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Impact of Hull Fouling on Vessel's Fuel Consumption and Emissions Based on a Simulation Model

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With an ever-increasing trend of analysing and improving vessel energy and economic efficiency in recent years and decades, every aspect of a vessel's system needs to be observed with the goal of reducing fuel consumption and emissions. Hull fouling can have a significant effect on these variables. Since hull maintenance is an expensive effort, its use must be optimized and fine-tuned to increase the economic efficiency of a vessel's exploitation cycle. In order to do this, data and a subsequent analysis have to be obtained on different stages of the hull fouling process and the effect these states have on vessel energy efficiency and consequently emissions and economic efficiency. This paper will analyse a set of data including emission pollutants such as nitrogen oxides (NO_X) and carbon dioxide (CO_2) as a greenhouse gas and the effect that different amounts of hull fouling have on the vessel's fuel consumption and emissions under different propulsion loads. The aforementioned data is obtained from a simulation model of a RoPax vessel. The advantage of using data from a simulation model of a RoPax vessel for the research discussed in this paper is the ability to analyse various conditions not easily reproduced on actual ships. Main research findings presented in this paper are consistent in proving that increased hull fouling leads to increased fuel consumption and emissions as high as 15% increase in extreme cases.

Keywords: *hull fouling, fuel consumption, pollutant, greenhouse gas, emissions, simulator*

Introduction

Due to new stringent regulations on ship's exhaust emissions and greenhouse gases, the shipping industry is trying to enhance energy efficiency and optimize fuel consumption with different measures. One of the main reasons for the fuel oil consumption increase is hull and propeller biofouling. The term fouling is generally used to describe the settlement of marine plants and microorganisms on the hull surface which leads to an increase in hydrodynamic hull resistance, ship drag and fuel consumption (Oliveira and Granhag 2020). This problem was recognized by the International Maritime Organization (IMO) which resulted in a Marine Environment Protection Committee Resolution MEPC 207(62) for the control and management of ships biofouling. Nowadays, most of the newer ships have installed anti-fouling systems on board and hull coatings, however some ships have prolonged time at berth so fouling could develop quickly.

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The analysis of power loss and increased fuel consumption from the economical point of view is presented in an article with a conclusion that voyage delay and fuel consumption are impacted by the ship's state (Giorgiutti et al. 2014). The engine performance degradation due to hull fouling is emphasized in the article where results have shown that 10% of fuel costs could be saved with efficient dry dock treatment (Munk 2006). The increase of propeller shaft torque caused by hull fouling is analyzed in the paper (Tarelko 2014). This problem is changing the structure of water flow which results in affecting propeller performance and efficiency. The increased hull resistance is also affecting the operating conditions of the crankshaft, pistons, cylinder cover, thrust bearings and turbocharger (Dere et al. 2016). Figure 1 presents the layer of marine plants and organisms on the ship's hull. The goal of this paper is to analyze how different percentages of hull fouling are affecting the ship's speed, fuel consumption and amount of air pollutants such as nitrogen oxides and carbon dioxides.

Figure 1. *Fouled Hull Before Cleaning*[1]

Methodology

The simulator used for the research in this paper is Wärtsilä ERS-LCHS 5000 TechSim engine room simulator, owned by the Maritime department of the University of Zadar. The modelled vessel is a RoPax ferry with twin four stroke medium speed non-reversible MAN B&W 8L32/40 diesel engines and controllable pitch propellers [8]. The ship model particulars are shown in Figure 2. This

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[1] https://www.we4sea.com/blog/the-effect-of-a-hull-cleaning-and-how-to-measure-it. (last accessed on 24.05.2022).

specific simulator model was based on an actual vessel (Bornholms Trafikken RoPax Ferry) and was validated against measurements taken on actual RoPax ferries sailing in the Adriatic Sea on routes between Italy and Croatia (Orović et al. 2022).

Some of the many features of the aforementioned simulator model are introducing various environmental and fault variables during vessel navigation such as environmental loads, late and early fuel injection, piston ring wear, damaged fuel nozzle etc. One of these variables is hull fouling degree which is used for the research in this paper. The limitations of using simulated data for scientific research is the possible inaccuracy of the mathematical model used for simulator programming. This can only be validated using data from onboard measurements on actual vessels.

Figure 2. *RoPax Ship Model Particulars (ERS 5000 TechSim 2019)*

- Length, overall – 125 m
- Breadth, molded – 23.4 m
- Designed draft, molded – 5.3 m
- Service speed – approx. 19 knots

Propulsion:

- 2 x MAN 8L32/40 Four stroke, medium speed, turbocharged, non-reversible main diesel engine, MCR 4,000 kW at 750 RPM
- 2 x Controllable Pitch Propeller (CPP)
- CPP Bow Thruster 1000 kW
- 2 x Fin Stabilizers

Electric Plant:

- 3 x Diesel Generator 600 kW, 450V AC, 60 Hz, 3 ph (diesel engine – CAT 3508B)
- 1 x Shaft Generator (PTO) 1160 kW, 450V AC, 60 Hz
- Emergency Diesel Generator 260 kW, 450V AC, 60 Hz

Area of navigation chosen for the simulations is the Adriatic Sea, however since environmental loads i.e., wind, waves, wave spectrum and sea current, were not simulated for the purposes of this research the area of navigation is of little importance and of no impact. The speed parameter, therefore, can be viewed as both speed through water (STW) and speed over ground (SOG). Without environmental load variables the sea is perfectly calm and the simulated vessel is sailing in ideal conditions. Fuel used for the combustion process in the main engines is a distillate marine fuel mark “X” (DMX) with less than 0.1% of sulphur content. The simulated parameters recorded for the purpose of this research were vessel speed (STW/SOG) shown in knots (kn), shaft power shown in kilowatts (kW), specific fuel oil consumption (SFOC) shown in grams per kilowatt-hour (g/kWh), carbon dioxide emission (CO_2) shown in percentage by volume (%) and nitrogen oxides emission (NO_x) shown in parts per million (ppm). The degree of hull fouling was chosen based on experience in this field of research and was set at values expressed in percentage (%) as is shown in Table 1. The degree of hull fouling was changed at specific time intervals chosen to give the parameters recorded enough time to stabilise at a relatively constant value. The observed time needed for parameter stabilisation was two minutes.

Table 1. *Hull Fouling Degree Change Related to Specific Time Intervals*

T (min)	0:00	2:00	4:00	6:00	8:00	10:00	12:00
Hull fouling (%)	0	25	50	75	85	95	100

All of the above-mentioned parameters were simulated under two different engine loads. The engine loads simulated are 90% and 80% of maximum continuous rate (MCR). These engine loads were chosen based on usual optimum engine load for the specific engine type used in the referent vessel and to simulate two different regimes of navigation in order to analyse the impact of hull fouling in different navigational regimes (L+V32/40 Project Guide 2010).

Results and Discussion

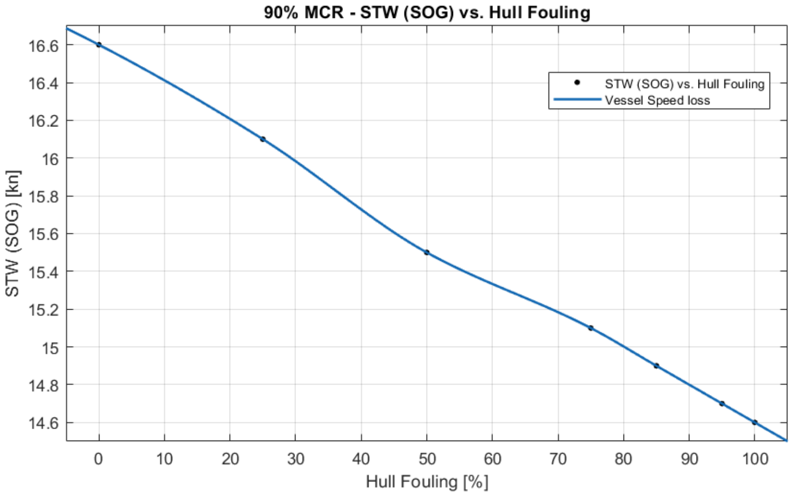
The purpose of this research was to gain insight about potential ship fuel consumption and emission increase due to a changing degree of hull fouling (HF) within the frame of conditions defined in the previous chapter. The results of the research are presented through various parameters (speed through water/over ground, shaft power, specific fuel oil consumption and CO_2/NO_X emissions). Two separate simulations were made based on two different navigational regimes (engine loads). The data accumulated for the 90% MCR engine load is shown in Table 2.

Table 2. *Effect of Hull Fouling at 90% MCR Engine Load Navigational Regime*

HF (%)	STW / SOG (kn)	Shaft Power (kW)	SFOC (g/kWh)	CO_2 (%)	NO_X (ppm)
0	16.60	2636	193.04	6.70	875.54
25	16.10	2666	193.04	6.70	885.70
50	15.50	2686	191.35	5.80	912.74
75	15.10	2700	191.35	5.80	917.08
85	14.90	2705	191.35	5.80	918.55
95	14.70	2710	191.35	5.80	919.98
100	14.60	2714	191.35	5.80	920.50

In the 90% MCR simulation, vessel speed reduction was analysed with respect to the reference vessel speed obtained in zero hull fouling value condition. The reference speed for this particular vessel was determined to be 16.60 kn under the 90% MCR engine load. Considering the ideal sea conditions with the only added resistance factor introduced in the form of steadily increasing hull fouling a significant speed loss occurs as is shown in Figure 3. The largest speed loss occurred in the transition between zero (0%) value hull fouling and 25% of hull fouling which amounts to 0.5 kn of speed loss. The second largest speed loss amounts to 0.4 kn and occurs in the transition between 50% and 75% of hull fouling. Vessel speed at the end of the simulation where hull fouling is at 100% value is 14.6 kn which indicates the total speed loss of 2.0 kn.

Figure 3. *Impact of Hull Fouling on Vessel Speed Loss at 90% MCR*



Continuing with the 90% MCR simulation, the shaft power has shown a steady but not a significant increase with every step of hull fouling degree rise. The reference shaft power for this analysis is 2636 kW at zero (0%) value of hull fouling while the maximum shaft power at 100% hull fouling value is 2714 kW which indicates an increase of 78 kW as is shown in Figure 4. Specific fuel oil consumption (SFOC) exhibits only one instance of change in value at the step between 25% and 50% of hull fouling value as is shown in Figure 5. This decrease of SFOC which equates to a drop from 193.04 g/kWh to 191.35 g/kWh can be attributed to an increase of turbocharger efficiency for this specific engine approximately at 2680 kW of shaft power.

Figure 4. *Impact of Hull Fouling on Shaft Power at 90% MCR*

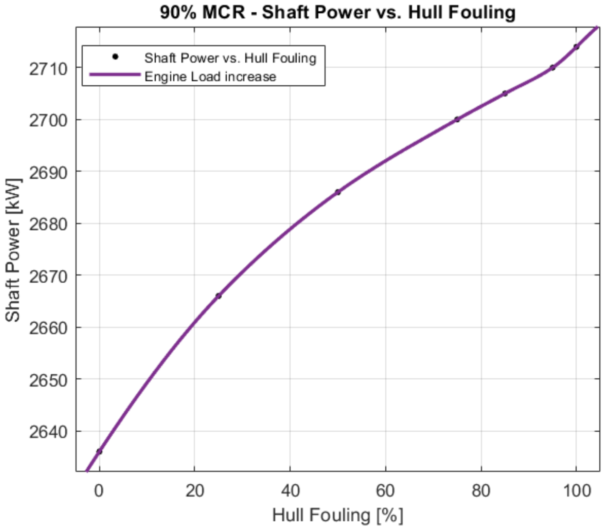
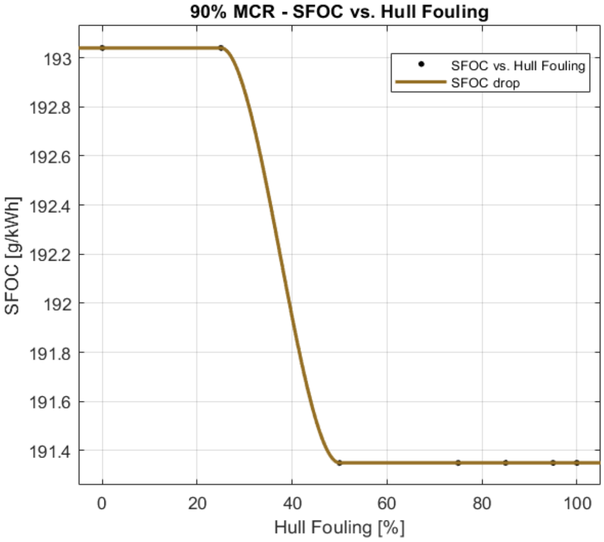


Figure 5. *Impact of Hull Fouling on SFOC at 90% MCR*



The last two parameters of the 90% MCR simulation are CO_2 and NO_X emissions for which the respective reference values, at zero (0%) hull fouling value, are 6.70% by volume of CO_2 and 875.54 ppm of NO_X. CO_2 exhibits a singular drop at the same point where SFOC decreases, as is shown in Figure 6, which is consistent with the increased turbocharger efficiency argument. On the other hand, NO_X shows a constant increase in value with every step of hull fouling value increase which can be attributed to higher maximum combustion temperatures which are a result of a consistently higher engine load indicated by the shaft power parameter. The impact of hull fouling on NO_X emission is shown in Figure 7.

Figure 6. *Impact of Hull Fouling on Carbon Dioxide Emission at 90 % MCR*

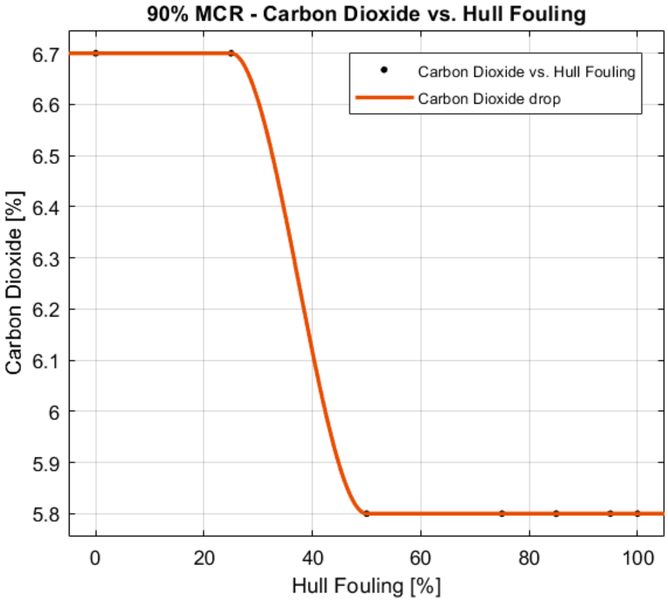
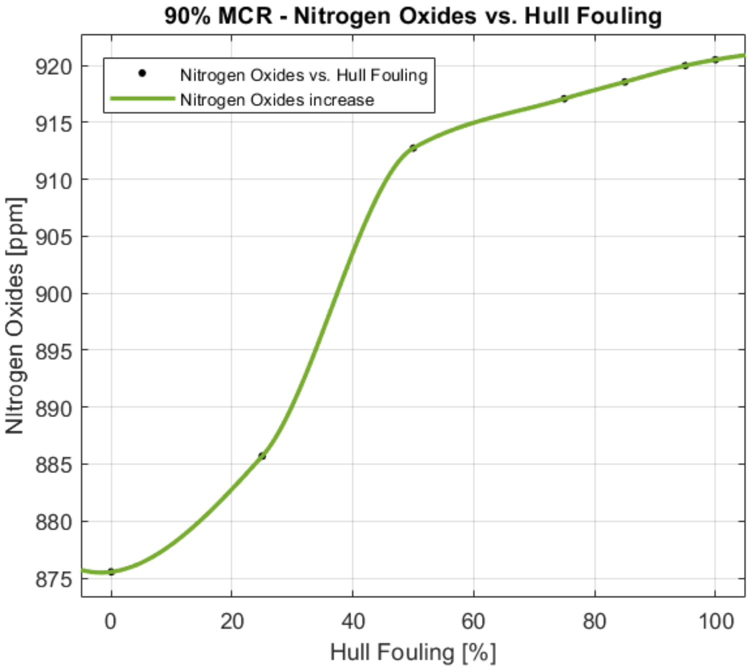


Figure 7. *Impact of Hull Fouling on MCR Nitrogen Oxides Emission at 90%*



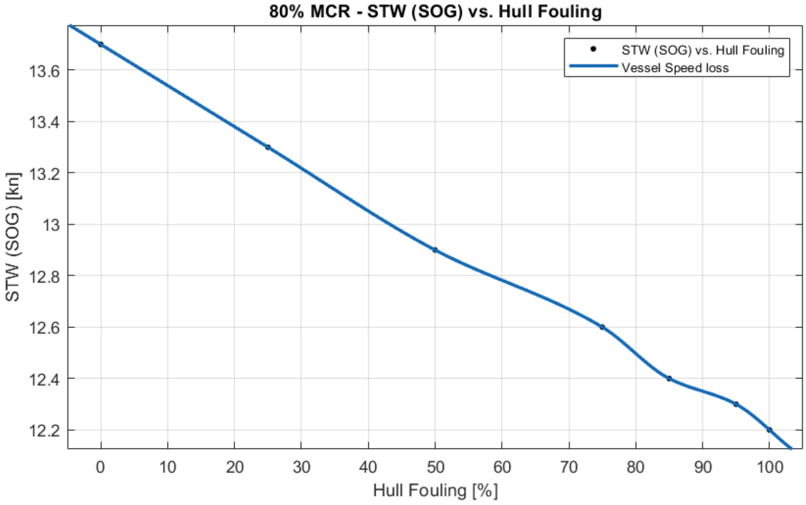
The second scenario simulated was at 80 % MCR engine load as stated in the text above. The data accumulated in this simulation is shown in Table 3.

Table 3. *Effect of Hull Fouling at 80% MCR Engine Load Navigational Regime*

HF (%)	STW / SOG (kn)	Shaft Power (kW)	SFOC (g/kWh)	CO_2 (%)	NO_X (ppm)
0	13.70	1768	196.35	6.30	678.61
25	13.30	1785	196.42	6.40	684.51
50	12.90	1801	196.42	6.40	689.51
75	12.60	1816	196.42	6.40	697.96
85	12.40	1824	196.42	6.40	699.98
95	12.30	1828	196.42	6.40	701.59
100	12.20	1832	196.42	6.40	702.81

The reference value of vessel speed is 13.7 kn at zero (0%) value of hull fouling. Speed loss is consistent with the increase of hull fouling degree, as is shown in Figure 8, and is significant like the speed loss in the first (90% MCR) simulation. However, the total speed loss is less than in the first scenario, and it equates to 1.5 kn with the lowest vessel speed being 12.2 kn at 100% hull fouling value.

Figure 8. *Impact of Hull Fouling on Vessel Speed Loss at 80% MCR*



Shaft power exhibits a consistent increase with the increase of hull fouling value with it being lesser than at 90% MCR load by approximately ~ 900 kW. The reference shaft power, at zero (0%) hull fouling value is 1768 kW. Maximum shaft power, at 100% hull fouling value, equates to 1832 kW exhibiting a total shaft power increase of 64 kW which is less than at the 90% MCR engine load scenario. Shaft power increase is shown in Figure 9.

However, SFOC is exhibiting different behaviour in this scenario than in the 90% MCR one, as shown in Figure 10. Instead of a decrease like in the first scenario, here there is a slight increase at the step between 0% and 25% hull fouling value and then a constant unchanging value until the end of the simulation equating to 196.42 g/kWh with the reference value of SFOC equating to 196.35 g/kWh. This indicates that there is a slight drop in the turbocharger efficiency for this type of engine before it starts increasing again which is also indicated by the value of CO_2 emission.

Figure 9. *Impact of Hull Fouling on Shaft Power at 80 % MCR*

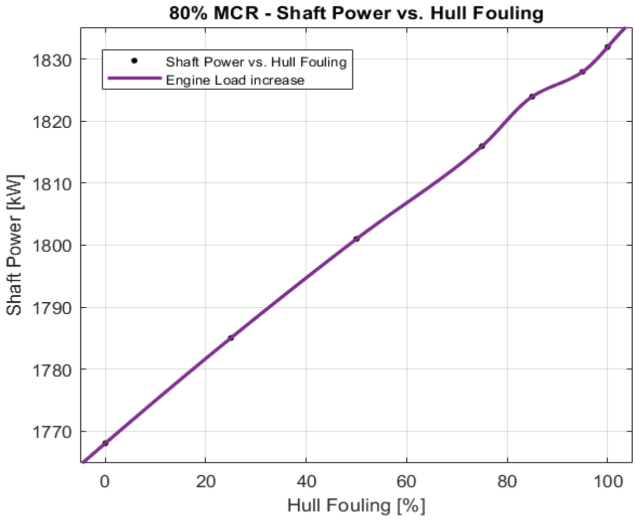
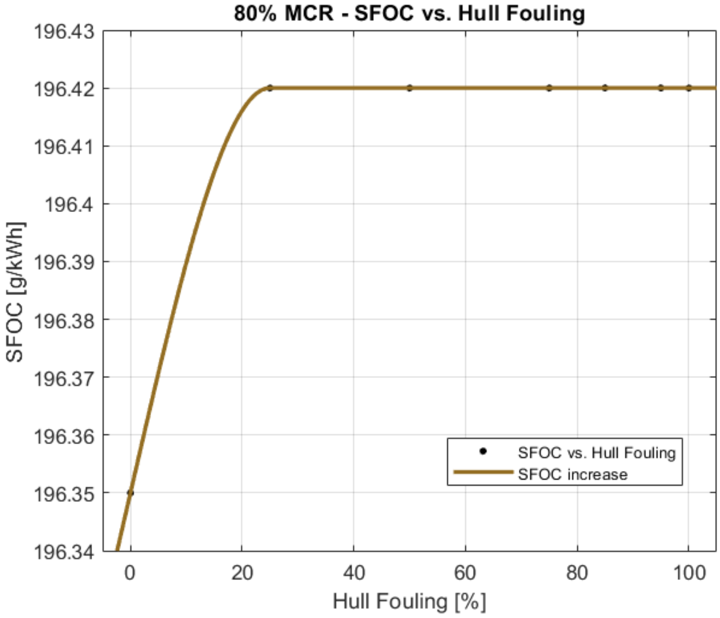


Figure 10. *Impact of Hull Fouling on SFOC at 80% MCR*



CO_2 reference value is 6.30% by volume. The only increase is at the same step as with the SFOC increase when hull fouling increases from 0% to 25% value, as shown in Figure 11. The increased value of CO_2 at that point equates to 6.40% by volume and stays constant until the end of the simulation. This complements the turbocharger efficiency discussion explained in the text above. Unlike SFOC and CO_2, NO_X is exhibiting the same constant increase in value with the increase of hull fouling and shaft power as in the first (90% MCR) scenario. This is consistent with the argument of increased engine load and maximum combustion temperatures in the cylinders of the main engine. NO_X increase is shown in Figure 12.

Figure 11. *Impact of Hull Fouling on Carbon Dioxide Emission at 80% MCR*

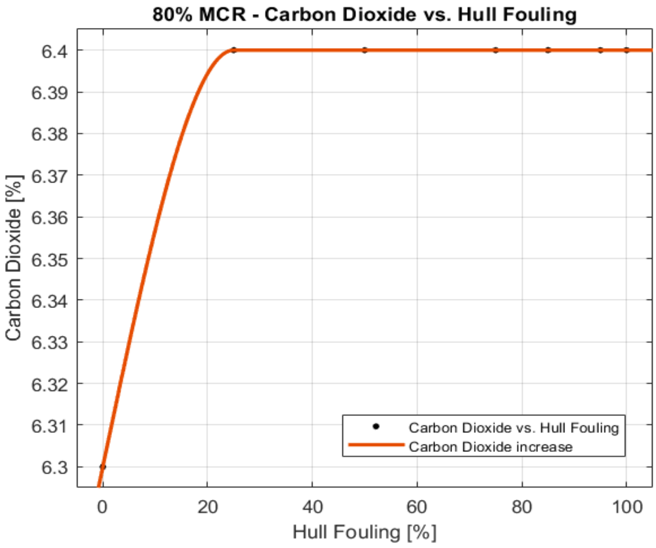
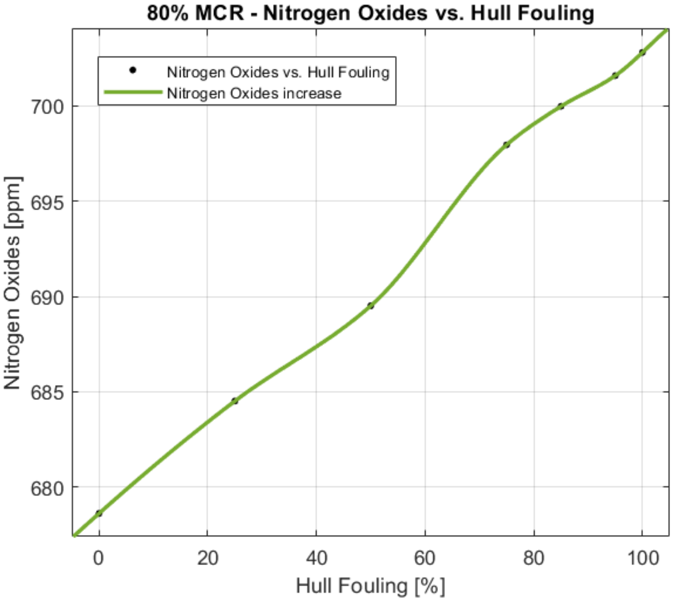


Figure 12. *Impact of Hull Fouling on Nitrogen Oxides Emission at 80% MCR*

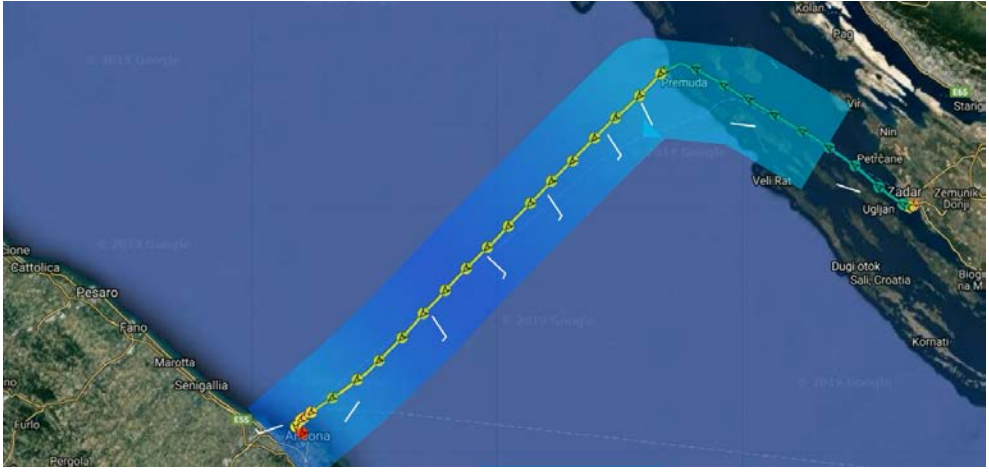


Of all the above analysed parameters the largest impact of hull fouling was on vessel speed loss at the 90% MCR engine load scenario and thus this parameter was chosen for the calculation in the example presented in the following text.

The following calculation will exhibit the effect of vessel speed loss due to full fouling on fuel consumption and emissions on an actual RoPax ferry route between Italy and Croatia. The ferry route chosen for the example is Zadar – Ancona with the length of 102 NM (nautical miles), shown in Figure 13. The parameters used for the calculation are from two hull fouling steps from the 90% MCR scenario and are as follows:

- zero value hull fouling with the reference vessel speed of 16.6 kn and
- 95% hull fouling value with the vessel speed of 14.7 kn.

Figure 13. *Zadar – Ancona Ferry Route (Pavin 2021)*



The recorded value of specific fuel oil consumption for zero value hull fouling equates to $SFOC = 193.04\ g/kWh$ while the value of specific fuel oil consumption for 95% hull fouling equates to $SFOC = 191.35\ g/kWh$. Shaft power for zero value hull fouling equates to $P = 2636\ kW$ while the value of shaft power for 95% hull fouling equates to $P = 2710\ kW$.

To calculate fuel consumption expressed in mass per unit of time the following formula was used:

$$FC = \frac{SFOC \cdot P}{1000} \tag{1}$$

where FC is fuel consumption expressed in mass per unit of time (kg/h), *SFOC* (g/kWh), and *P* is shaft power (kW).

The fuel consumption calculated for the 0% hull fouling voyage equates to $FC_0 = 508.85\ kg/h$ while the fuel consumption calculated for the 95% hull fouling voyage equates to $FC_{95} = 518.56\ kg/h$.

Due to the occurring vessel speed loss the time of voyage will differ and thus needs to be calculated and introduced into the total calculation. In order to calculate the voyage time between the ferry ports of Zadar and Ancona the following formula was used:

$$t = \frac{s}{v} \tag{2}$$

where *t* represents voyage time (h), *S* represents voyage lenght (NM), a *V* represents vessel speed (kn).

The calculated voyage time for the 0% hull fouling scenario equates to $t_0 = 6.15\ h$ (6 hours 9 minutes) while the voyage time for the 95% hull fouling scenario equates to $t_{95} = 6.94\ h$ (6 hours 56 minutes) indicating that the 95% hull fouling voyage is 47 minutes longer.

By multiplying voyage time (t) with fuel consumption (FC) the total fuel consumption for each voyage is calculated. The total fuel consumption for the 0% hull fouling voyage equates to $FC_{0,TOT} = 3129.43\ kg$ while the total fuel consumption for the 95% hull fouling voyage equates to $FC_{95,TOT} = 3598.81\ kg$. This calculation shows a significant increase of total fuel consumption due to increased hull fouling. The total fuel consumption is higher in the 95% hull fouling scenario by 469.38 kg of fuel or by ~ 15%. The increased fuel consumption per voyage indicates a significant increase in CO_2 and NO_X emissions as well.

Conclusion

The results of this research were effective at proving that increased hull fouling leads to increased fuel consumption and by extension to increased exhaust gas emissions. Considering that the prevalent fuels used in maritime transportation are still fossil fuels this leads to increased greenhouse gas and pollutant emissions.

The results have also shown that voyage delay and energy efficiency are impacted by the degree of fouling. The example shown in the text above indicates how significant the impact of a ship's hull fouling is on voyage time and fuel consumption, thus if daily fuel oil consumption in that scenario is multiplied by ongoing fuel oil price it leads to high financial costs. The improved propulsion efficiency and reduced daily fuel consumption could be achieved by periodic hull cleaning and adequate dry-docking. Moreover, the optimal frequency of hull maintenance could be selected depending on differences in fuel consumption. The data in this research can be used to further analyse the maritime vessel exploitation economy and to improve hull maintenance strategies.

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