuel costs, but increases operating costs due to longer voyage durations.

The results of the research presented in [8] indicate that selecting the optimal sailing speed is a dynamic process that requires balancing advantages and disadvantages. At the same time, fuel prices, charter rates, and the ability to adjust the ship's propulsion system significantly influence the choice of optimal slow steaming speed.

According to [9], almost all global shipping companies use slow steaming. They also emphasize that slow steaming is an effective measure for reducing fuel consumption and CO₂ emissions, and that it can be used to reduce overcapacity and adapt to different operating conditions in the maritime sector. This measure must be used rationally to avoid negative effects, such as increased total costs and negative impacts from long-term operation of diesel engines under low load.

Analysis of the impact of slow sailing on the total costs of bulk carriers presented in [10] shows that a significant reduction in sailing speed increases the additional costs of transporting bulk cargo. However, these additional costs of transporting bulk cargo are compensated by the reduction in fuel costs in most scenarios, unless fuel prices are extremely low.

In the study [11], the impact of reduced sailing speed in different sea states on the reduction of CO₂ emissions when using low sulphur marine gas oil (LSMGO) and liquefied natural gas (LNG) is analyzed using the example of a typical container ship (KRISO container ship) sailing on a route approximately 2100 NM long. The numerical model for propulsion characteristics and resistance in calm seas is defined based on viscous flow theory using computational fluid dynamics (CFD), and wave resistance is considered using potential flow theory. The research showed that it is possible to achieve a reduction in CO₂ emissions of around 31% when using LSMGO, and up to 49% when using LNG as fuel.

The impact of reduced sailing speed on fuel consumption in different weather conditions is the topic of the article [12]. The authors concluded that the potential for fuel savings depends significantly on weather conditions, but that the additional fuel consumption caused by waves does not depend on the ship's speed. Therefore, the reduction in fuel consumption achieved by reducing sailing speed was smaller in heavy weather conditions compared to sailing in calm seas.

The impact of reduced sailing speed on fuel consumption and CO₂ emissions for four different propulsion systems with mechanical power transmission was analyzed in detail on the example of a Post-Panamax containership in [13]. The power required to sail the ship at different speeds was determined from data obtained by testing the ship

model with a fixed pitch propeller (FPP). To determine the specific fuel consumption at different sailing speeds, a numerical model according to [14], [15], and [16] was used, calibrated with the engine manufacturer's data. The research results show that, depending on the selected propulsion system, at a sailing speed of 12 knots, it is possible to achieve a reduction in fuel consumption of 72.36% to 76.25% compared to a sailing speed of 23 knots.

The analysis carried out in [17] shows that the majority of Post Panamax, Post Panamax Plus, and very large container ships built until 2016 do not meet the new EEXI requirements. The research results show that an average speed reduction of 86%, 86.6%, and 91.3% is required to meet the requirements in a representative sea state. These speed reductions correspond to mean engine load values of 45.3%, 45.8%, and 55.2% for certain categories of ships.

A numerical model of a two-stroke marine engine in the MATLAB/Simulink environment was used in paper [18] to investigate the operation of the main engine of a large container ship under stationary and transient conditions at loads below 50% of the maximum continuous rating (MCR). The research results show that it is necessary to turn on auxiliary blowers at engine loads of 35% MCR or less to avoid excessive increases in exhaust gas temperature. In the load range from 25% to 10% MCR, the authors suggest disabling one or more turbocharger units or switching on auxiliary blowers to ensure reliable engine operation. They also recommend using the model to test the performance of marine engines when slow steaming is applied.

The influence of slow steaming on fuel consumption and CO₂ emissions is analyzed in paper [19] for a very large crude oil carrier (VLCC) with a slow-speed MAN-B&W MC90 L5 main engine and a container ship with an RT-Flex 82C L11 main engine. The research was carried out using the Kongsberg engine room simulator. Data on fuel consumption obtained by simulating navigation with an engine load of 100% MCR and reducing speed to 12 knots – corresponding to 60% MCR for a VLCC and 40% MCR for a container ship – were used to calculate CO₂ emissions. The CO₂ emission of a VLCC is approximately one third lower if a shaft generator (SG) and turbo generator (TG) are used, while without them the reduction is only 23% compared to sailing at a speed of 15 knots.

In paper [20], an economic model was proposed to determine the optimal sailing speed for container ships with a carrying capacity of 2,000 to 20,000 TEU. Fuel costs, container loading and unloading costs, port fees, and other charges are taken into account. The analysis is carried out for three scenarios in which emission costs are 0%, 50%, and 100% of the allowed emission. The research showed that container ships from 5,500 to 13,000 TEU have the highest optimal sailing speeds. Without emission costs, the optimal speed is 19.6 knots; for 50% emission costs, it is 18.7 knots; and for 100% emission costs, the optimal speed is 18.0 knots.

In paper [21], the authors analyze the potential of slow steaming to compensate for the costs of using more environmentally friendly fuels. The research results showed that sailing at a reduced speed can reduce, but not completely compensate the costs,

when MGO is used instead of HFO. The study found that reducing sailing speed at an engine load below 50% is not efficient, and that fuel prices significantly impact the selection of the optimal sailing speed.

Using the example of a Post-Panamax container ship, paper [22] investigates in detail the impact of slow steaming on fuel consumption and carbon dioxide emissions. Numerical simulation of the ship's performance during calm sea navigation was used in the study. The data obtained by numerical simulation were validated by comparison with extrapolated data from ship model testing. The results of the research for reducing the ship's speed compared to the design speed by 10%, 20%, and 30% showed a reduction in CO₂ emissions of 16.89%, 21.97%, and 25.74%, respectively, for constant transport work.

The impact of reducing sailing speed on energy efficiency, emissions, and the energy potential of waste heat from the main engine WinGD 6X82-2.0 is investigated in paper [23]. The results obtained show that a reduction in sailing speed of 8.7% reduces fuel consumption by 19.02%, while sailing time increases by 9.52%. With a reduction in speed of 30.4%, fuel consumption is reduced by 53.1%, and sailing time is extended by 43.8%. Operating the main engine at a lower load leads to a reduction in the potential of waste heat and its possible use, which negatively impacts overall efficiency.

2. Ship and propulsion system data

To investigate the impact of reduced sailing speed on fuel consumption and carbon dioxide emissions, the Kongsberg ERS Sulzer 12RTA84C engine room simulator was used. The software provides realistic simulation and monitoring of parameters for all important processes related to the operation of propulsion systems and ship navigation. Basic data on a container ship with a Sulzer 12RTA84C main engine are shown in Table 1.

Table 1. General characteristics of ship (source: [24])

Characteristics	Data
Length over all (L_{oa})	295 m
Length between perpendiculars (L_{pp})	281 m
Breadth moulded (B)	32 m
Dead weight	55000 t
Container capacity	4200 TEU
Reefer container capacity	600
Speed	25 knots
Propeller	Fixed Pitch Propeller (FPP)

Main engine	
Main engine (ME) type	Sulzer RTA84C
ME Continuous Service Rating (CSR)	48600 kW
Engine speed at CSR	102 rpm
Electrical power plant	
Diesel engine driven synchronous generators	2 x 2300 kW, 440 V, 60 Hz
Diesel engine driven synchronous generators	2 x 1700 kW, 440 V, 60 Hz
Emergency generator	1 x 250 kW, 440 V, 60 Hz

Basic data for the low-speed two-stroke Sulzer 12RTA84C are given in Table 2.

Table 2. General characteristics of main engine 12RTA84C (source: [24] [25])

Characteristics	Data
ME Continuous Service Rating (CSR)	48600 kW
Number of cylinders	12
Number of turbochargers	3
Number of charge air coolers	3
Engine speed at CSR	102 rpm
Mean piston speed	8.16 m/s
Cylinder bore	840 mm
Piston stroke	2400 mm
Mean indicated pressure	1.84 MPa
Break mean effective pressure (BMEP)	1.79 MPa
Max. cylinder pressure	14.0 MPa

3. Validation of specific fuel consumption

The ERS 12RTA84C engine model used in this research allows the engine to be loaded with a hydraulic brake, simulating engine testing on a test bench. For model validation, the brake specific fuel consumption (BSFC) obtained by simulation at 100% and 85% MRC was compared with factory data. The obtained data and the BSFC deviation in percentage are shown in Table 3.

Table 3. Factory and ERS model data for brake specific fuel consumption

Load, R1	BSFC, factory data, [26]	BSFC, ERS [24]	difference in BSFC
100%	171 g/kWh	178 g/kWh	3,93%
85%	168 g/kWh	178 g/kWh	5,95%

The data in Table 3 were obtained for fuel oil 730 cSt/50°C, ISO 8217, category ISO-F-RMK. The simulation of engine operation when determining BSFC was carried out at standard reference conditions: ISO 3046-1: 2002; ISO 15550: 2002: air temperature 25 °C, air pressure 100 kPa, relative humidity 30% and cooling water temperature upstream charge air cooler 25 °C.

4. The impact of sailing speed on fuel consumption and emissions

The impact of slow steaming on reducing fuel costs and carbon dioxide emissions on the example of a container ship using the ERS Sulzer 12RTA 84(C) was analyzed for three different cases. In the first case, the ship sails in calm seas, and in the second and third cases, the ship sails with a wind of 3 Bf and 6 Bf in the bow, respectively. The reference speed in the first and second cases, provided the engine load does not exceed 95% of MCR, is 25 knots, while in the third case, a speed of 22.4 knots is achieved. Engine loads as a percentage of MCR for navigation in the three analyzed cases are shown in Figure 1, and changes in the specific fuel consumption (SFC) of the main engine are shown in Figure 2.

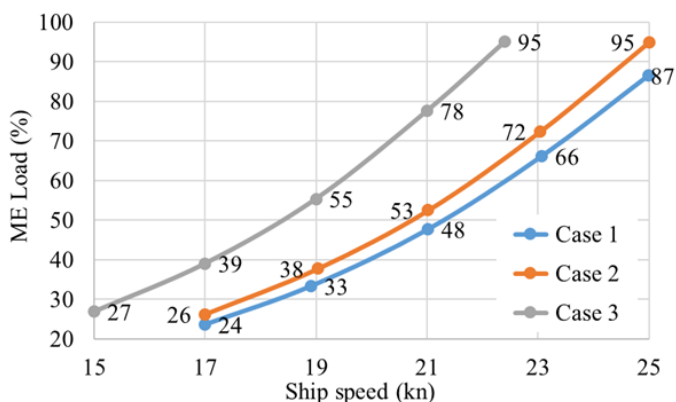


Figure 1. Main engine load at different sailing speeds

The data in Figure 1 show that when sailing at 17 knots in the given weather conditions, the required engine power, and consequently the fuel consumption, increases by 2% in Case 2 and by 15% in Case 3 compared to Case 1. At higher speeds, the difference increases and at a speed of 21 knots it is 5% and 30%, respectively. This indicates that sailing at reduced speed in adverse weather conditions has significant potential for reducing fuel consumption and emissions, while also enabling safer navigation and lower additional load on the propulsion system and the ship's hull.

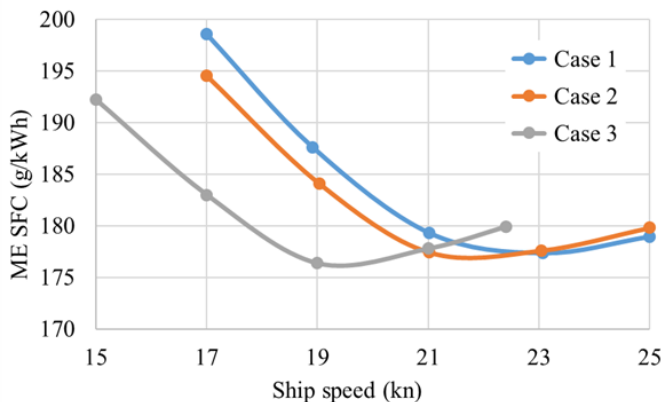


Figure 2. Main engine specific fuel consumption at different sailing speed

Differences in specific fuel consumption at the same sailing speed, but under different weather conditions (Cases 1, 2 and 3), result from changes in the main engine load, as shown in Figure 1 and Figure 2.

The following data are provided for fuel consumption, CO₂, and NO_x emissions for the main engine in kg/NM, along with the percentage change in their values compared to the reference sailing speed, as well as the increase in voyage duration at reduced sailing speeds. Fuel consumption for electric generation is not taken into account.

The effect of speed reduction on fuel consumption and emissions during navigation in calm seas (Case 1) is shown in Figure 3, while Figure 4 presents the same data for Case 2 (headwind of 3 Bf). In the figures on the left, the diagrams show the variation in absolute values (kg/NM) relative to the ship's speed. In the figures on the right, the diagrams show the percentage of relative changes in fuel consumption (FC), CO₂ and NO_x emission and travel time in relation to the reference ship speed of 25 knots.

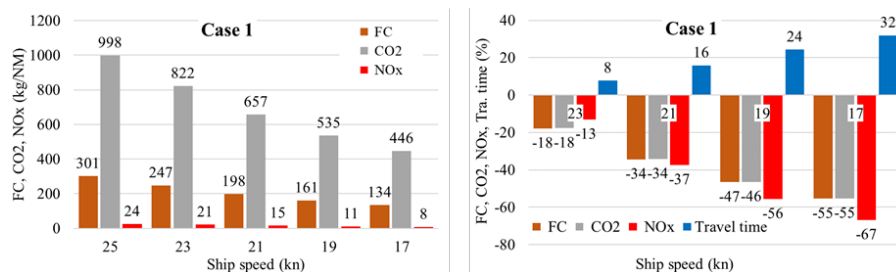


Figure 3. The impact of speed reduction on FC, CO₂ and NO_x emissions (Case 1)

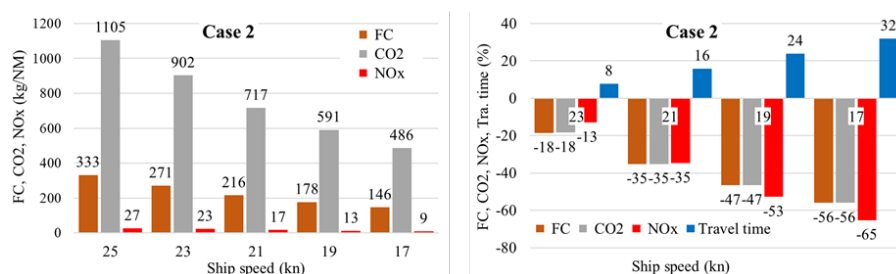


Figure 4. The impact of speed reduction on FC, CO₂ and NO_x emissions (Case 2)

In both cases, when the speed is reduced by only two knots, fuel consumption and CO₂ emissions decrease by 18%, and NO_x emissions by 13%, while travel time increases by only 8%. When the speed is reduced to 17 knots, travel time increases by 32%, fuel consumption and CO₂ emissions decrease by 55–56%, and NO_x emissions by 65–67%. When sailing on calm seas at 17 knots, fuel consumption and CO₂ emissions are approximately 2.24 times lower than at 25 knots. In the Case 2, fuel consumption and CO₂ emissions are 2.28 times lower.

The effect of speed reduction on fuel consumption and emissions when sailing with a 6 Bf bow wind in Case 3 is shown in Figure 5. In Case 3, the engine load at a speed of 22.4 knots was approximately 95% MCR, so this speed is used as the reference speed. The diagram in Figure 5 shows the change in absolute values in kg/NM on the left, and the percentage of relative changes in FC, CO₂ and NO_x emission, and travel time relative to the reference ship speed of 22.4 knots.

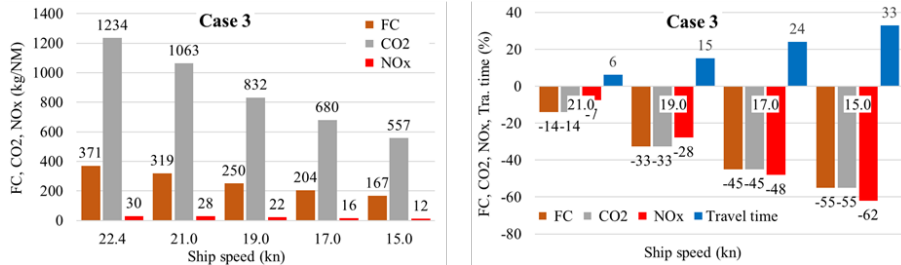


Figure 5. Impact of reduced sailing speed on FC, CO₂ and NO_x emissions (Case 3)

In Case 3, when the speed is reduced from 22.4 knots to 21.0 knots, fuel consumption and CO₂ emissions are 14% lower, and NO_x emissions are 7% lower, while the journey time is only 6% longer. When the speed is reduced to 17.0 knots, travel time increases by 24%, fuel consumption and CO₂ emissions decrease by 45%, and NO_x emissions decrease by 48%. At 17 knots, fuel consumption and CO₂ emissions are approximately 1.81 times lower than at 22.4 knots.

The fuel consumption of diesel generators (DG) depends on the load of the ship’s power plant, which is significantly influenced by the number of reefer containers being transported. Figure 6 shows the reduction in fuel consumption of the main engine for three sailing speeds (left), and the total reduction in fuel consumption assuming that approximately 80% of the total reefer container capacity is transported (right). Note that for Cases 1 and 2, the reference speed is 25.0 knots, and for Case 3, it is 22.4 knots.

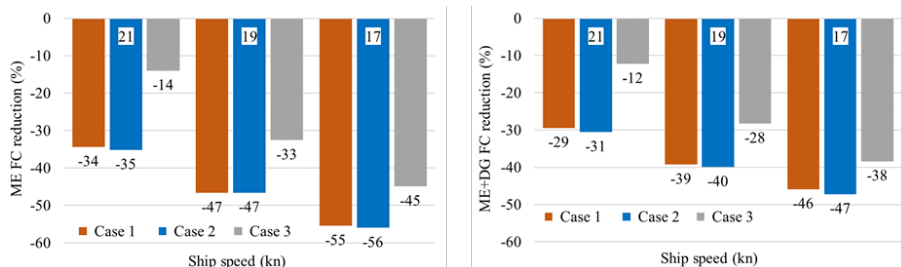


Figure 6. Reduction of ME consumption (left) and total fuel consumption (right)

The ME fuel consumption reduction ranges from 34% to 56% at a reference speed of 25 knots, and from 14% to 45% at a reference speed of 22.4 knots. When DG consumption is included, fuel consumption is reduced by 29% to 47% for Case 1 and Case 2, while for the lower reference speed (Case 3), the reduction is from 12% to 38% in the speed range of 21–17 knots. However, even when total fuel consumption is considered, sailing at a reduced speed significantly decreases fuel consumption and, consequently, carbon dioxide emissions.

5. Conclusion

Using the ERS 12RTA84C simulator, the paper analyzed the influence of reduced sailing speed on fuel consumption and emissions when sailing with wind in the bow of 0 Bf, 3 Bf, and 6 Bf. Provided that the engine load does not exceed 95% MCR, the reference speed for the first two cases is 25.0 knots, while in the third case, due to increased resistance, the reference speed is lower and amounts to 22.4 knots.

The lowest specific fuel consumption of the main engine for Cases 1 and 2 occurs at sailing speeds between 21 and 23 knots, while for Case 3, it is lowest at about 19 knots. Reducing the sailing speed to 23 knots results in an 18% reduction in main engine fuel consumption, with only an 8% increase in voyage duration. Reducing the speed to 21 knots decreases fuel consumption by 34–35%, with a 16% increase in voyage duration for Cases 1 and 2.

At a sailing speed with a headwind of 6 Bf (Case 3), sailing at 21 knots reduces fuel consumption by 14%, with only a 6% increase in voyage duration. Reducing the speed to 19 knots decreases fuel consumption by 33% compared to the value at 22.4 knots.

The effect of reducing fuel consumption, when considering total consumption, is somewhat smaller. At a sailing speed of 21 knots for Cases 1 and 2, the reduction amounts to 29–31%, and 12% for Case 3. At 19 knots, total fuel consumption is lower by 39%, 40%, and 28% compared to consumption at the reference sailing speed.

To avoid the negative effects of long-term engine operation with a load of less than 30% of the MCR, the minimum navigation speed is approximately 19 knots for Case 1, 18 knots for Case 2, and 17 knots for Case 3. In extremely adverse weather conditions, this speed can be further reduced because the increased total resistance of the ship's movement will allow for adequate main engine load even at lower speeds.

The profitability of a shipping company's business is significantly influenced by the ability to adapt to regulatory requirements and market conditions, and the energy efficiency and environmental friendliness of the propulsion system play a significant role. Sailing at a reduced speed – slow steaming – is an effective measure that, if used rationally, enables significant reductions in fuel consumption and, consequently, carbon dioxide emissions.

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