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The Impact of the Underwater Hull Anti-Fouling Silicone Coating on a Ferry's Fuel Consumption

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Abstract: There are well-known specifics of ro-pax ferry shipping, such as the time factor as a consequence of keeping a regular timetable and the priority given to minimizing heeling, pitching, and rolling caused by maximum focus on passenger comfort and ro-ro cargo safety. It is also extremely important to control the ferry's fuel consumption, being one of the most important cost components. The aim of the article is to draw the attention of shipping company managers to the great potential that lies in the use of routine operational data, collected exclusively on board the ferries. It is worth noting that the research in this paper is based on standard office software packages rather than advanced statistical methods of data analysis, which are usually not accessible for shipping managers. Contrary to typical ocean-going vessels, there are a number of factors that need to be taken into consideration when analyzing ro-pax ferry fuel consumption. Moreover, these factors occur, in many cases, accidentally and, thus, they are difficult to observe on board the ferry without utilizing expensive and time-consuming methods. The possibility of fuel control is important not only for economic reasons but also due to air pollution caused by engine exhausts. The article presents an estimation of increased fuel consumption caused by the degradation of the hull silicone anti-fouling coating. The presented estimations of fuel consumption may be treated as the base for calculations of the economic effectiveness of ferries. The attempt to resolve the above-mentioned problem was made on the basis of research on a real ferry, which took place on the Świnoujście-Trelleborg line between 2007 and 2019.

Keywords: ferry navigation; fuel consumption; hydrometeorological conditions; main engine load; marine traffic engineering; restricted areas; silicone anti-fouling coating

1. Introduction

The ability to estimate fuel consumption is one of the key aspects of merchant ship operation and requires advanced statistical methodology [1]. There are formulas for determining the fuel consumption of ships taking into account loading conditions [2]. In the case of ferry berthing, it is extremely important to maneuver effectively in the most difficult hydrometeorological conditions. Any reduction in draft changes the maneuverability by increasing the windage area, among other factors. Therefore, action should be taken (including ballasting) to maintain a stable draft, optimal from the point of view of maneuvering. For this reason, for ferry navigation, dependencies may be especially useful that specify fuel consumption in which the displacement of the ferry is not included [3,4]. Usually, based on the technical data and the results of the sea trials, a fuel consumption curve is determined for a given vessel speed [5,6]. The ship's owner determines the maximum fuel consumption and corresponding minimum attainable speed for the ship under acceptable hydrometeorological conditions. Due to the possibility of determining significant factors disrupting the amount of main-engine fuel combustion, ship charter agreements precisely define the fuel consumption during navigation only in non-restricted areas [7]. Most often, the ship is obliged to comply with charter party requirements regarding fuel consumption if the sea state does not exceed four degrees on the Douglas scale or the wind force is not more than five on the Beaufort scale [8]. The above-described principles no longer apply when there are vertical or horizontal restrictions in a given area when the ship is maneuvering or navigating with a pilot on board. Therefore, in such cases, typical charter party agreements do not contain precise pre-imposed fuel consumption quantity standards. This situation occurs due to the fact that it is extremely difficult to determine fuel consumption when additional movement resistances are observed. These resistances are the result of frequent course and speed changes and the effects of shallow water. However, during the operation of a commercial ship, for example, bulk carrier or general cargo ship, periods of sailing in unrestricted areas are dominant. As a result, it is here that fuel efficiency criteria can be effectively defined.

The situation is different in the case of liner shipping, where vessels very often sail in restricted areas. However, on the Baltic Sea, ferries and other ships sail entirely in restricted areas; thus, they often change both course and speed [9]. In other words, the number of factors that may have an influence on fuel consumption seems to be enormous, and moreover, is difficult to estimate precisely in such conditions.

The next section of the article presents the ferry as the research object, along with a brief description of the area in which the ferry operates. The same section also shows the sources and the method of data collection and the initial data classification. The aim of Section 3 is to analyze the collected data. It also focuses the readers' attention on the possible impact of the degradation of silicone coating of the underwater part of the hull on the increase of ferry fuel consumption. At the end of the article, the obtained results are discussed. Finally, the disruptive factors that may affect the conclusions of the research are presented.

2. Materials and Methods

2.1. Object of the Study

The assessment of ferry fuel consumption is important for the economic results of a business project. However, the existing methods based on the ship's daily reports require advanced mathematical formulae for analysis [10]. This article proposes a simple method of controlling the ferry fuel consumption with research based on operational data available on the vessel. The data comes from routine observations carried out by the ferry crew and noted in the ship's logbook. For the data analysis, the popular spreadsheet Microsoft Excel was used but with the statistical analysis block, which allowed the possibility of using the method among people with only basic spreadsheets skills. The direct purpose of the research is to exemplify the increase of fuel consumption as a result of time degradation of the anti-fouling coating. The object of the research was a ferry (overall length 158 m, width 28.5 m, twin controllable pitch propeller, with the total power of two engines being 7920 kW) with silicone paint covering the entire underwater section of the hull. Silicone paint smoothness and elasticity (being the bending ability under the influence of overboard water flow during the movement of the ferry) allows for detachment of organisms trying to stick to the hull. The effectiveness of silicone coating has been proven for faster ferries, especially in the absence of ice; however, on the tested ferry, silicone coating was applied experimentally due to its slow speed, with the highest value not exceeding 16 kts. The silicone coating was applied in August 2007, and since then, significant renovation has not been carried out Figure 1 with the only maintenance being hull water pressure washing operations undertaken during dry docking (five times). The ferry operates continuously in similar loading conditions and, regardless of loading condition differences, ballasts are used to achieve the same optimal trim and draft. Therefore, this factor is omitted in the data analysis.

Figure 1. View of the silicone coating before high-pressure washing with water at the shipyard in June 2019.

2.2. Ship's Operational Data

Operational data were collected during 6663 round-trip voyages between two southern Baltic ports: Trelleborg and Świnoujście. These so-called "sea passages" did not include areas covered by compulsory pilotage as specified in the relevant regulations for both ports. Data were recorded separately for every voyage and for each set, the time (days) from the moment of applying the anti-fouling silicone coating was also specified. Because the aim of the research is not to compare the silicone coating to the classic anti-fouling biocide coating, the data does not include the period before silicone paint was applied.

The average speed (in kts) is based on the length and time of the sea passage. The average setting for both controllable pitch propellers of the ferry is specified as percentage of the pitch angle of the propeller blade, in the range of 0%–100%. It is worth noting that neither pitch propeller settings are stable during the sea passage; settings are often changed, among other things, due to the necessity of adjusting the passage time, as stated in the planned timetable. Changes of pitch settings are also forced by ferry speed maneuvers, which may take place due to anti-collision actions in accordance with COLREG Rules. Speed adjustment is also required to ensure ferry safety in severe hydrometeorological conditions.

The average length of the "sea passages" (pilot station–pilot station) was 88.8 Nm (Figure 2). However, due to the lack of stabilizing devices and in order to ensure the safety of passengers and ro-ro cargo in severe hydrometeorological conditions, the weather route was often extended, in extreme cases increasing up to 177.7 Nm. The average specific fuel consumption (kg/Nm) over the "sea passage" and the average direction and wind force on the Beaufort scale were the next recorded data. Wind data were determined on the basis of an anemometer located at a height of 47 m above sea level. This device is coupled with the data of the continuous automatic (relative wind–real wind) conversion system. The averaging of prevailing winds data was subjectively made by officers on watch based on their own nautical experience. Figure 3 presents the frequency of occurrence of three types of weather/winds according to ferry navigator classification:

1. Calm weather—1–3 Beaufort scale wind. It does not affect navigation and does not produce the need for the reduction of propeller settings due to weather.
2. Moderate weather—4–6 Beaufort scale wind. Its strength can affect navigation and may require propeller setting reductions due to weather conditions.

3. Severe weather—7–10 Beaufort scale wind. This strength has a significant impact on navigation and enforces reduction in propeller settings due to weather. Additionally, the route may be changed as per the captain's instruction.

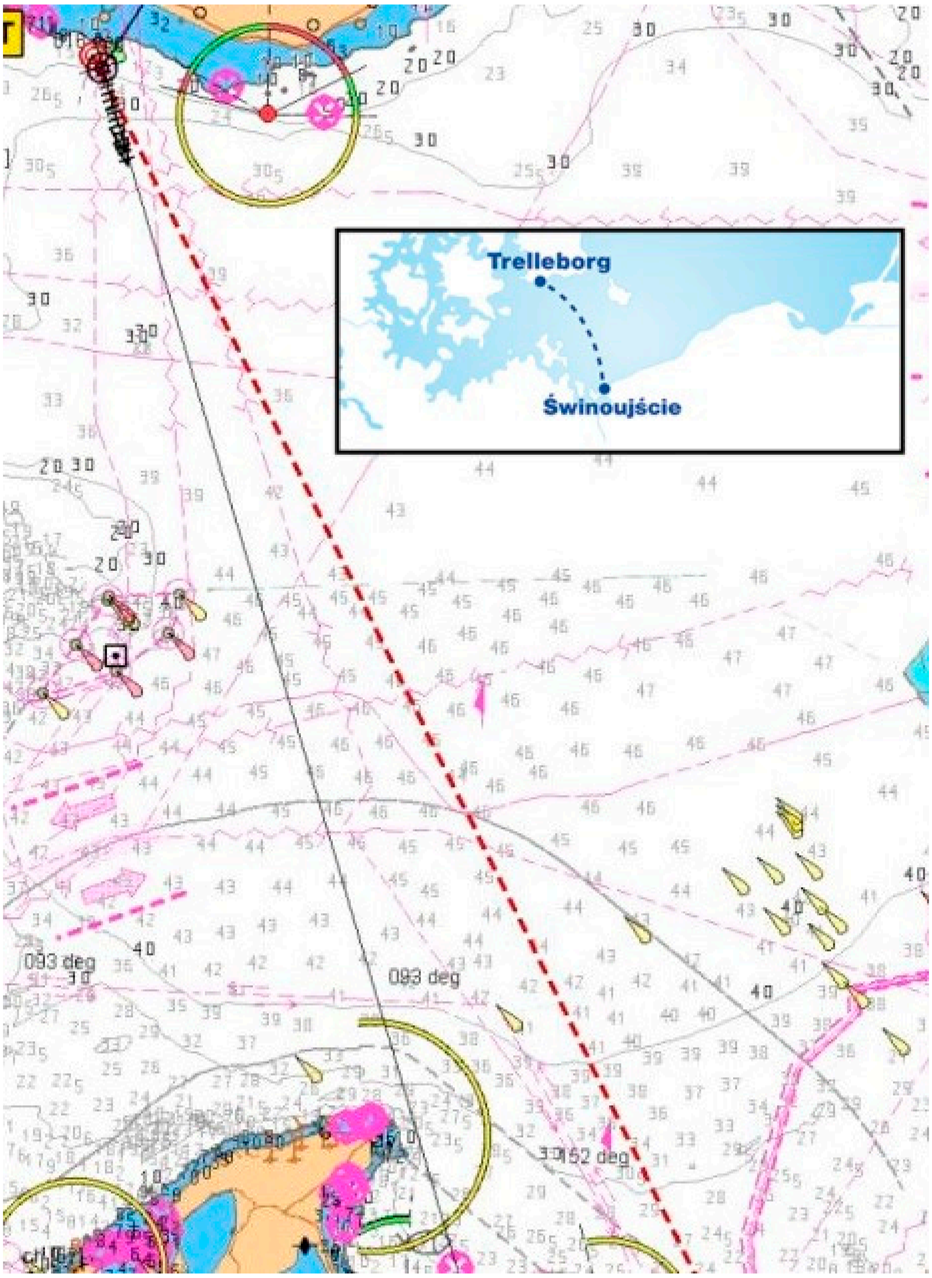

Figure 2. The northern part of the Trelleborg (Sweden)—Świnoujście (Poland) ferry route in the Southern Baltic Sea.

The distribution of wind forces (Figure 3) is based on ferry navigator logbook notices, made only when the ferry undertook voyages, and do not contain periods of planned breaks in ferry operation. The distance traveled by the ferry was calculated on the basis of the DGPS-log unit. Fuel consumption data came from flow meters accessible to mechanic officers who also receive data on the average settings of the propellers.

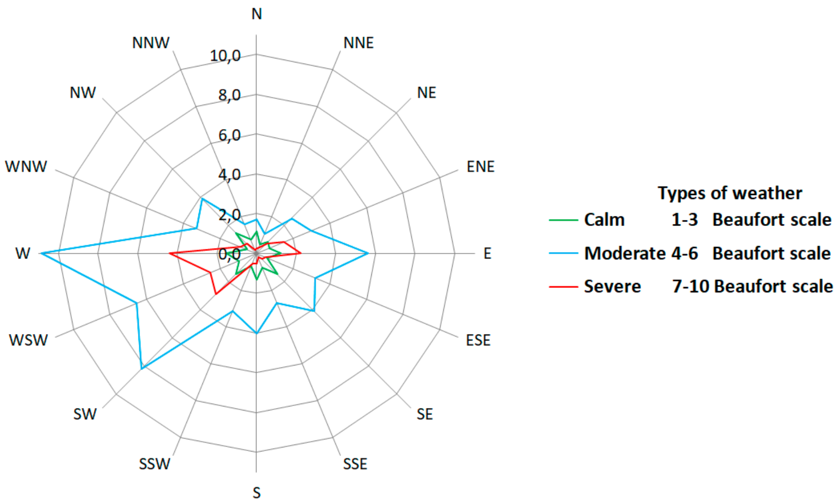

Figure 3. Distribution (%) of the forces and directions of winds observed during the research period.

3. Ferry Fuel Consumption Analysis

3.1. General Operational Characteristics

On the horizontal axis of all subsequent figures, the number of days with the application of the silicone coating is marked. Here, there are 12 vertical markers, one for each annual period. During the ship's docking, the silicone coating was washed only by high pressure water. The characteristics presented in Figures 4–7 have vertical dashed lines placed for each of the five dry dock cleanings. All diagrams include operational data as a function of the number of days since the silicone coating was applied.

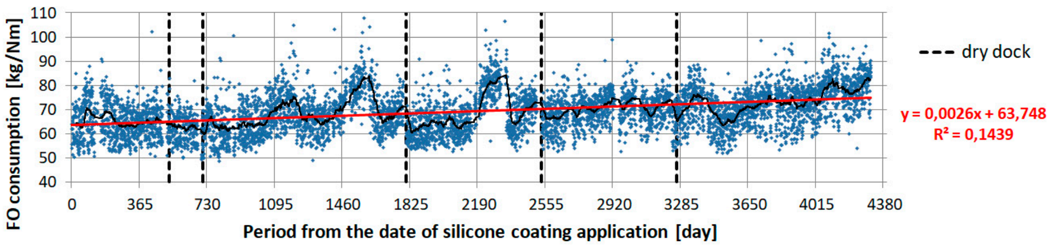

Figure 4. Main engine average fuel consumption for the whole period of study on the route Świnoujście/Trelleborg—both directions.

Figure 4 presents a diagram of average fuel consumption for both directions of voyages. In this diagram, fuel consumption fluctuations during each annual period are presented. These fluctuations significantly hinder the selection of the curve for modeling fuel consumption. Nevertheless, the curve shows a fairly clear growing tendency of increased fuel consumption over the period studied as well as the minimal influence of dry dock cleaning. For the above reasons, it was decided to use the simplest possible characteristic—the linear data, based on which an increased consumption from about 63.8 kg/Nm to 75 kg/Nm was observed. Calculation of daily fuel consumption on the ferry route round-trip shows additional increased daily consumption for the average length of a round-trip (11.2 kg/Nm × 2 × 88.8 Nm) 1989 kg.

The timetables are not symmetrical in both directions, and therefore, the passage times are different for the journey to Świnoujście and to Trelleborg. In addition, the fuel consumption distribution was subject to multiple timetable adjustments over a period of almost 13 years. Reduction in the passage time entails increasing of speed, which, in turn, implies increasing of fuel consumption. Among other things, further analysis is required to eliminate factors interfering with the relationship presented in Figure 4.

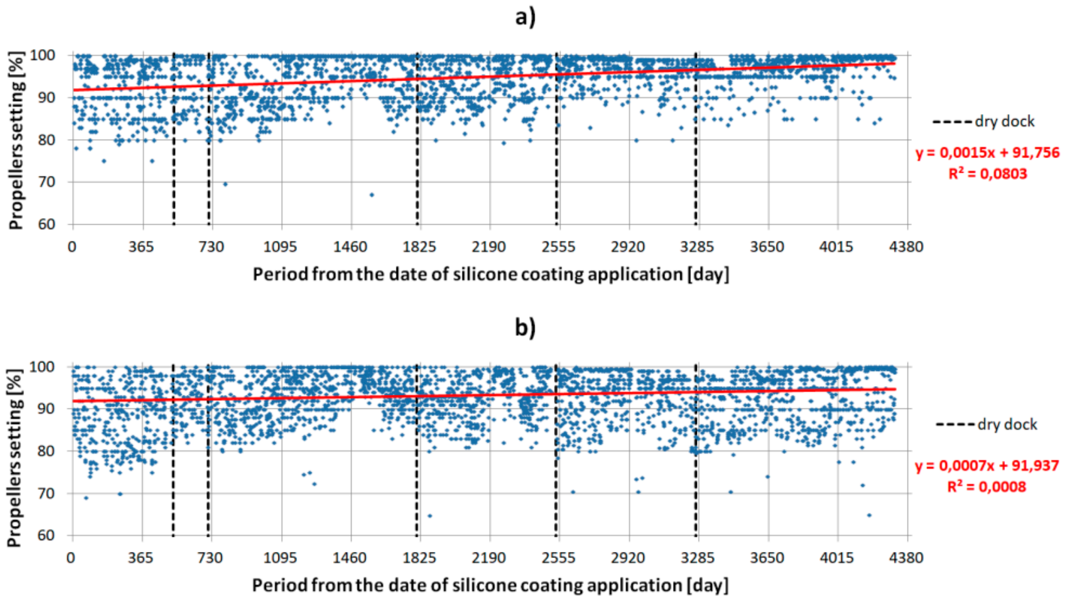

Figure 5. Average variable pitch propeller settings for the entire period of study on the Świnoujście/Trelleborg route—divided into two voyage directions. Ferry bound for Świnoujście (**a**) and for Trelleborg (**b**).

On the route to Świnoujście, the variable pitch propeller setting changed from 91.7% to 98.2% (absolute increase of 7.0 percent), and to Trelleborg, the setting changed from 91.9% to 95.0% (absolute increase of 3.3 percent). The above situation is presented in Figure 5.

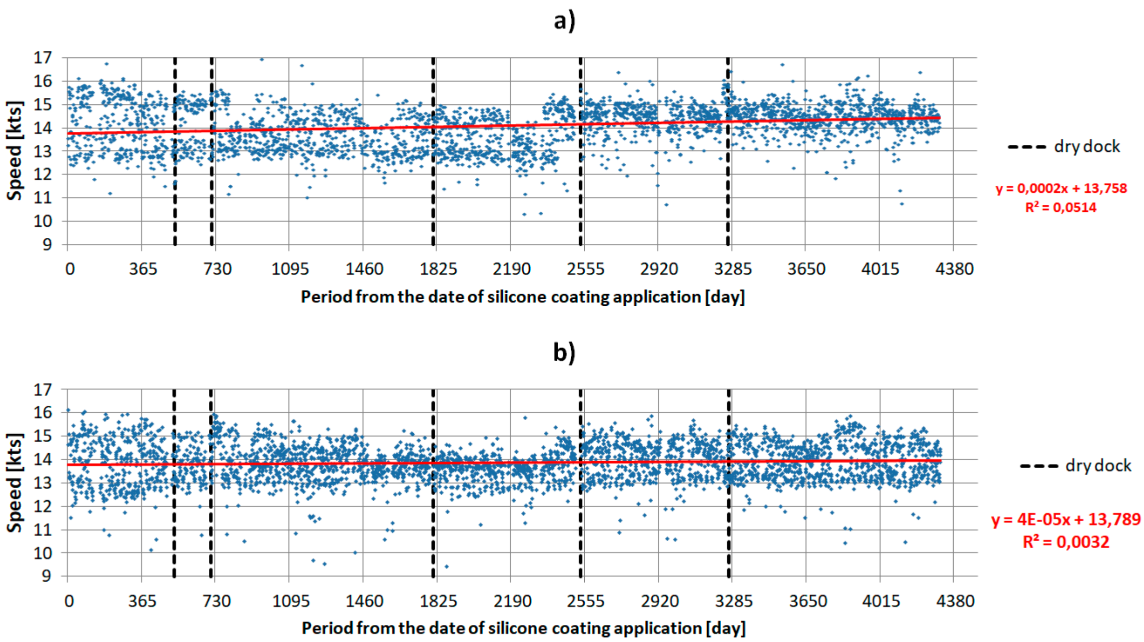

Figure 6. Average speed for the entire period of study on the route Świnoujście/Trelleborg—divided into two voyage directions. Ferry bound for Świnoujście (**a**) and for Trelleborg (**b**).

As shown in Figure 6, changes to the average speed of the ferry to Świnoujście from 13.76 kts to 14.62 kts (increase of 6.4%) occurred and on the road to Trelleborg, from 13.79 kts to 13.96 kts (increase of 1.2%). The above increases in average speed needed to be accompanied by an increase to the setting of the variable pitch propeller (Figure 5).

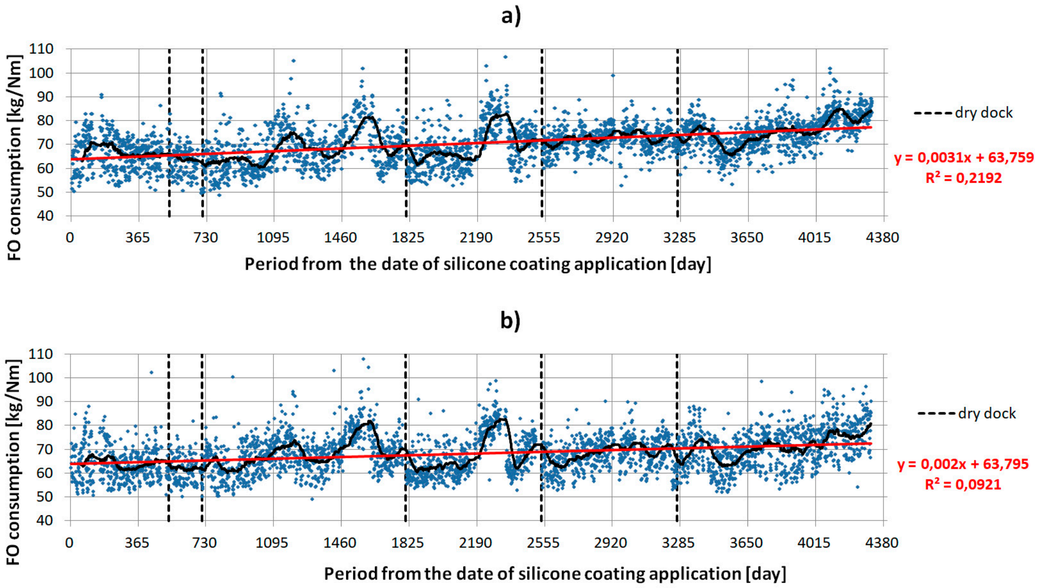

Figure 7. Main engine average fuel consumption for the entire period of study on the Świnoujście/Trelleborg route—divided into two voyage directions. Ferry bound for Świnoujście (**a**) and for Trelleborg (**b**).

Figure 7 shows fuel consumption characteristics separated for both directions traveled by the ferry. While the fuel consumption on the route to Trelleborg increased in the period under consideration by 8.6 kg/Nm, on the route to Świnoujście, this increase was higher, reaching 13.4 kg/Nm. This demonstrates a systematic shortening of the passage time as a result of timetable changes. At the same time, the phenomenon of passage shortening can be seen much more clearly in the direction of Świnoujście. Confirmation of this is shown in Figure 6.

3.2. Detailed Analysis of Fuel Consumption

The general relationship of the ship's propulsion fuel consumption without the influence of additional factors, such as shallow water or wind, etc., can be represented as [4]:

$$Cons = k \times V^{n}$$

where *Cons* is fuel consumption per unit of time, *k* is an individual factor, depending on the ship's characteristics and type of propulsion, *V* is the ship's instantaneous speed, *n* is an exponent within a value of 3 to 4.

Speed and fuel consumption are related in theory by the given equation; however, using the average speed and average fuel consumption rather than the moment-by-moment values makes the equation inadequate because the speed will vary during the passage, and the type of variation depends on the weather as well as the need to keep to timetabled arrival and departure times. This is most clearly demonstrated by the situation on the passage to Trelleborg where, based on an approximation of the consumption characteristic (Panel (b) on Figures 5 and 6), a 13% increase of specific fuel consumption caused, in practice, only a barely noticeable increase of the average speed of 0.17 kts. Therefore, it seems likely that during the tests, there are different impacts on fuel consumption than from an increase of the variable pitch propeller settings and so, further attempts were made to find an answer to this question by, firstly, taking into consideration the impact of hydrometeorological conditions on fuel consumption over time since the application of the silicone anti-fouling coating.

Figures 8–11 show four cases of the ferry's movement direction relative to the wave pattern. Three types of weather signaled previously (1–3, 4–6, 7–10 Beaufort scale) have been included:

(1) With the wind and wave—Figure 8.
(2) Against the wind and the wave—Figure 9.

(3) Crosswind and large waves from the side—Figure 10.
(4) Crosswind and small waves from the side—Figure 11.

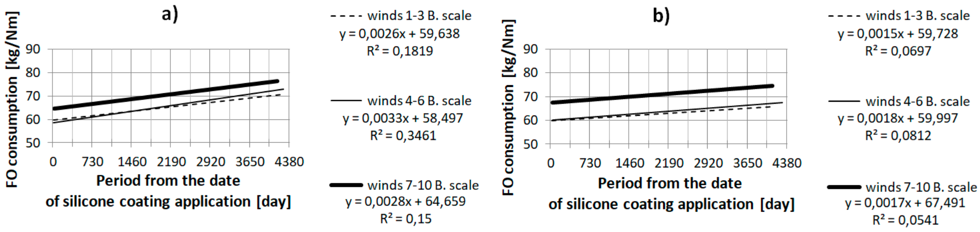

Figure 8. Average fuel consumption—sailing with the wind and wave. Ferry bound for Świnoujście, winds NW/NNW/N (**a**) and for Trelleborg, winds SE/SSE/S (**b**).

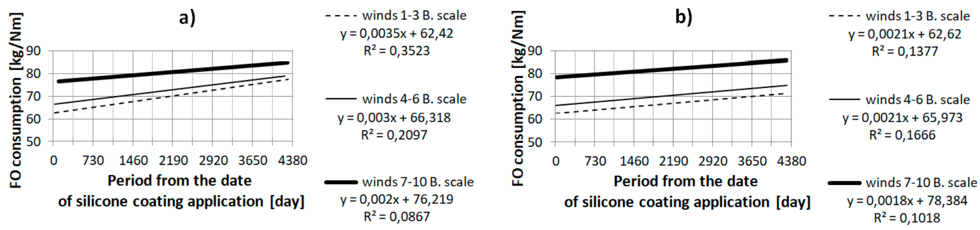

Figure 9. Average fuel consumption—sailing against the wind and the wave. Ferry bound for Świnoujście, winds SE/SSE/S (**a**) and for Trelleborg, winds NW/NNW/N (**b**).

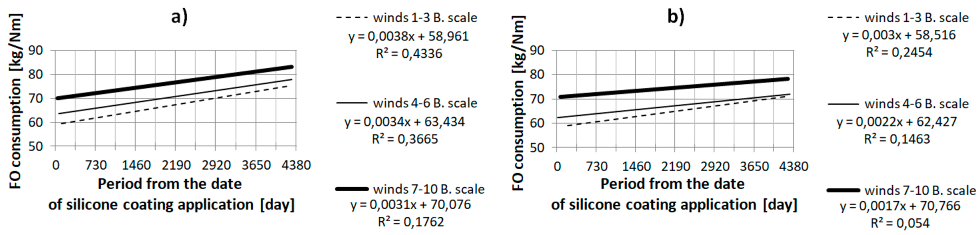

Figure 10. Average fuel consumption—sailing crosswind and large waves from the side. Ferry bound for Świnoujście, winds NE/ENE/E (**a**) and for Trelleborg, winds NE/ENE/E (**b**).

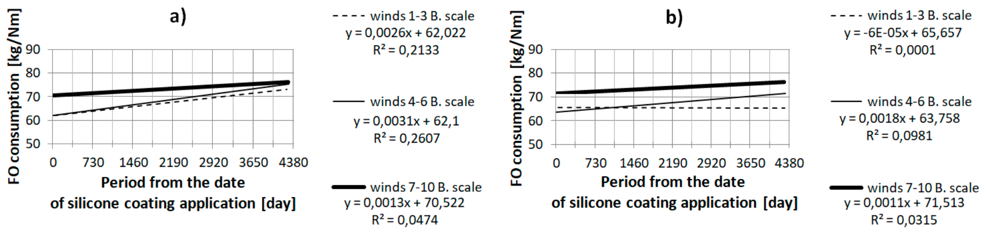

Figure 11. Average fuel consumption—sailing crosswind and small waves from the side. Ferry bound for Świnoujście, winds W/WSW/SW (**a**) and for Trelleborg, winds W/WSW/SW (**b**).

Figures 12 and 13 introduce selected options for more detailed weather conditions, as presented on previous graphs (Figures 8–11). The primary measure of choice was to analyze conditions for which the above relationship was the least visible. These conditions were met for navigation in both directions during relatively low wave action, for winds W/WSW/SW (Figure 12). Taking the above data into consideration ensured a sufficiently large number of records for subsequent analysis. The afore-mentioned wind directions occurred most often among the observed weather conditions (Figure 3), thus, further ensuring the largest possible amount of data for analysis. The following groups of variable pitch propeller settings were considered:

97%–100% - full sea speed, maximum engine power;

94%–96% - high power of engines;
85%–93% - reduced power of engines;
75%–84% - slowing down the engines below the required operating speed.

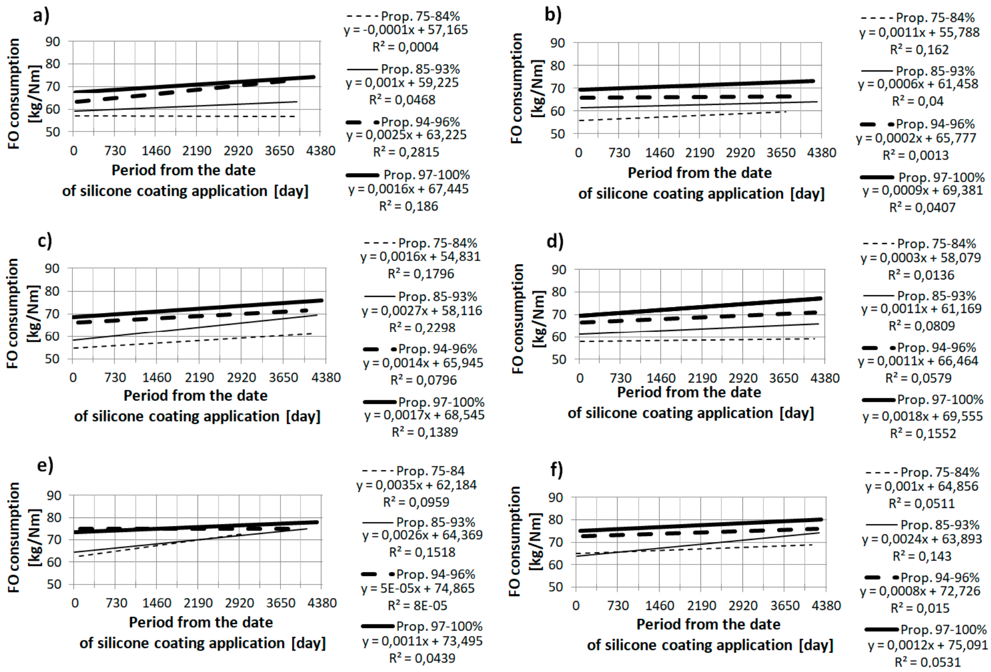

Figure 12. Average fuel consumption, sailing crosswind, small waves from the side, variable pitch propeller settings. Ferry bound for Świnoujście, winds W/WSW/SW, force: 1–3 B. (**a**), 4–6 B. (**c**), 7–10 B. (**e**), and for Trelleborg, winds W/WSW/SW, force: 1–3 B. (**b**), 4–6 B. (**d**), 7–10 B. (**f**).

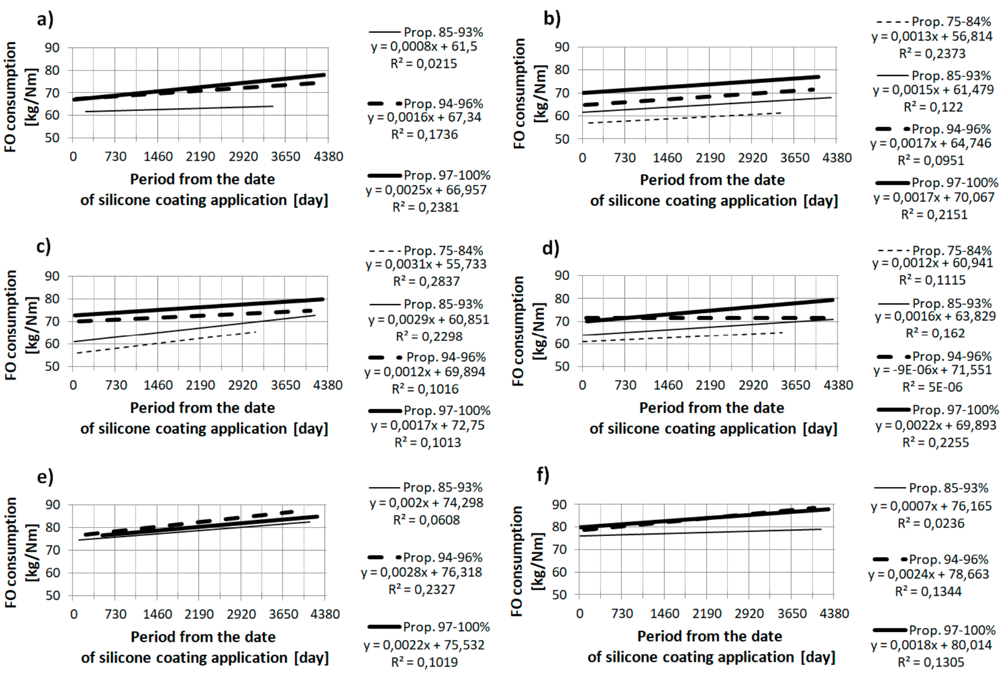

Figure 13. Average fuel consumption, sailing against the wind/wave, variable pitch propeller settings. Ferry bound for Świnoujście, winds SE/SSE/S, force: 1–3 B. (**a**), 4–6 B. (**c**), 7–10 B. (**e**) and for Trelleborg, winds NW/NNW/N, force: 1–3 B. (**b**), 4–6 B. (**d**), 7–10 B. (**f**).

Despite the maximum sample size, due to the lack of data, 75%–84% of settings were not obtained for the very tight timetable trip to Trelleborg (Figure 12). This fact does not change the conclusion that real operational tests fully confirm the dependence of the specific fuel consumption on the time period of the silicone coating application.

Figure 13 illustrates the most adverse weather conditions when the ship sails against the wind and waves. With one exception (small amount of data, voyage to Trelleborg, wind NW/NNW/N with a force of 4–6 Beaufort scale, average pitch propeller setting 94%–96%), the diagram confirms the relationship between the fuel consumption and the time from the moment of applying the anti-fouling silicone coating. For severe weather, winds NW/NNW/N 7–10 Beaufort scale, it can be seen that the fuel consumption for smaller settings of the variable pitch propellers is greater than for large settings.

This apparent inconsistency results from the fact that, for these very heavy conditions, the ferry tries lower propeller settings (average pitch angle 94%–96%) but with a continuous very high engine load in order to continue the voyage directly on the shortest route, against the wind and waves. However, if due to safety reasons this is not possible, the ship undertakes frequent course changes to avoid wave impacts directly into the bow [11]. In such a situation, the average propeller settings will rise (pitch angle 97%–100%) because there are no extreme opposing forces and a lower-than-before average engine load is possible.

3.3. Multiple Linear Regression Analysis of Fuel Consumption

Multiple linear regression was used for the next data analysis. Through the previously proposed data selection, different weather and operating conditions have been identified for the ferry passages. Four selected analyses were then carried out for the same data, as shown in the diagrams in Figures 12 and 13, and the following circumstances were distinguished: the ferry is sailing against the wind and against the waves, the ferry is sailing crosswind and across the waves. The impact of time pressure resulting from the ferry timetable differences was also taken into account by analyzing data taken from voyages in two directions: Świnoujście-Trelleborg and Trelleborg-Świnoujście. The following five independent variables were used to explain the amount of the ferry's consumption: ferry speed raised to the second power ($speed^2$), time/days elapsed since the silicone anti-fouling coating was applied (*time*), the Beaufort scale force of the wind (*wind B*), the length of the ferry journey (*distance*), and the average setting of the variable pitch propellers (*propellers*). The fuel consumption is known to be related to speed raised to a power rather than to speed alone, which is then checked to ensure that the model fits better with speed raised to the second power.

For all variables in the above four cases, the probability *p*-value is lower than the assumed level of statistical significance. Therefore, the hypothesis that the proposed variables do not affect the analyzed specific fuel consumption can be rejected.

Therefore, the hypothesis that the proposed variables do not affect the analyzed specific fuel consumption can be rejected. The above-mentioned variables at the adopted confidence level (95%) explain from 54% to 63% of the analyzed data. Not taking into account the variable associated with time elapsed since the silicone anti-fouling coating was applied (*time*), meant that the four remaining variables were only able to explain 48% to 59% of the analyzed data.

The results presented in Table 1 for variables *speed* and *distance* require additional explanation. In two cases, the model coefficient *b* has a negative value, despite that the impact of these variables on the model's accuracy cannot be excluded. This phenomenon is observed due to the correlation between the variable representing the propellers' settings and the variable representing the speed of the ship. A similar correlation occurs between the variable *distance* and variable *wind B,* which represents weather conditions. In this case, to minimize the negative impact of the weather on the ship's safe passage, it is necessary to change the ferry course, and thus, the voyage distance is extended.

Table 1. Multiple linear regression statistics for the selected data: specific fuel consumption versus variables *time*, *speed*^{2}, *distance*, *propellers*, and *wind B*.

	Sailing Against the Wind/Wave To:		**Sailing Crosswind To:**	
Fuel Consumption Model [kg/Nm]	**Świnoujście, Winds SE/SSE/S**	**Trelleborg, Winds NW/NNW/N**	**Świnoujście, Winds W/WSW/SW**	**Trelleborg, Winds W/WSW/SW**
Multiple R	0.7550	0.7972	0.7372	0.7660
R^2	0.5700	0.6355	0.5434	0.5868
Adjusted R^2	0.5656	0.6315	0.5412	0.5852
Standard Error	5.4374	5.0543	5.3448	5.1345
Observations	506	466	1214	1338
Coefficient *b* (*time*)	0.00194	0.00136	0.00167	0.00116
Coefficient *b* (*speed*^{2})	−0.0554	−0.0414	−0.0431	−0.0546
Coefficient *b* (*distance*)	−0.5111	−0.6037	−0.4180	−0.3322
Coefficient *b* (*propellers*)	1.0310	0.9056	0.9445	0.9272
Coefficient *b* (*wind B*)	1.6658	1.9093	1.0967	1.4240

On the basis of the above-presented reasoning, Table 2 has been made to show multiple regression with the exception of variables *speed* and *distance*. In this case, the variables *time*, *propellers*, and *wind B* at the adopted confidence level (95%) explain from 54% to 61% of the analyzed data. In this case, similarly to Table 1, by excluding the variable associated with the time degradation of the quality of the silicone anti-fouling coating, only 47% to 57% of the analyzed data can be explained. The reasoning presented above allows again to state that there is a significant impact of the passing time on the fuel consumption due to the degradation of the silicone coating since its application.

Table 2. Multiple linear regression statistics for the selected data: specific fuel consumption versus variables *time*, *propellers*, and *wind B*.

	Sailing Against the Wind/Wave To:		**Sailing Crosswind To:**	
Ferry Fuel Consumption Model [kg/Nm]	**Świnoujście, Winds SE/SSE/S**	**Trelleborg, Winds NW/NNW/N**	**Świnoujście, Winds W/WSW/SW**	**Trelleborg, Winds W/WSW/SW**
Multiple R	0.7336	0.7819	0.7213	0.7521
R^2	0.5381	0.6114	0.5203	0.5657
Adjusted R^2	0.5353	0.6088	0.5191	0.5647
Standard Error	5.6238	5.2076	5.4742	5.2601
Observations	506	466	1214	1338
Coefficient *b* (*time*)	0.00183	0.00135	0.00156	0.00117
Coefficient *b* (*propellers*)	0.8630	0.8032	0.7947	0.9272
Coefficient *b* (*wind B*)	1.9998	2.0988	1.3376	1.4240

4. Discussion

The characteristics presented on the graphs in Sections 3.1 and 3.2 validate the relationship between the increase of fuel consumption and the time that has elapsed since the application of the silicone anti-fouling coating. From the point of view of formal statistical analysis, the presented single characteristics do not justify the statement that the available data are accurately matched to the presented regression equations, because the values of the determination coefficients R^2 are relatively low [12]. However, the multiple linear regressions presented in Section 3.3 justify the impact on average fuel consumption of the time elapsed since the silicone anti-fouling coating was applied. The single linear equations may only lead to an approximate determination of the amount of average increase of fuel consumption. Equations and multiple linear regressions are disrupted by such factors as:

- Variable hydrometeorological conditions may have changed during the passage,
- Possible errors of the subjective hydrometeorological conditions assessment,
- Large approximation in hydrometeorological data grouping—three groups of wind strength only,
- Large approximation in grouping of variable pitch propeller settings data—four groups of settings,
- Speed changes,
- Different speeds and courses at any stage of the voyage resulting from COLREG,
- Changes of the average speed as a result of ferry timetable adjustments,
- Due to the varying intensity of the shallow water effect resulting from route changes all over the Trelleborg/Świnoujście area,
- Fluctuations in propulsion efficiency associated with periodic repairs of main engines,
- Differences of fuel quality, especially due to new Sulphur Control Emission Control Areas implemented during the research period.

The subsequent graphs allow more objective and precise validation of the tendency to increase specific fuel consumption, as shown in Figures 3–13. The same tendency can be observed in both voyage directions. The following parameters have been taken into account: variable pitch propeller settings and hydrometeorological conditions. The above graphs confirm that the average increase of estimated fuel consumption of abt. 2 tons (abt. 17 percent) per day was observed after nearly 13 years since the silicone anti-fouling paint was applied. This tendency is confirmed in other research [13–15].

With the help of the proposed characteristics and multiple regression analysis eliminating the impact of increases of ferry speed, it is also possible to estimate the financial loss resulting from increased fuel consumption due to degradation of the anti-fouling coating, as presented in the paper. In this case, fuel consumption monitoring is accessible not only for researches but also for the owner's office staff with a knowledge of standard office software packages. It is also more likely to be able to choose the most appropriate moment for and scope of repair works regarding the underwater section of the hull. Finally, continuous control over the increase of the ferry's fuel consumption allows for decision-making in the context of minimizing exhaust fume emissions.

Moreover, the described approximate technique allows for estimating the tendency and the value of the average specific fuel consumption after each change of ferry operating conditions. This may happen after applying new anti-fouling layering, main engine repair or adjustment, hull cleaning or adjusting the timetable for passage time.

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References

1. Bochetti, D.; Lapore, A.; Palumbo, B.; Vitiello, L. Statistical approach to ship fuel consumption monitoring. *J. Ship Res.* **2015**, *59*, 162–171. [CrossRef]
2. Barras, B. *Ship Design and Performance for Masters and Mates*; Elsevier: Oxford, UK, 2004.
3. Alderton, P.M. The optimum speed of ship. *J. Navig.* **1981**, *34*, 341–355. [CrossRef]
4. Wang, S.; Meng, Q. Sailing speed optimization for container ships in a liner shipping network. *Transp. Res.* **2012**, *48*, 701–714. [CrossRef]
5. Carlton, J. *Marine Propellers and Propulsion*, 2nd ed.; Elsevier: Oxford, UK, 2007.
6. Molland, A.F.; Turnock, S.R.; Hudson, D.A. *Ship Resistance and Propulsion, Practical Estimation of Propulsive Power*; Cambridge University Press: New York, NY, USA, 2011.
7. Kowalski, A. Optymalizacja kosztów paliwa statku w czasie podróży morskiej. *Autobusy* **2013**, *3*, 575–582.

8. Kowalski, A. *Wybrane Aspekty Eksploatacji Statku Handlowego—Poradnik Kapitana Statku*; Fundacja Promocji Przemysłu Okrętowego i Gospodarki Morskiej: Gdańsk, Poland, 2017.
9. Dzwonkowski, J.; Gucma, M.; Gucma, S.; Kowalski, A. *Nawigacja pilotażowa: Nawigacja na akwenach ograniczonych*; Wydawnictwo Naukowe Akademii Morskiej w Szczecinie: Szczecin, Poland, 2019.
10. Bialystocki, N.; Konovessis, D. On the estimation of ship's fuel consumption and speed curve: A statistical approach. *J. Ocean Eng. Sci.* **2016**, *1*, 157–166. [CrossRef]
11. Nowicki, A. *Manewrowanie w Warunkach Specjalnych*; Oderratum Ltd.: Szczecin, Poland, 1999.
12. Larose, D.L. *Metody i Modele Eksploracji Danych*; Wydawnictwo Naukowe PWN: Warszawa, Poland, 2008.
13. Sonak, S.; Giriyan, A.; Pangam, P. A method for analysis of costs and benefits of anti-fouling systems applied to a ship's hull. *J. Ship Technol.* **2010**, *6*, 73–83.
14. Westergaard, C. Comparison of fouling control coating performance to ship propulsion efficiency. In *FORCE Technology*; Report no. 107-24111, Part 2; Hempel Marine Paints A/S: Brøndby, Denmark, 2007.
15. Munk, T.; Kane, D.; Yebra, D.M. The effects of corrosion and fouling on the performance of ocean-going vessels: A naval architectural perspective. In *Advances in Marine Anti-Fouling Coatings and Technologies*; Woodhead Publishing: Cambridge, UK, 2009; pp. 148–176.