Article

Impact of Port Shallowness (Clearance under the Ship’s Keel) on Shipping Safety, Energy Consumption and Sustainability of Green Ports

Vytautas Paulauskas *, Viktora Senčila, Donatas Paulauskas and Martynas Simutis

Marine Engineering Department, Klaipeda University, H. Manto 84, LT-92219 Klaipeda, Lithuania; viktor.sencila@ku.lt (V.S.); paulauskasd75@gmail.com (D.P.); martynas.simutis@gmail.com (M.S.)

* Correspondence: vytautaskltc@gmail.com

Abstract: In a majority of ports, a ship’s speed is limited for reasons of navigational safety. At the same time, captains and port pilots choose the speed of the ship, but it cannot be higher than the speed allowed in the port. Therefore, the speed of the ship also depends on the experience of the masters and harbor pilots and the sailing conditions in specific situations. Choosing the optimal speed of the ship in the port, considering the hydrodynamic effect of shallow water and the controllability of the ship, can help reduce fuel consumption and ship emissions, which is important for the development of a sustainable port. In all cases, the safety of the shipping is the highest priority. The main objectives of this article are determining the optimal speed of ships in ports with low clearance under a ship’s hull, ensuring navigational safety, reducing fuel consumption and emissions, and creating a sustainable port. This article presents the methodology for calculating the optimal ship speed as the minimum controllable speed, fuel consumption and emission reduction, as well as its implications for sustainable and green maritime transport and port development. The methodology presented has been tested on real ships and using a calibrated simulator, navigating through port channels and port water’s restricted conditions.

Keywords: energy efficiency; green and sustainable port; ship safety; environmental impact; emissions

1. Introduction

Sustainable and green ports are of great importance to all regions of the world and need to be pursued in various ways. It is important to note that maritime transport exhibits a degree of inertia. Ships are designed to operate for a period of 15–20 years, and retrofitting their power plants to use new fuels or energy sources is not always feasible. At the same time, even small advances in the reduction in environmental impact are important.

The entry of ships into ports is a daily procedure, but at the same time, the different experience of ship captains and port pilots and the different characteristics of ships’ maneuverability, traditions and other elements have a great influence on ships entering and leaving ports, the fuel consumption and the amount of emissions produced. Analysis of the main engine manœuvres of ships entering ports shows very large differences between ships of the same type, which are mainly related to the knowledge, experience and individual character of the ship’s captains and port pilot [1–3]. In many ports, pilots have been working as navigators and masters on relatively small ships for a long time before they become pilots [4,5]. As pilots become more competent, they are allowed to operate larger vessels, but the long hours on smaller vessels have a great impact on the way they work.

Very good understanding of the ship’s maneuverability by the ship’s captain and port pilots ensures the ship’s navigational safety when entering ports and other places [2,6], as well as to optimize the ship’s manœuvres and thus reduce the ship’s fuel consumption and emissions [7,8].
Analysis of accidents and incidents when ships enter a port has shown that they are mostly related to mistakes made by ship captains, port pilots or VTS (vessel traffic system) operators, but very rarely are ship accidents and incidents related to the speed of the ship in port channels and port waters [1,3]. Many ports have speed limits for ships and in most cases, these limits are between six and ten knots [3,9,10].

In some situations, due to a lack of information about the ship’s maneuverability or a lack of experience, captains and harbor pilots did not take into account the technical and maneuvering parameters of the ships, which affected the ship’s behavior in the case of small clearances (the space between the ship’s keel and the bottom of the channel), leading to errors in the ship’s maneuvers, especially when the ships navigated the bends of navigational channels [3,11]. It should be noted that in cases where the professional education and practical training of personnel is based on modern knowledge of the ship’s maneuverability in various shipping conditions, it can increase the navigational safety of ships entering and leaving ports with independent navigation and/or additional use of external assistance (e.g., harbor tugs) or without it [12–14]. The speed of ships in ports is determined by many factors, but most of them are related to the configuration of the port channels and water areas, mostly recurring external influences, traditions, knowledge and qualifications of the port services, as well as accident and emergency statistics [1,2,4,6,10].

The optimal speed of ships in port entrances and internal navigation channels, assessing the maneuverability of ships, has not been well studied, so the available experience of ship captains and port pilots is often relied on, but such solutions are not always optimal [15,16].

Ships emit a lot of emissions—for example, the global fleet emits about 2.8% of carbon dioxide—but this is mainly concentrated in the approaches and harbors of major ports where there is the highest concentration of ships. In some major ports, ship emissions account for up to 12–16% of the total emissions generated in the region, so even small reductions in ship emissions are very important [7,15,16].

The main objective of the paper is to present a developed methodology to determine the optimal ship speed in a restricted clearance condition where the ship is still well controlled, minimizing fuel consumption and ship emissions, which is very important for the development of sustainable and green ports. The novelty of this article is based on the development of a methodology that allows one to calculate the minimum controllable speed of the ship, depending on the size of the clearance (in case of restricted clearance). The scientific novelty of this article is also found in the focus on combining and solving technical and environmental problems and minimizing the fuel consumption of ships and the amount of emissions generated in ports, with a positive impact on social and living conditions in port cities.

The research methodology is based on the assessment of the external and internal forces and moments acting on the ship when sailing in port channels and port waters, determining the minimum controllable ship speed, with small clearances and possible minimum fuel consumption, adapting to specific port conditions and at the same time generating minimum emissions.

The main objective of the article is to create a methodology that would allow the calculation of the minimum controllable speed of the ship at restricted shipping conditions, ensuring navigational safety in port channels and water areas, with minimum fuel consumption and ship emissions, which is necessary for the development of sustainable and ecological ports.

This article consists of research analysis of the existing situation, the principles of creating a mathematical model and the mathematical model itself. The application of the developed mathematical model in specific conditions and the results of experiments carried out on real ships and using a calibrated visual simulator are presented. The discussion and conclusions of the calculated and experimentally verified results of the optimal ship speed in port channels and port waters with minimum fuel consumption are also presented.
The scientific contribution and novelty of the research carried out are the new methodology that makes it possible to determine the optimal speed of ships in port channels and waters, with minimum fuel consumption and environmental impact, which is important for the development of sustainable and green ports.

2. Analysis of Ship Speed and Emissions Generation in Ports—Situation and Literature Review

Numerous resources have analyzed ship speed in ports and inland waterways [2,10,15,17,18]. Ship speed in ports is limited by the hydrodynamic effect of ship-to-bed (ship squatting due to restricted under keel clearance), ship-to-ship or ship-to-wall interaction (navigating and mooring to quays) and by waves caused by moving ships, which erode shorelines and negatively affect (destroy) port infrastructure. Reduced ship speed also reduces the probability of ship collisions [13,17,19–22]. For example, in the port of Klaipeda, the speed limit is up to 8 knots [9], in the access channels to the port of Hamburg (in the Elbe river), the speed limit is up to 13 knots and in the port areas, the speed limit is up to 9 knots. Some places have special requirements for approaching individual port locations and individual inland waterways for canal sections) [23]. Vessel speed limits are up to 12 knots in the canals of the port of Rotterdam and up to 8 knots in some sections [24]. Similar speed limits can be found in other ports around the world [13,18,19,21]. At the same time, the permitted speed of ships in ports is often not optimal in terms of energy (fuel) consumption and ship-generated emissions [16,25]. For a sustainable approach, it is very important to find optimal solutions for ship speed when entering the port and in the internal shipping channels, as well as for the approach to individual important points of the port (areas defined by port administrations) [19]. The reduction in ship speed is also important for the reduction in energy (fuel) consumption and emissions of ships [25,26].

Analysis of shipping accidents and port emergencies has shown that most of them were caused by excessive or insufficient speed in ports [1,3,8,13,20]. It is therefore very important to have a minimum and, at the same time, safe ship speed in ports, both from the point of view of ship safety and from the point of view of environmental impact [7,15].

After an assessment of the main aspects of ship navigation in port channels and port waters (safety of navigation being the priority), they can be grouped as follows [20,27,28]:

- ship navigation must be safe for the sailing ships themselves;
- the passage of ships must not reduce the safety of other ships sailing in channels or moored at quays;
- ships traffic must meet the general needs of the port (ships sailing schedules, positioning of ships, minimal interaction with other ships entering and leaving the port);
- have minimal impact on port infrastructure and superstructure;
- use the minimum fuel consumption;
- emit as little pollution as possible during navigation.

Ship navigation in port channels and port waters must be safe for the ship itself and its speed must allow good controllability of all operations entering the port (navigating through channels; turning in turning basins; stopping, approaching and leaving quays) [21,29]. Thus, the maneuverability of the ship is very important in the whole process of entering the port.

When a ship sails through port channels and port water areas, it must not create impacts for other ships due to the high hydrodynamic interaction between ships and the impact of waves created by sailing ships on berthing or passing ships, as well as during sailing clauses to other constructions [28,30]. Ports are sometimes very congested and ships sailing to and from the port must not create additional time wasting for other ships and port operations [13,17,19,31]. In many ports, the approaches and especially the inner channels are not very busy, giving ships the opportunity to sail at a minimum but safe speeds, with minimum fuel consumption and emissions.

When sailing through port channels and port water areas, ships must not cause negative consequences or additional risks to the port infrastructure and superstructure due
to the waves caused by the sailing ship or the risks of collision with the port infrastructure or superstructure [25,28,31,32].

It is very important for ships to use as little fuel as possible when sailing through port channels and port waters, which is very important for the economic indicators of the ship itself; at the same time, it is also important to generate minimal emissions in the port area, while positively influencing the creation of green and sustainable ports [15,33–35].

The above-mentioned factors are very important, but they partly contradict each other, for example, a very low speed of the ship in the port channels and port waters, as long as the ship is well controlled, increases the safety of the ship and reduces the hydrodynamic impact on other ships, but at the same time, it takes more time and worsens the port indicators because other ships have to wait and in some cases they have to stop loading operations for a longer period of time, etc. [25,33]. Many ports have installed modern navigation systems that provide a high level of vessel traffic management, but they cannot accurately assess the minimum speed required to control vessels, which is very important to ensure safe navigation in port channels.

Much attention is paid to the planning of port channels and water areas to meet the safety requirements of shipping [33,36–39], but in old and sometimes newly built ports, it is not always possible to meet all requirements (standards and recommendations) due to geographical and other conditions, e.g., existing towns, protected historical objects, etc. For example, in Helsinki, Haugesund and other ports in similar geographical situations, the navigational channels are located between islands with historical structures, and it is very difficult or impossible to implement channel width standards or recommendations [18,36,37]. In this case, restrictions regarding wind speed and direction, requirements for the use of tugs, etc., have to be adopted to ensure the safety of shipping [12,22], so it is not always possible to use the optimal calculated conditions.

Existing environmental regulations and recommendations, in particular for ship emissions [40–42], encourage ship operators to reduce fuel consumption and emissions simultaneously, but this is not always possible because of the priority given to navigational safety. If captains and harbor pilots doubt the possible minimum speed of the ship due to insufficient research on the maneuverability of the ship in specific conditions or due to a lack of knowledge and practical experience, they always choose a speed that seems safe to them, and often it is higher than the optimal speed [19,31].

The minimum speed of the ship at which it can navigate the harbor channels and waters must be such that the ship can be well controlled, especially when braking in turning basins or when approaching quays, depending on external forces [22]. In such cases, vessels must use rudder-propeller assemblies and thrusters, if available on board, or use tug(s) to maintain good control of the vessel. The minimum possible ship speed when the ship is still well controlled has been analyzed in various literature sources [43–45], but minimum ship speed in shallow water conditions, which are typical of harbors, has not been the subject of much research. At the same time, the minimum controllable speed of the ship when navigating in port channels is particularly important in extreme hydro-meteorological conditions when it is very difficult to correct even the smallest inaccuracies in the control of the ship.

Many studies deal with the problem of vessel schedules in port channels and port waters [31,46]. Due to the uncertainty of the arrival times of container ships and other liner ships at large container ports and other similar ports and terminals, modelling capabilities are often used. Separate works identify the main navigational processes and operations related to the port’s marine infrastructure and review and evaluate existing port modelling methods [12,25]. The studies listed are for port assessment purposes with a focus on safety and capacity. The evaluation of various similar models focuses on determining the appropriate criteria for ship navigation based on what processes are included in each model and how they have been considered in each model, but many models are incompletely related to optimal ship speed in port channels and port waters by estimating minimum fuel consumption and minimum emissions [43,47–49].
The analysis of previous theoretical and experimental works by different authors allows one to partially solve the practical problems of ship safety and reduction of environmental impact in ports, but at the same time, new challenges are very important because ports are trying to attract ships of the maximum possible size to reduce the environmental impact as much as possible, i.e., to become green and sustainable ports; therefore, further research is essential.

The literature review carried out on the subject shows that a number of studies have been carried out, but at the same time, there is a lack of complex studies relating to the minimum controllable speed of ships when sailing in ports in order to minimize fuel consumption and the amount of ship emissions when sailing at optimal speed at given clearance in port channels and harbor waters, which is the novelty of the studies presented in this article.

In this way, this article analyzes the minimum speed at which the ship can be operated with a minimum fuel consumption in port conditions where there is little or, in some cases, the minimum possible clearance, which is important both for navigational safety and for reducing environmental impact, and which has been the subject of detailed study.

In this context, there is a need to study the optimal ship speed in port channels and water areas in order to optimize the ship’s speed in ports and minimize fuel consumption and emissions, thus influencing the sustainable and green development of ports, while at the same time ensuring the necessary navigational safety of ships.

3. Research Methodology

The following steps of the research methodology were used to conduct the research (Figure 1). After the situation analysis and literature review, the mathematical model was developed.

![Figure 1. The algorithm of the research methodology.](image-url)

3.1. Research Methodology Basic Ideas

In order to prepare the methodology, an analysis of the available situation and the literature was carried out, which allowed an overview of the situation of ships entering ports to be analyzed, including navigational safety, use of the necessary fuel and the influence of shallow water on the sailing characteristics of ships. The movement of ships in port channels and waters, the reduction in emissions from ships in port channels and waters, etc., have also been studied. The necessary data were collected from literature sources and observations of real ship sailing conditions in port channels and port waters, as well as experimental data obtained from VTSs (vessel traffic systems) operating in ports, from shipping companies and from calibrated full mission simulators.
Thus, the methodology developed in the study has to take into account the possible attraction of the largest ships to the ports, the parameters of the port channels and the port water area, the maneuverability of the ships, the fuel consumption, the effect of shallow water, the hydrological and hydro-metereological conditions in the ports, as well as the possible minimum speed of the ships in the port navigation in the channels and in the port areas, in order to guarantee the navigational safety of the ships (Figure 1).

The hydro-meteorological and hydrological conditions during the navigation of ships in port channels and port waters, which must be evaluated when developing research methods, are the following: wind speed, wind course angle, current speed, current course angle, etc.

Additional data needed for the research and to be collected and analyzed include the width of navigation channels (waterways), depths of port navigation channels and port water areas intended for ship navigation and maneuvering [50]. In addition, the relevant calibration coefficients of the simulator obtained from theoretical and experimental studies [51–53] were considered.

On the basis of theoretical and experimental research, a mathematical model has been created that allows one to calculate the possible minimum and optimal ship speed in the port channels and in the port water area, with the possibility of good ship control, the sailing time of the ships, fuel consumption, and emissions, as well as to evaluate the hydrological and hydrometeorological conditions in the port channels and in the port water areas. This model considers the implementation of the following steps:

− collect and analyze of the aforementioned data;
− plan possible sailing distances in the port;
− calculate the ship’s minimum speed in real port conditions based on the necessary data collected;
− calculate specific ship sailing parameters: speed, time, costs and fuel consumption;
− calculate and analyze the total amount of emissions while the ship is sailing in the port channels and in the port water area at optimal speed;
− make conclusions and recommendations on specific conditions.

The boundary conditions of the methodology and the model are as follows: the sizes of ships and their sailing speed in the port channels and in the port water area depend on the infrastructure parameters; the minimum ship speed depends on the external impact forces (wind, current, waves) and the clearance in case of good ship controllability; the optimal ship speed is due to ship control limitations; and tug assistance is available to improve ship handling. At the same time, many ports have set a maximum wind speed up to which ships are allowed to enter the port, which may be higher or lower than the minimum controllable speed of the ship.

The proposed methodology was verified based on a case study. The possible ships speed whose draft to depth ratio was up to 0.92–0.96 were analyzed in detail, and calculations were made based on the real data. Based on the results obtained, recommendations, discussions and conclusions were proposed regarding possible minimum ship speeds in port channels and harbor waters with the lowest emission values. At the same time, the proposed methodology can be applied in different ports.

3.2. Mathematical Model

Many ports in the world have long approach and internal navigation channels in which ships can keep an optimal speed. External forces and moments acting on ship sailing by port navigational channels and port waters shall be compensated by forces and moments created by the ship’s rudder, or if the ship uses tugs assistance—created by additional tugs forces and moments. Thus, the calculation of the forces and moments can be conducted using the following mathematical model, based on the D’Alembert principle [22,39,54]:

\[
X_{in} + X_{k} + X_{\beta} + X_{P} + X_{N} + X_{d} + X_{c} + X_{p} + X_{sh} + X_{T} + X_{tug} + \cdots = 0
\] (1)
where \( X(X) \) propellers, which could be calculated using the methodology stated in [51, 56]; and of the sailing ship (specific port). In each specific case, Equations (4)–(6) must be adapted to the specific situation do not take into account the effects of waves, forces and moments created by tugs and steering devices: tugs and steering devices, such as thrusters. In this case, the equations could be calculated using the methodology stated at [14]; \( M_T, Y_T, M_{h} \) are the forces and the moment created by the ship’s rudder or other steering equipment [51, 53]; \( Y_{sh}, M_{sh} \) are forces and the moment created by thrusters [22, 53]; \( X_{a}, Y_{a}, M_{a} \) are aerodynamic forces and the moment, which could be calculated using the methodology stated at [51, 53, 54]; \( X_{c}, Y_{c}, M_{c} \) are forces and the moment created by the current, which could be calculated using the methodology stated in [51, 53]; \( X_{b}, Y_{b}, M_{b} \) are the forces and the moment created by waves, which could be calculated using the methodology stated in [51, 53]; \( X_{sh}, Y_{sh}, M_{sh} \) are the forces and the moment created by shallow water effect [22, 55]; \( X_{T}, Y_{T}, M_{T} \) are the forces and the moment created by ship’s propeller (propellers), which could be calculated using the methodology stated in [51, 56]; and \( X_{tug}, Y_{tug}, M_{tug} \) are the forces and moment created by tugs [22, 51]. Additional forces and moments could be created by anchor or mooring ropes or other factors.

When a ship is moving through port channels and port waters (typical procedures for ships entering ports) without the assistance of tugs, the ship’s rudder forces and moments could be calculated using the methodology stated in [51, 53, 54] and others.

Forces and moments expressed in Equations (4)–(6) could be calculated using methodologies, presented in [14, 51, 53, 55] and others.

When sailing in port channels and waters, there are often no waves, the ship’s speed is six knots or more, the ship’s steering is not affected by tugs and steering devices (thrusters) and only traditional ship steering devices (ship’s propeller(s) and rudder(s)) are used to steer the ship. In most such cases, where the ship is sailing with no or minimal drift angle and the ship’s speed does not change significantly (if the power of the ship’s main engine(s) does not change), dependencies (4)–(6) are written:

\[
X_{in} + X_{k} + X_{\beta} + X_{a} + X_{c} + X_{b} + X_{sh} + X_{T} + \cdots = X_{p} \tag{4}
\]

\[
Y_{in} + Y_{k} + Y_{\beta} + Y_{a} + Y_{c} + Y_{b} + Y_{sh} + Y_{T} + \cdots = Y_{p} \tag{5}
\]

\[
M_{in} + M_{k} + M_{\beta} + M_{a} + M_{c} + M_{b} + M_{sh} + M_{T} + \cdots = M_{p} \tag{6}
\]

Equations (7)–(9) are adapted to harbor conditions when there are no waves and the ship is moving straight or in small turns and does not require the use of additional ship control devices: tugs and steering devices, such as thrusters. In this case, the equations do not take into account the effects of waves, forces and moments created by tugs and thrusters. In each specific case, Equations (4)–(6) must be adapted to the specific situation of the sailing ship (specific port).
Forces and moment created by the rudder (rudders) \((X_P, Y_P, M_P)\), acting on the ship’s steering, could be calculated as follows \([22,51,53,56]\):

\[
X_P = C_x \frac{\rho}{2} S_P v^2
\]  
(10)

\[
Y_P = C_y \frac{\rho}{2} S_P v^2
\]  
(11)

\[
M_P = Y_P l_P
\]  
(12)

where \(C_x, C_y\) are the rudder hydrodynamic coefficients, which could be taken into account until the rudder turn angle reaches 20 degrees (to have steering reserve) \([22,57,58]\); \(v\) is the ship’s speed; \(\rho\) is the water density; \(S_P\) is the area of projection of the rudder plane into the diametrical plane (area) \([39,53,57]\); and \(l_P\) is the rudder’s transverse force shoulder \([39,53,57]\).

The lateral (lift) force generated by the ship’s steering mechanism, depending on the angle of rotation of the rudder feather on shallow waters, can be calculated using the following formula:

\[
Y_P = C_y \frac{\rho}{2} S_P v^2 k_w
\]  
(13)

where \(k_w\) is the turning velocity coefficient as the effect of shallow water factor \([22,54,55]\).

In port channels and water areas, the ship will be steered without external help (tug) until the moment created by the rudder (assessing the ship’s controllability reserve) is greater than or equal to the moments created by external forces, i.e., \([22,48,53,59]\):

\[
M_P \geq M_a + M_c + M_T + \cdots
\]  
(14)

Aerodynamic forces and the moment \((X_a, Y_a, M_a)\), could be calculated using the methodology presented in \([51]\). The aerodynamic moment could be calculated as follows \([51]\):

\[
M_a = C_a \frac{\rho_1}{2} S_x (x_0 + x_a) \left( v_a sin q_a \right)^2
\]  
(15)

where \(C_a\) is the aerodynamic coefficient, and for the calculations, it could be taken between 1.07 and 1.30 depending on the ship’s architecture \([51,53]\); \(\rho_1\) is the air density, and for calculations, it could be taken as 1.25 kg/m\(^3\); \(S_x\) is the space of projection onto diametrical plane (DP) of the wind surface area of the ship \([39,50,53]\); \(x_a\) is the abscissa of center of gravity of aerodynamic force, which can be calculated by the methodology as presented in \([22,39,53,57]\); \(v_a\) is the wind velocity; \(q_a\) is the wind course angle; and \(x_0\) is the abscissa of the ship’s turning pivot point \([57]\), which can be calculated as follows:

\[
x_0 = L \left( k_{x0} + k_{x1} \frac{T_a - T_b}{L} - k_{x2} a^0 \right)
\]  
(16)

where \(L\) is the ship’s length between perpendiculars; \(k_{x0}\) is the abscissa coefficient, which for many types of ships is between 0.3 and 0.4; \(k_{x1}\) is the abscissa coefficient depending on the ship’s draft differences, which for many types of ships is between 11.0 and 12.0; \(k_{x2}\) is the abscissa coefficient depending on the rudder turn angle, which for many types of ships is between 0.004 and 0.0045; \(T_a\) is the ship’s astern draft; \(T_b\) is the ship’s bow draft; and \(a^0\) is the ship’s rudder turn angle in degrees.

The current moment could be calculated as follows \([51,53]\):

\[
M_c = C_c \frac{\rho}{2} L T v_c^2 x_0 sin q_c
\]  
(17)

where \(C_c\) is the current hydrodynamic coefficient, which for many types of ships could be taken between 1.2 and 1.5 (1.5 is for double propellers and ships with bulb); \(T\) is the ship’s average draft; \(v_c\) is the current velocity; and \(q_c\) is the current course angle.
A ship’s propeller(s) creating moment could be calculated as follows [22,51,53] (in case of twin propellers with different turning sides, this moment is equal to zero):

\[ M_T = K'_p \rho n_{pr}^2 D_{pr}^4 \left( \frac{L}{2} + x_0 \right) \sin \alpha_{pr} \]  

(18)

where \( K'_p \) is the propeller’s coefficient, which for many type of conventional propellers could be used for calculations as 0.2 (a more accurate coefficient could be taken from the propeller’s specification); \( n_{pr} \) is the rotation frequency of the ship’s propeller, \( s^{-1} \); \( D_{pr} \) is the ship’s propeller diameter; \( \alpha_{pr} \) is the deviation angle of the propeller flow, which for conventional propellers is from 2 to 4 degrees, and about 3 degrees can be accepted in the calculations [22,39,53].

A ship’s rudder(s) creating moment could be calculated as follows [22,51,53]:

\[ M_P = C_y \frac{P}{D} \rho S P^2 k_w \left( \frac{L}{2} + x_0 \right) \]

(19)

Finally, the ship’s minimum steering speed in the navigational channel could be calculated as follows:

\[ v = \sqrt{\frac{2(M_d + M_t + M_T + \cdots)}{C_y \rho S P k_w \left( \frac{L}{2} + x_0 \right)}} \]  

(20)

When a ship is sailing in port channels and waterways, it is very important that the ship is well controlled and, at the same time, that its speed is such that fuel consumption is minimized. The power of the ship’s main engine and the relative fuel consumption can be expressed in a graph obtained by analyzing relevant data from the literature sources [60–63] and the experimental data obtained from real ships (Figure 2).

**Figure 2.** The relative fuel consumption coefficient of a ship’s engine (\( \Delta q_s \)), depending on the relative power of the ship’s engine(s) (\( N' \)).

The relative power of the ship’s main engine(s) and the ship’s relative speed can be expressed as shown in Figure 3 [29,53,62,64,65]. Engine power and ship speed are related by a quadratic relationship [57,66]. In most cases, the relative power of the ship’s engine(s) and the ship’s speed can be used. A graph based on experimental results from more than 1000 ship passages can be used for this purpose [53,54,61] (Figure 3).
Figure 3. The relative speed of the ship \( v' \) as a function of the relative power of the ship’s engine(s) \( N' \).

The limitation of the chart (Figure 3) is for ships with a very high overall hull fullness factor \( (\delta) \). If the total fullness factor of the ship’s hull is higher than 0.9, the resistance parameters of the ship’s hull shape change significantly, and the accuracy of the graph is not good enough (the error size can reach more than 10%) [54].

Figure 3 shows the relative power of the ship’s engine(s), which could be calculated as follows [14]:

\[
N' = \frac{N}{N_n}
\]

(21)

where \( N \) is the current power of the ship’s engine, while the ship is sailing at speeds \( v \) and \( N_n \) is the nominal power of the ship’s main engine(s).

As shown in Figure 3, the relative ship’s speed \( v' \) is calculated as follows [51]:

\[
v' = \frac{v}{v_0}
\]

(22)

where \( v_0 \) is the ship’s speed at the rated power of the ship’s engine(s).

Many harbors have limited depths, and with a small clearance between the ship’s hull and the bottom of the navigation channel, the added water mass increases and, at the same time, the resistance of the ship’s hull increases. The decrease in ship speed at low depth can be calculated using the following formula [22,55]:

\[
v_s = v \sqrt{\frac{1 + k_{11}}{1 + k'_{11}}}
\]

(23)

where \( v_s \) is the ship’s speed in shallow water; \( v \) is the ship’s speed in deep water; \( k'_{11} \) is the attached water mass coefficient in shallow water; \( k_{11} \) is the attached water mass coefficient in deep water.

Added water mass coefficients in deep and shallow waters could be taken from the below graph (Figure 4) [22].

Figure 4. Dependences of the added water mass coefficient \( k'_{11} \) on the \( T/H \) ratio and the ship’s sailing speed \( v \).
The added mass of water depends on the speed of the ship and the draft of the ship, as well as on the depth of the navigational channels and port water area, i.e., the ratio \((T/H)\). Additional water mass coefficients are usually used for the calculation, as shown in Figure 4, when the ship is moving longitudinally, which corresponds to the navigation of ships in port channels [4,5].

The generation of emissions when a ship navigates the port channels and water areas depends on the amount of fuel consumed by the engine(s) and the engine(s) operating time and can be calculated using the methods presented in [7,35].

The Kalman filter [66] and the maximum distribution method [67] were used for the processing and generalization of the obtained theoretical and experimental results.

The methodology presented in this section makes it possible to determine the optimal speed of the ship in the port channels and the water areas of the port, when the ship is still well controlled during the passage and at the same time consumes the minimum amount of fuel.

By minimizing the power of the ship’s engine(s) and fuel consumption, the ship produces minimal emissions [62,64], which is important for the development of sustainable and green ports.

The main tasks of the developed methodology are based on theoretical models that can help to find the optimal parameters of ship movement in port channels and water areas. As ships move at optimal speed through port channels and water areas, while ensuring navigational safety, the safe minimum power of the ship’s engine(s) is used and the possible minimum fuel consumption is used to minimize emissions and environmental impact, which is important for the development of sustainable and green ports. The developed methodology can be applied in practice.

4. Case Study of the Ships Sailing in Port Channels and Port Water Areas

Klaipeda port [9,68] (Figure 5) and two types of ships are taken as a case study: PANAMAX class container ship and POST PANAMAX class bulk cargo ship.

![Figure 5](image-url) Klaipeda port navigational channels and port waters [9,68].

The PANAMAX class container vessel length is about 294 m, the length between perpendiculars is about 278 m, the width about 32.5 m, the draft is up to 12.5 m (fully loaded), the block coefficient is about 0.7, the engine power is about 20 MW, the maximum speed is about 22 knots, the minimum speed is about 5 knots, and the container capacity is about 4800 TEU. The POST PANAMAX bulk ship length is about 235 m, the length between perpendiculars is about 210 m, the width is about 36 m, the draft is about 13.3 m, the deadweight is about 78,000 tons (fully loaded), the block coefficient is about 0.82, the
engine power is about 8 MW, the maximum speed is about 14.5 knots, and the minimum speed is about 3.5 knots.

For the analysis of the case, the mentioned real ships sailing in the shipping channels of the port and in the port water area and the calibrated simulator “SimFlex Navigator” [69] were used. The experimental data of the mentioned real ships were used for the simulator calibration, and the later part of the research was carried out with the help of the mentioned simulator. The obtained simulation results were additionally compared with the results of real ships sailing under analogue conditions. Summarized calculation results were obtained using the developed methodology presented in Section 3 and experimental results were obtained from real ships and with the help of a simulator, as well as using the AIS system for additional comparisons [70]. The results obtained were analyzed and the best possible solutions were sought by using the methodologies presented in [64,65] and other sources, as well as by adapting the developed methodology.

The minimum controllable speed of ships passing through shallow water channels, depending on the wind speed and direction, has been determined by calculation using the methodology presented in Section 3 and experimentally on real ships and using a calibrated simulator (results are presented in Figures 6 and 7).

![Figure 6](image6.png)  
*Figure 6.* The minimum speed at which the PANAMAX container ships can be controlled depends on the wind speed and the angle of the wind course ($q_{w}^0$) in the case of $T/H = 0.87$.

![Figure 7](image7.png)  
*Figure 7.* The minimum speed at which the POST PANAMAX bulk ships can be controlled depends on the wind speed and the angle of the wind course ($q_{w}^0$) in the case of $T/H = 0.9$.

According to the obtained optimal solutions, the fuel consumption of the ships’ main engines and the resulting emissions were analyzed when the ships sailed from the port
entrance to different port terminals: container and bulk terminals, where the total sailing distance was about 5.0 nautical miles.

Firstly, the minimum relative fuel consumption of the ships (PANAMAX container ship and POST PANAMAX bulk carrier) was investigated when sailing at great depths ($T/H$ less than 0.2). The study found that the main engine power of the PANAMAX container ship at minimum typical relative fuel consumption was about 5 MW and the corresponding ship speed was about 8.4 knots. The main bulk carrier POST PANAMAX had an engine power of about 2 MW at minimum relative fuel consumption, corresponding to a ship speed of about 5.8 knots.

Depending on the ratio of the ship’s draft to the depth of the navigation channel and as it increases, the resistance of the ship’s hull increases. In this way, with an increasing $T/H$ ratio and with minimal typical relative fuel consumption, the speeds of the PANAMAX containerships and POST PANAMAX bulk carriers, calculated according to the methodology presented in Section 3 and verified on real ships and with the help of a calibrated simulator, are presented in Figure 8.

![Figure 8](image.png)

**Figure 8.** The speed of ships at minimum relative fuel consumption is calculated according to the methodology presented in Section 3 and received from real similar ships and by calibrated simulator.

The possible optimal speed of the investigated vessels in the navigation channel of the port was studied, depending on the ratio between the draft of the ship and the depth of the channel, as well as the wind speed and the most unfavorable angle of the wind course (the angle of the wind course is about 90°) (underestimated current, because the direction of the current coincides with the direction of the channel). Speed evaluations of the PANAMAX containerships and the POST-PANAMAX bulk carriers and other ships with similar parameters were carried out in the most unfavorable wind directions and the minimum fuel consumption calculated according to the methodology presented in Section 3 was evaluated. The evaluation results obtained with the calibrated SimFlex Navigator simulator [68] and verified by experiments under the same conditions with real ships of the same type are also presented.

As an example, Figure 9 shows the minimum controllable speed and the minimum relative fuel consumption (Min RFC) of a PANAMAX container ship at various wind speeds and at the most unfavorable wind angle (about 90°), depending on the ship’s draft/depth ratio. This figure also shows the results calculated using the methodology presented in Section 3, at a wind speed of 10 m/s, using analogous parameters from the same real ship experiment and using calibrated simulation results (triangles on Figure 9). As an example, Figure 10 shows the minimum controllable speed and the minimum relative fuel consumption (Min RFC) of a POST PANAMAX bulk carrier at various wind speeds and at the most unfavorable wind course angle (about 90°) as a function of the ship’s draft/depth...
ratio. This figure also shows the parameters calculated using the methodology presented in Section 3, at a wind speed of 8 m/s, by analogy with the same real ship experiment and using a calibrated simulation result (circles on Figure 10).

![Figure 9](image1.png)

**Figure 9.** Minimum controllable speed and minimum relative fuel consumption (Min RFC speed) of a PANAMAX container vessel at various wind speeds.

![Figure 10](image2.png)

**Figure 10.** The minimum controllable speed and minimum relative fuel consumption (Min RFC speed) of a POST PANAMAX bulk ship at various wind speeds.

Thus, the optimal speed of the Panamax container ship when entering the port of Klaipeda would be about eight knots (permitted speed of ships in the port—up to eight knots), with a sailing time of about 0.625 h. At a speed of eight knots, the main engine of the Panamax container ship has a relative fuel consumption of about 0.15 kg/kWh, and during the test voyage (5 miles), this ship consumed about 470 kg of diesel fuel and generated about 860 kg of CO₂ [7]. The optimal speed of a bulk carrier of the type POST PANAMAX when sailing to the port of Klaipeda would be about 5.6 knots (the permitted speed in the port is up to 8 knots), and the sailing time would be about 0.89 h. Sailing at a speed of 5.6 knots, the bulk carrier POST PANAMAX had a relative main engine fuel consumption of about 0.15 kg/kWh, and during the test voyage (5 miles), this vessel consumed about 270 kg of diesel fuel and generated about 860 kg of CO₂ [7].

When a POST PANAMAX bulk carrier enters the port of Klaipeda at a speed of 8 knots, the sailing time is about 0.625 h. At eight knots, the POST PANAMAX bulk carrier has a relative main engine fuel consumption of about 0.19 kg/kWh, and during the test voyage (5 miles), this vessel consumed about 325 kg of diesel fuel and generated about 1040 kg of CO₂ [7]. A POST PANAMAX bulk carrier in the port of Klaipeda consumes about 55 kg
less diesel fuel and generates about 180 kg less emissions than when sailing at a speed of 8 knots, when sailing the same route at a speed of 5.6 knots. Approximately 300 bulk carriers of a similar size enter the port of Klaipeda each year, so considering the arrival and departure of ships from the port, sailing at the optimal speed (5.6 knots) compared to the permitted speed (8 knots) would save about 33,000 kg of diesel fuel and generate about 106,000 kg CO\textsubscript{2} less.

In the case study, the study only covered diesel fuel with a sulfur content of no more than 0.1% (the Baltic Sea is included in the SO\textsubscript{X} control area), and this is currently the main fuel used in the analyzed ships. When evaluating fuel consumption and generated emissions, using other fuels, the developed model can be applied, and it is only necessary to evaluate the coloration of specific fuels and the likely types of emissions generated, for example, when using LNG fuel, sulfur oxides and particles mate are not generated, and the amount of carbon dioxide generated is lower.

The optimal speed of ships makes it possible to guarantee the safety of navigation in ports, to reduce fuel consumption and, at the same time, to reduce the generation of emissions when ships navigate in port navigation channels and port water areas, which has a positive impact on the development of sustainable and green ports.

The results of the calculation and experimental research of the case study clearly prove that the optimal speed of the PANAMAX container ship in the port channels and in the port water area is about 8 knots, while the optimal speed of the POST PANAMAX bulk carrier in the port channels and in the port area is about 5.6 knots (the speed allowed in the port is 8 knots). At the specified speed and under standard sailing conditions, the ships in the test have the lowest energy (fuel) consumption and the lowest emissions.

The results of the experiments on minimum ship controllability speed and minimum fuel consumption obtained from real ships were used to calculate simulator correction factors (provide simulator calibration). With the help of a calibrated simulator, more than 20 tests of ships passing through port channels at limited clearance were performed, which showed that the methodology developed and presented in the article can be used for scientific research and practical use in planning port channels, determining optimal conditions for ships passing through ports, and sustainable and green port development.

Synthesis of experiments with real ships sailing at a minimum controllable speed and minimum fuel consumption and calibration of the simulator based on real experiments and subsequent comparison of the obtained results with the calculation results using the developed methodology allowed the assessment of the reliability of the methodology and the possibility of using the methodology in other ports and waterways.

Similar partial studies have been carried out in Polish ports and other ports [48,55], the results of which are presented in [7,22,28,55] and other works with different types of ships.

The results of this study also revealed that the qualifications of port pilots, ship captains and tugboat captains are important when ships are sailing in ports, so their high qualifications and good knowledge of ship controllability can help minimize fuel consumption and emissions generated by ships.

5. Discussions

The paper discusses a number of measurements of ship movements in navigable harbor channels, carried out during the case study. Although this number was limited, it is representative of the research topic. Differences in operator behavior during maneuvering operations were observed and demonstrated that the skill level of port pilots, vessel and tugboat masters varies and is related to optimal vessel selection speeds [4]. Therefore, it should be noted that the results of the study can be considered satisfactory and allow the first research question to be answered, i.e., whether optimization ensures optimal speed in port navigation channels and port water areas.

It should be emphasized that the research results were influenced by external conditions that limited the number of experiments. The interface between real experiments and the use of a calibrated simulator made it possible to extend the research and the con-
ditions of its performance [8]. At the same time, it would be appropriate to continue the experiments, considering the external conditions in different seasons, in other ports and to compare the results. Based on this, it is possible to define more precisely the external conditions under which it is particularly important to ensure the navigational safety of shipping, taking into account the qualifications of the personnel, in order to be able to make the right decisions and reduce needed power of ship engines when sailing and maneuvering ships in ports, to reduce fuel consumption when navigating port navigational channels and port water areas and minimize the amount of emissions generated by ships entering and leaving ports; this should also have a positive influence on sustainable and green ports’ development [7].

Companies may organize regular training and invest in employees’ education, aiming at improving staff qualifications in supporting decision making during sailing and maneuver operations in ports. These activities may affect the development of companies’ navigational safety and environmental policy in order to decrease the costs of ships’ energy (fuel) consumption, as well as the volume of emissions [5,8].

The methodology presented in this article could be successfully used to optimize ship speed in port navigation channels and port water areas. Port services responsible for the navigational safety of shipping should also be made aware of the minimum controllable ship speed in various situations and evaluate it when organizing shipping in the port.

The results of the research on the possible minimum speed of the ships in the port, depending on the impact forces and the depth of the channels, using the calculation method presented in the article, showed the possibility of using this method in port conditions and reducing fuel consumption and the amount of emissions in the port. The minimization of fuel costs, using the optimal ship’s speed in the port, which guarantees the safety of navigation, is especially important in ports located within the boundaries of cities because it can significantly reduce the environmental impact of the port and improve the living conditions of city residents due to reduced ship emissions [21,26].

At the same time, it is an important scientific contribution to the ongoing research, as a new methodology has been developed to determine the optimal ship speeds in port channels and waters, with minimum fuel consumption and environmental impact, when there is little clearance, highlighting the novelty of this research and the article.

Detailed studies of the minimum ship handling speed under the influence of external forces and at shallow water, as well as a good knowledge of these phenomena, can increase the safety of ships operating in port channels and waterways.

The developed method provides an opportunity to analyze empirical data from real ships obtained by various modern methods (using high-precision navigation equipment, automatic ship identification systems, and calibrated simulators) and can be applied in practice. In addition, the presented method can be useful for seaports and shipping companies in reducing fuel consumption and reducing environmental impact, as well as in sustainable and green port development.

More detailed and complex studies of the external factors influencing the optimal maneuvering of ships in port channels and water areas, the fuel consumption of ships and the reduction in generated emissions, the turning of ships in port turning basins, bringing ships to and from port quays, using ship thrusters and tugs, in the presence of high wind and current speeds will be the direction of our further research. In future studies, we will try to increase the number of measurements and include more vessels and operators in similar studies.

6. Conclusions

Thus, based on the research conducted and the results presented in this article, the following conclusions can be drawn:

The methodology developed for calculating the minimum ship-controlled speed at low clearance allows it to be used in different conditions to improve navigational safety in the port. Experiments carried out with real ships in order to verify the minimum ship
controllability speeds and fuel consumption of the vessels have confirmed the accuracy of the theoretical models obtained.

Matching the minimum controllable speed of the ship with the minimum fuel consumption when navigating in restricted conditions under keel clearance waterways will not only reduce the ship’s fuel consumption by 12–15%, but also reduce the ship’s emissions by a similar amount. Estimating the optimal speeds of ships, using the developed model, allows the fuel consumption and the amount of generated emissions to be reduced, which has a positive impact on the development of sustainable and green ports. It aims to improve the quality of life in port cities.

Ship operators can successfully use the presented methodology to ensure navigational safety, reduce fuel consumption in port canals and port waters, and reduce emissions in the low clearance conditions typical of ports and other waterways. The results of the study also revealed that the qualifications of port pilots, ship captains and tugboat captains are important when ships sailing in ports, so their high qualifications and good knowledge of ship controllability can help minimize fuel consumption (up to 10–15%) and the emissions generated by ships.

The developed methodology for the assessment of minimum ship speed, minimum fuel consumption and minimum emissions from ships can be successfully applied (adapted) in any port and used for training and research purposes, evaluating the elements of port navigation safety and environmental impact.

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