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Impact of Port Clearance on Ships Safety, Energy Consumption and Emissions

Vytautas Paulauskas [1,*], Donatas Paulauskas [2] and Vytas Paulauskas [3]

1 Marine Engineering Department, Klaipeda University, H. Manto g. 84, LT-92219 Klaipeda, Lithuania
2 Maritime Engineering Department, Klaipeda University, H. Manto g. 84, LT-92294 Klaipeda, Lithuania; paulauskasd75@gmail.com
3 Klaipeda Shipping Research Centre, V. Berbomo str. 7-5, LT-92219 Klaipeda, Lithuania; vytaspaulauskas1@gmail.com
* Correspondence: vytautaskltc@gmail.com

Abstract: The safety of shipping, energy consumption and environmental impact in ports and port channels is very critical. One of the most important elements in the provision of safe navigation, energy consumption and emissions generation is the depth of ports so that under all conditions the hull of a ship does not touch the bottom of the channels or the bottom of the basin, as well as optimizing energy consumption and minimizing the environmental impact. The very high depth reserves in ports make it possible to ensure the safety of shipping, but at the same time require huge investments in the dredging and maintenance of a port's channels and basins, which can have a negative impact on a port's economic results. Optimizing the depth of port channels and basins is very important from an economic, maritime safety, energy saving and environmental point of view, as vessels navigating port channels and basins must not only keep their hulls off the bottom of the channel or basin, but also have good controllability, use minimal energy consumption and minimize their environmental impact. With good maneuverability, the number of and need for auxiliary vehicles (tugs) can be minimized. This article analyses the relationship between ships' draught and port channels and basins depths, which influences the aspects of a ship's controllability, in order to optimize the depths of port channels and basins and, at the same time, minimize energy consumption and environmental impact while preserving the necessary navigational safety.

Keywords: ship draught; depth of port channels and basins; ship maneuverability at low depths; energy consumption; emissions generated by ships

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1. Introduction

Depth in port channels and basins is one of the most critical elements in ensuring navigation safety in ports, which is why ports carry out maintenance and dredging operations to reach and maintain the necessary depths [1]. The depth of navigational channels is important to ensure not only that vessels navigating the channels do not touch the bottom of the channel with their hulls, but also that the vessel has good controllability [2]. The clearance (the distance between a ship's hull and the navigational channel bottom) in a port's channels and basins has an influence on energy consumption due to the ship's increased resistance while maintaining speed, as well as an environmental impact [3,4].

Today, the depth of channels and basins is calculated by mainly taking into account the potential maximum draught of the vessel; the accuracy of the depth measurement; the water level and its possible change (accuracy of the measurement); the variance in the ship's draft depending on the ship's speed and clearance [1,4,5]; the potential increase in the vessel's draft due to the vessel's corner angle; and the navigational margin, which takes into account the potential changes in the bottom of the channel (accumulations of soil sediments) [4,5].

The depth of the channel must be sufficient enough to ensure the safe passage of vessels, including in and out of the ports under difficult conditions, i.e., when the speed of the biggest possible vessel entering the port may be increased by up to 1.3–1.5 times [1,5,6].

The maneuvering of vessels in port is subject to external forces such as wind, current, swell and the effects of tugboats, as well as internal influences such as the ship's own speed and the ship's inclination during maneuvering. Thus, all possible influences have to be taken into account when planning the depths of port channels and basins [2,4,5,7].

When planning the depths of port channels and basins, it is also necessary to take into account the processes of sediment accumulation, movement and the possibility of periodic dredging in order to guarantee optimum depths in port channels and basins at all times [4,8].

When ships are sailing in port approaches and port internal channels at shallow depths, the resistance of the ship's hull increases significantly [3,5]. To maintain the proper speed of the ship, it is necessary to increase the power of the main engine(s) of the ship [3,9,10]. Increasing the power of a ship's main engine(s) significantly increases fuel consumption [11,12] and, accordingly, generates more emissions [13].

Ports are trying to become "green ports"; therefore, the amount of emissions generated from shipping in ports is a very important goal, so it is necessary to follow international and national requirements to reduce emissions from shipping [14–16].

Air quality in regions and especially in large ports has a significant impact on human health; therefore, the issues of environmental protection and decarbonization of shipping are very important for the quality of life and the economy of countries [17–19].

People play a very important role in reducing emissions in ports, i.e., the human factor, without which significant results cannot be achieved in any field, including the development of "green port" ideas [16,20].

The main objective of this article is to develop a methodology to determine the required optimal or minimum possible ship clearance in port channels and basins (the space between the ship's hull and the bottom of the port channel) while maintaining the appropriate ship speed and guaranteeing the safety of shipping in port channels (shipping safety is a priority) and to assess the relationship between the ship's clearance and energy (fuel) consumption and emissions. In this way, the main aims of this article are as follows: to assess ships' safe navigation capabilities in port channels, i.e., the ability of a ship to navigate independently in the bends of a port channel with the existing relationship between the draft of the ship and the bottom of the navigation channel; to determine the change in the power of a ship's main engine(s) at shallow depths to maintain the specified speed of the ship in the navigation channel, i.e., at the existing draft of the ship and the depth of the navigation channel to maintain the prescribed safe cruising speed; to determine the change in energy (fuel) of a ship's main engine(s) and the emission levels generated based on the current ratio of the ship's draft to the depth of the port (navigation) channels.

In this way, the structure of the research and the article is oriented as follows: first of all, it must be assessed whether the ship can enter the port, which is related to the depths of the navigation channels (port entrance and internal navigation channels compared to the ship's berth). In the event that the ship has the opportunity to enter the port independently, then the following task is solved, i.e., the power of the ship's main engine(s), depending on the ratio of the ship's draft to the depth of the navigation channels, respectively, energy (fuel) consumption and the amount of generated emissions. If the depth of the port channels is satisfactory, the ship can enter the port independently or, if necessary, port tugs or additional special maneuvers can be used. In the event that it is possible for the ship to enter the port on its own, then the task is solved, i.e., the power of the ship's main engine(s), depending on the ratio of the ship's draft to the depth of the navigation channels, energy (fuel) consumption and generated emissions, respectively, is sufficient.

2. Analysis and Literature Review of Clearance in Port Channels and Basins

Many ports in the world have different requirements for minimum depths in port channels and basins and generally use guidelines such as PIANC [21] and EAU [22]. The distance between a ship's hull and the bottom of a navigation channel is very important in order to avoid the ship's hull coming into contact with the bottom of the navigation channel and to maintain sufficient controllability of the ship. Studies have been conducted on this topic [1,4,5,7,8]. At the same time, it should be noted that ship handling hearings require additional research, as ports try to attract larger and larger ships, and sometimes emergency situations occur due to too little clearance when ships touch the bottom of the navigation channel with their hulls due to ship heeling caused by external forces, or ships sink due to the ship's speed in the shipping channel or become uncontrollable and float outside the shipping channel [3,6,7].

At the same time, other very important aspects, such as the energy consumption of ships entering and maneuvering in ports and the environmental impact of low clearance under the ship's hull, have not yet been taken into account when assessing depths in port approaches and internal navigational channels and basins. The above aspects of energy consumption and environmental impacts from ships have been analyzed individually and without considering the potential impact of clearance on these aspects [16,23,24].

Vessel speeds are restricted in many ports and are linked to maritime safety and environmental impacts (the effect of waves generated by the vessel on moored vessels and the coastline) (Figure 1) [25–27].

Figure 1. LNG tanker sailing in port (Klaipeda port), permitted speed up to 8 knots.

Tugboats are widely used for assisting with maneuvering large ships in port because they are equipped with powerful engines and can use high engine power; however, they consume a lot of energy (fuel), generating large amounts of emissions, especially when turning ships and approaching or leaving the quay (Figure 2) [8].

Figure 2. LNG tanker turns in ships turning basin using port tugboats.

The assessment of sustainable transport systems in ports and their environmental impact is very important for the ports themselves and for individual regions, so research in this area is very essential [28,29].

Maritime transport plays an important role for many countries and creates a significant part of their gross domestic product (GDP). At the same time, maritime transport, especially in port regions, has a significant impact on the environment, so many countries are conducting research on that issue and are looking for optimal solutions to minimize the impact on the environment while improving the economic situation of the countries [29–33].

The emission control regions adopted by the International Maritime Organization (IMO) such as the SO_x emission control areas—the Baltic and North Seas, the English Channel and the east and west coasts of North America—have allowed a significant reduction of SO_x emissions from ships in these regions [13,34,35].

Ports, as the most important maritime transport points, also try to maximize their influence on the reduction of emissions from ships and other vehicles [15,16,36,37].

The navigational safety of ports and the necessary minimum depths of ports are studied in many countries, since dredging works are expensive and in the development of sustainable ports it is necessary to combine navigation safety, economic, environmental and other possible factors [16,17,24–26].

For the provision of navigation safety, when sailing ships in shallow depths, i.e., the minimum depth below the ship's hull, methods for its determination, such as Bernoulli's flow formulas ideas [4], estimates of the connected liquid mass and others [1,5,12,21,22], are used in many countries, but the results obtained are often similar.

As follows from the analysis of the situation and the literature, the necessary depths in ports and the minimum clearance under the ship's hull in ports and navigation channels, as well as emissions from ships, have been studied by many researchers. At the same time, the change in the ship's controllability at low depths (clearance under the ship's hull) and the clear connection between the clearance under the ship's hull and the ship's energy consumption and emissions are missed.

3. Basis for the Theoretical Calculations of Possibilities for the Ships Sail in Port Channels and Basins, Energy Consumption and Emissions Generation

3.1. Steps of Research Methodology

The following steps of research methodology were used to conduct the research (Figure 3). After conducting the literature review, the mathematical model was developed.

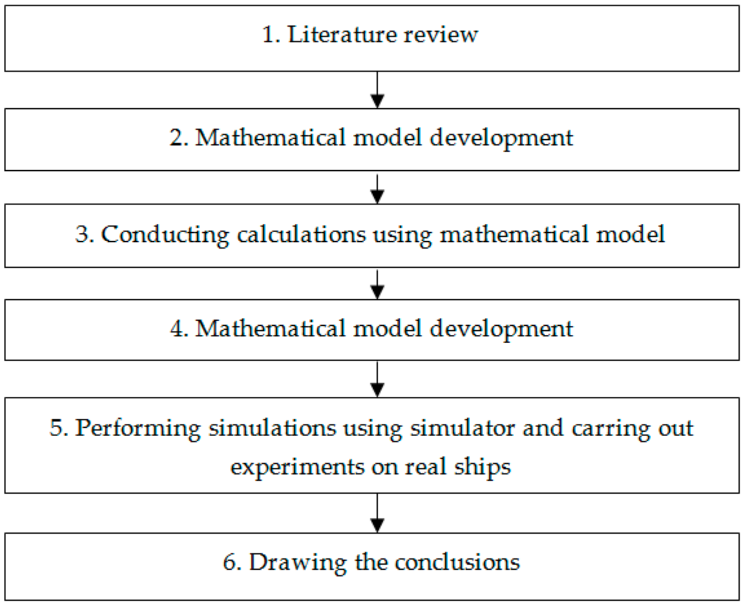

Figure 3. The steps of research methodology.

Based on the presented methodology, theoretical calculations of possibilities for ships sailing in port channels and basins, energy consumption and emissions created by ship were performed. The variation of hull resistance to longitudinal movement with clearance, i.e., the ratio *T*/*H* (draught to depth), was used to estimate the ship's sailing speed in ports [1,5]. For the assessment of the ship's controllability, the methods of calculation of the ship's circulation elements and trajectory at low depths were used [3,8,27]. The method of calculating the ship's circulation trajectory in shallow depth was applied as given in sources [4,5]. The method is based on the calculation of the basic ship movement parameters (ship speed, ship angular velocity and ship drift angle) and the ship's trajectory in the case of low clearance, which often occurs in port navigation channels and basins. Estimation of the ship's sailing trajectory in the presence of small clearances is necessary when navigating port approach and internal navigation channels so that the ship can safely pass through channel bends. Due to the variation of the ship's draft and the power of the main engine(s) when sailing in shallow waters (port navigation channels) and maintaining the set speed, at low depths (clearance), additional resistance forces of the ship hull are formed which are related to the change of the added water mass [4,5].

For the calculation of the ship's energy consumption, fuel consumption was calculated as a function of the engine power at a given speed, and for the assessment of emissions, the parameters of the ship's fuel consumption, engine power and operating time were used [15,38]. For this calculation, the maximal distribution method was used utilizing data achieved by conducting experiments on simulators and real ships [39]. The maximal distribution method could be applied in case at least 5 measurements were carried out.

In order to verify theoretical calculations and practical application of the presented methodology, experiments were performed with the assistance of a simulator and on real ships. Simulations were carried out using the full mission simulator "SimFlex Navigator" (Force Technology product) [40], which analyzed similar maneuvers as the real ships, considering the set forces acting on ships sailing in port channels and ships turning in turning basins. Experiments performed on real ships covered two port areas with specific navigational conditions (port approach and internal navigational channels).

Then, the results were analyzed, discussions initiated, conclusions were drawn and suggestions for future research were outlined.

3.2. Mathematical Model

The results of the literature review, the results of simulators and the results of the real ship tests when different clearances were used between the ship's hull and the bottom of the channels were used to develop mathematical models of shipping navigational safety, energy (fuel) consumption and emission generation at shallow depths [1,9,15,37,41–44]. When conducting research and creating mathematical models, it was assumed that ships in navigational channels sail independently, and the controllability of the ship is ensured by the ship's own steering equipment. In channel bends and turning basins, ships turn with the help of their control equipment (propulsion complex), and if necessary, they can use the help of ship steering devices and tugboats [5,7]. It is also assumed that when ships move straight through channels due to the effect of low depth, only the longitudinal resistance of the ship changes, and when ships sail in bends of navigation channels and when turning in turning basins, the resistance of the ship's lateral movement additionally increases [43,45].

The safe depth of the port channels and port water areas, so that the largest ship in the port does not touch the bottom of the navigation channels and basins with its hull, can be calculated with the help of the following formula [1,4]:

$$H_{\min} = T + \Delta T_v + \Delta T_\theta + \Delta T_\Psi + \Delta H_m + \Delta H_{V.L} + \Delta H_{\Delta V.L} + \Delta H_n, \quad (1)$$

where T—the maximum draught of the calculated vessel; ΔT_V—the increase in draught due to settlement (speed), sometimes named squat [4,5]; ΔT_θ—the increase in draught due to heeling [4,5]; ΔT_ψ—the increase in draught due to the effect of swell (change in the difference) [5]; ΔH_m—the accuracy of the depth measurement, depending on the port depth measurement technique used; $\Delta H_{V.L.}$—the level of the water in the particular port; $\Delta H_{\Delta.V.L.}$—the accuracy of the measurement of the water level, depending on the port water level measurement technique used; $\Delta H_{n.}$—navigational margin, which can be decomposed into a direct navigational margin, which is assumed to be about 2–3% of the ship's draught, by means of accurate bottom depth measurements (using modern depth measurement techniques), and a layer of sediment, which has to be periodically removed (cleaning). The above elements of Formula (1) can be calculated using the methodology presented in [4,5].

The increase in draught (ΔT_v) due to low-depth effects and the ship's speed can be calculated using the following formula and graph (Figure 4) to estimate the added water mass coefficients [1,4,5]:

$$\Delta T_V = \frac{\rho L B}{\delta} \sqrt{\frac{1 + k'_{11}}{1 + k_{11}}} \quad (2)$$

where ρ—water density; L—ship's length between perpendiculars; B—ship's width; δ—overall hull fullness factor; k_{11} and k'_{11}—added water mass coefficients at high depth and in shallow water, depending on the ship's speed and T/H ratio (Figure 4) [5].

The added water mass depends on the speed of the ship and the draft of the ship, as well as the depths of the navigation channels and the port water area ratio (*T*/*H*). Added water mass coefficients, which are presented in Figure 4 when the ship is moving in the longitudinal direction, are usually used for calculation [4,5].

In the article, the water mass coefficients presented in Figure 4 are used to calculate the change in the ship's draft and the increase in the ship's draft, as well as the correspondence of the specified coefficients, verified by experiments by measuring clearance on real ships [4,5].

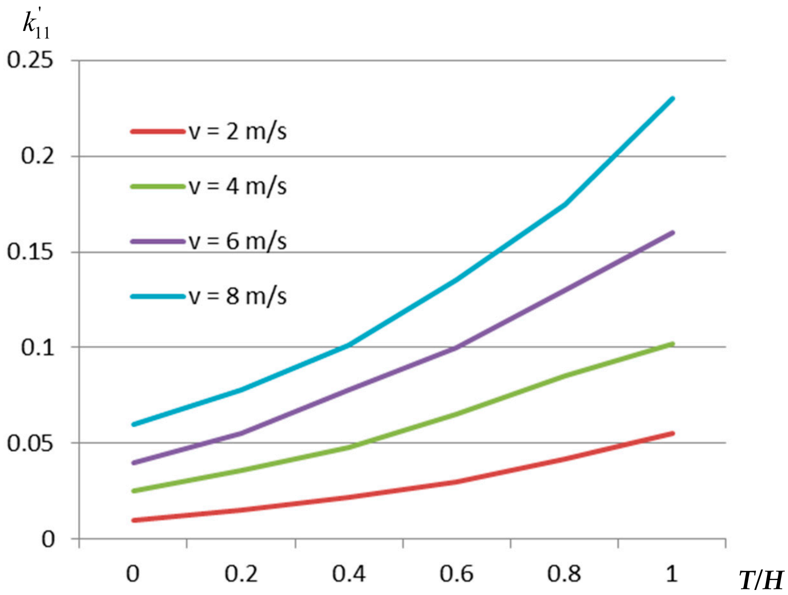

Figure 4. Dependence of the added water mass coefficients (k_{11}—deep water, T/H ratio is zero); k'_{11}—shallow water) on the T/H ratio and the vessel's sailing speed v.

Formulas can be used to calculate the trajectory of a ship at shallow depth and in the presence of wind and current, which is a characteristic of ports [4,40,43,45]:

$$X_{0i(s)} = \int v_{i(s)} \cdot \cos(\int (\omega_{i(s)} dt - \beta_{i(s)}))dt + \int v_{cr} dt \cdot \cos q_{cr} + \int v_d dt \cos q_a; \quad (3)$$

$$Y_{0i(s)} = \int v_{i(s)} \cdot \sin(\int (\omega_{i(s)} dt - \beta_{i(s)}))dt + \int v_{cr} dt \cdot \sin q_{cr} + \int v_d dt \cdot \sin q_a, \quad (4)$$

where $v_{i(s)}$—ship's speed at low depths; $\omega_{i(s)}$—turning velocity at low depths; $\beta_{i(s)}$—drift angle at low depths; v_{cr}—current velocity; q_{sr}—current course angle during the start of the maneuverer; v_d—ship's drift speed; q_a—wind course angle during the start of the maneuver. The above elements of Formulas (2) and (3) can be calculated using the methodology presented in [5].

When examining the passage of ships in ports, it is assumed that the movement of ships in the port approach and internal navigation channels lead to the fact that ships independently sail on a straight or almost straight trajectory (turning up to 30–40 degrees). The research also assumes that the change in the power used by the ship's main engine due to the effect of shallow water is basically related to the change in the resistance of the ship's longitudinal movement [3,10,11]. Experiments with real ships were carried out in the open sea and in ports (shallow waters) for the power factor, maintaining a set constant speed and accurately recording the main engine power, the speed of the ship with the help of electronic lag and DGPS and the depth with the help of echo sounder. On the basis of studies carried out on real ships, a dependence of the calculation of the power factor of the ship's main propulsion system (ΔN) on the T/H ratio (ship's draught/depth ratio) and the overall hull fullness factor is obtained as follows:

$$\Delta N = (1 + 1.25(\frac{T}{H})^2)\sqrt{\frac{\delta}{0.65}}, \quad (5)$$

Calculation of the power factor of the ship's main engine due to the influence of shallow water according to Formula (5) and experimental tests with real ships showed that the difference between the calculations and the results of experimental tests is no more than 10%. Thus, Formula (5) can be successfully used in practice. The limitations of Formula (5) evaluated during the experiments are as follows: the speed of the ships should be between

6 knots and 10 knots, and the overall fullness factor of the ship's hull should be between 0.65 and 0.90. If the overall fullness ratio of the ship's hull is less than 0.65, Formula (5) can be used when the ratio of the ship's draft to the depth of the navigation channel (*T*/*H*) is greater than 0.3.

As hull resistance increases, the power of the ship's engine must be increased to maintain the ship's target or planned speed. The relative power of the ship's engine (N') and the relative speed of the ship (v') can be expressed in the following formula:

$$N' = \frac{N}{N_0}; \tag{6}$$

$$v' = \frac{v}{v_0}, \tag{7}$$

where N_0—nominal power of the main engine(s) of the vessel; v—speed of the vessel at the power of the vessel's engine(s) N; v_0—speed of the vessel at the nominal power of the vessel's engine(s) N_0.

The relationship between the ship's relative speed and the relative power of the ship's main engine(s), presented in the literature [3,10,11], was verified by the authors through experiments on real ships of various types and sizes. Some of the results of the experiments carried out on real ships are presented in Table 1. Comparing the results of real ship experiments regarding the relative power of the ships' main engine(s) and the ships' relative speed using the maximum distribution method, the maximum changes, expressed as a percentage, were obtained (presented in Table 1). Experiments were carried out for many years on various ships, in which at least one of the authors of the article participated. The navigation equipment available on the ship was used for the experiments (ship speed was measured with an accuracy of at least 0.1 knots) as were the power measurement indicators of the main engine(s) on board the ships, the measurement accuracy of which was at least 2% of the instantaneous power.

Table 1. Experiments results of relative main engine power and relative speed of the real ships.

Ship Type	Displacement, t	N_0, MW	v_0	N'	v'	Max Difference between Calculation and Experiments Results, %
Container	220,000	75	25	0.15	0.28	5.2
Container	130,000	50	24	0.17	0.32	4.8
LNG tanker	91,500	24	21	0.44	0.69	7.6
Bulk	80,000	10	14.6	0.33	0.54	8.5
Oil tanker	72,900	10	14	0.34	0.58	6.5
Container	70,230	25	23	0.33	0.52	4.6
Oil tanker	34,300	11	15.5	0.31	0.51	5.4
General	15,200	7	14.3	0.24	0.41	3.5
Ro-Pax	10,200	12	18.2	0.41	0.65	4.4
Coaster	5200	3.5	12.5	0.45	0.70	8.9

The power of the engine and the speed of the ship are related by a quadratic relationship [3,10,38]. In most cases, the relative power of the ship's engine(s) and the ship's speed can be used. For this purpose, a graph based on the experimental results from more than 1000 ship passages can be used [3,10,11] (Figure 5).

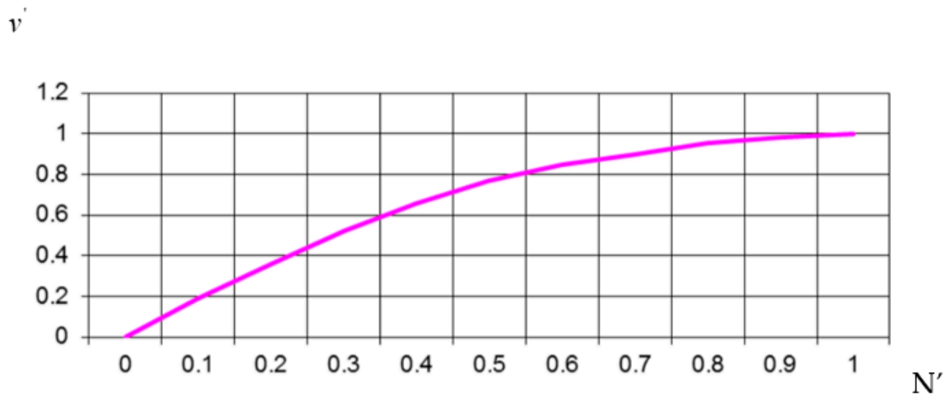

Figure 5. Relative vessel speed (v') versus relative engine power (N').

A limitation of the graph (Figure 5) with a very high overall hull fullness factor (δ) is that with the overall fullness factor of the ship's hull greater than 0.9, the form resistance parameters of the ship's hull shape change significantly and the accuracy of the graph is not good enough (error size can reach more than 10 percent).

Engine power can be calculated by taking into account the amount of fuel consumed over a given period of time, e.g., an hour, and the relative fuel consumption, i.e., [9,11,12]:

$$N = \frac{q_k}{q_k' \cdot t}, \tag{8}$$

where N—engine power, kW; q_k—fuel consumption, kg; q_k'—relative fuel consumption, kg/kWh; t—engine running time, h.

Due to their powerful engines, ships consume a lot of fuel while sailing, especially when performing additional, not always justified, maneuvers in ports. A ship's fuel consumption is often calculated over a voyage or other period. In a general case, the fuel consumption of a ship on a voyage (q_{LP}) or other sailing places and times can be calculated according to the following formula [9,11,38,42]:

$$q_{LP} = \int_0^t q_k' \cdot N_{av} \cdot dt, \tag{9}$$

where N_{av}—ship main engine average power during time t.

The relative fuel consumption of the main and auxiliary engines of most ships ranges from 0.13 to 0.25 kg/kWh (for more precise data, please refer to the engine specification of the individual ship) [11]. Depending on the type of fuel, the amount of fuel used can be different, so when using LNG, its calorific value is on average about 15 percent higher than other petroleum products, which means that about 15 percent less fuel mass is consumed [15,46].

Emissions from ships and other transport vehicles directly depend on the quantity and quality of fuel used, engine power and engine running time [11,17,42]. The main emissions from ships constitute carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), sulfur oxides (SO_x) and particulate matter (PM) [11].

Emissions are calculated according to the formula that includes fuel consumption, actual engine power used and the relative magnitude of specific emissions. Thus, the carbon dioxide emissions are calculated according to the following formula [15,47]:

$$CO_2 = q_{LP} \cdot \Delta CO_2, \tag{10}$$

where ΔCO_2—carbon dioxide coefficient, which for petroleum products (diesel, fuel oil) is between 3.0 and 3.5 and for LNG between 2.5 and 2.9.

The Sulphur oxide content can be calculated using the following formula [14,15]:

$$SO_x = q_{LP} \cdot \Delta SO_x, \quad (11)$$

where ΔSO_x—Sulphur oxide coefficient, which depends on the type of fuel; for petroleum products, it ranges from 0.001 to 0.035 and for LNG it is around zero.

The carbon monoxide content can be calculated using the following formula [41]:

$$CO = \int_0^t N_{av} \cdot \Delta CO \cdot dt, \quad (12)$$

where ΔCO—carbon monoxide coefficient, which depends on the type of engine [42].

The amount of nitrogen oxides generated is calculated using the following formula [41]:

$$NO_x = \int_0^t N_{av} \cdot \Delta NO_x \cdot dt, \quad (13)$$

where ΔNO_X—nitrogen oxide coefficient, depending on the engine type.

The particulate matter generation is calculated using the following formula [48]:

$$PM = \int_0^t N_{av} \cdot \Delta PM \cdot dt, \quad (14)$$

where ΔPM—the particulate matter coefficient, which depends on the type of engine and the type of fuel, and is up to 10 g/kWh for petroleum products and close to zero for LNG fuels [48].

The emission factors and sizes of marine engines depend on the type of engine and the type of fuel used. For marine engines, average emission factors and relative values are given in Table 2 (as an example) [11].

Table 2. Average emission factors for marine engines by fuel type.

Types of Emission	Petroleum Products	LNG
CO_2—depending on the amount of fuel	3.2	2.5
SO_x, %—depending on the amount of fuel	0.1	0.0–0.1
NO_x, g/kWh	10	4
CO, g/kWh	5	3
PM, g/kWh	0.5	0.0–0.1

Thus, the reduction of emissions from engines depends on the type and design of the engine, the type of fuel used and the engine's operating conditions (maneuvering mode). Fuel consumption depends on the operating mode of the engine, especially the modes of transitional mechanisms.

The qualifications and experience of ship crews and port pilots greatly influence the amount of emissions from ships [15,38,48,49].

The power of engines used in ships has a significant influence on the generation of individual emissions. Emission factors and relative magnitudes are shown in Table 3 (as an example) [11,49,50].

Table 3. The relative amount of emissions based on engine power.

N, kW	*CO*, g/kWh	NO_x, g/kWh	*PM*, g/kWh
30	5.0	7.5	0.40
100	5.0	7.2	0.30
250	5.0	7.2	0.20
1000	5.0	7.5	0.25
3000	5.0	9.8	0.50
10,000	5.0	10.5	0.50
≥10,000	5.0	11.0	0.50

Thus, shipping emissions depend on the type of fuel, the quality of the engine and its power. Knowing how much fuel is consumed in shipping, what type of emissions are emitted and what their quantities are, it is possible and necessary to look for opportunities and methods to reduce the impact on the environment.

4. Case study and Results

This case study has analyzed a few types of ships: PANAMAX type bulk ships (length about 206 m, width about 36.0 m, draft about 12.5 m, deadweight about 80,000 t), POST PANAMAX container vessels (length about 300 m, width about 46 m, draft about 13.0 m, container capacity about 8500 TEU, deadweight about 130,000 t), G class container vessels (length about 400 m, width about 61 m, draft about 13.5 m, container capacity about 19,500 TEU, deadweight about 220,000 t) and LNG standard tankers (length about 290 m, width about 49 m, draft about 12 m, capacity about 150,000 m^3 LNG).

Real ships and the full mission simulator SimFlex Navigator were used for the experiments. The following methodology of conducting experiments was used: first, an experiment plan was drawn up to achieve specific goals, then possible real ships were selected and the possibility of using the simulator was checked. Experiments with real ships were carried out both at sea and while entering and leaving ports.

For the purposes of this article, previously mentioned conducted experiments and targeted experiments were used when sailing ships at sea at great depths and when sailing in ports or other navigational channels where there were limited depths, such as the Oresund, Belt and other straits where there are limited depths, in which one or all authors participated. During the experiment, the ship's speed was recorded using the ship's navigation equipment (DGPS or GPS and others on the ship's bridge), as well as a port pilot RTK (real-time kinematic) system, which was implemented in Klaipeda port, clearance (distance between ship's hull and navigational channels bottom) was measured by the ship's navigational equipment (ship's echo sounder on the ship's bridge), the load (power) of the ship's main engine(s) and the propeller rotation frequency (on the ship's bridge and in the ship's engine room) were measured and in separate cases, when there was a real possibility, fuel consumption during a particular voyage (in the ship's engine room) was measured.

Experiments were carried out to measure the advance of the ship during circulation (during the ship's waiting for entry into ports or special trials of ships after their construction or repair, in which at least one of the authors participated) as well as during navigation during large turns.

According to the obtained results of real ship experiments, a suitable ship was selected in the simulator and the relevant ship movement and other parameters obtained in real ships and in the simulator under identical conditions were compared. During the matching process between the real ship and the ship in the simulator, the calibration coefficients were calculated, and then the experiments were continued with the help of the simulator using the calibration coefficients.

For the checking ship's advance [5,51] (Figure 6), all tested ships sailed with an initial speed of 8 knots and a rudder turn angle of 25° to starboard. All tested ships had conventional propulsion, i.e., one propeller and one rudder [52]. The vessel's advance in circulation analysis is important to assess whether the vessel is able to turn on bends in the channel on its own, whether it needs the assistance of tugboats or whether additional maneuvers by the vessel are necessary [1,7,43].

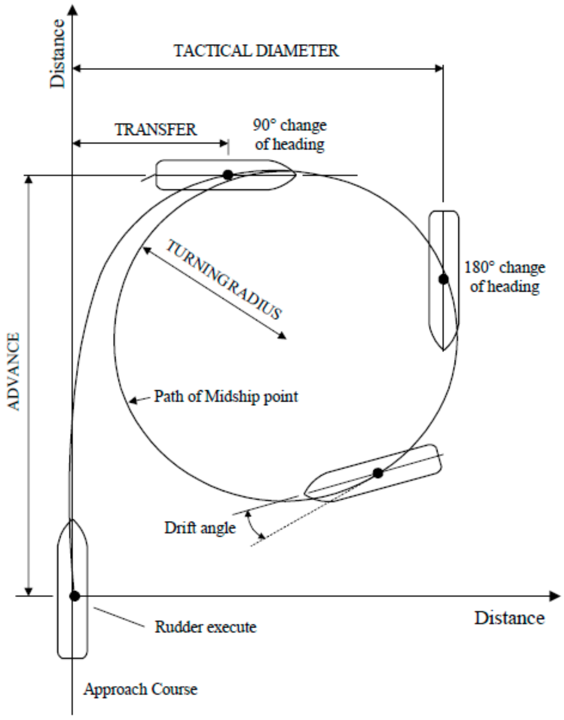

Figure 6. Ship's circular trajectory details.

Ships advance testing was made in good navigational conditions, i.e., wind velocity less than 10 m/s, wave height less than 1 m and current less than 0.5 kn. The mentioned ship's advance testing results are presented in Figure 7. In all cases, a rudder angle of 25 degrees was adopted (to leave a margin of maneuverability). Tests of real ships for simulator calibration were performed as follows: bulk cargo ship—three ships; container ship (9000 TEU)—two ships; container ship (19,500 TEU)—one ship. The "Tables of maneuvering elements" available on the ship's bridge were also used. With the help of a calibrated simulator, at least 10 tests (for G class container vessel—10 tests; for 9000 TEU container vessel—12 tests; for 80,000 t bulk cargo ship—12 tests) of each mentioned ship were carried out. In the simulator, we selected ships from the simulator library which were analogous to real ships with which real experimental tests were performed in terms of type and parameters. The differences, although minor, were mostly due to differences in draft and displacement. For example, the simulator library contained a G-class container ship with an average draft of 14.0 m, while the real ship had a draft of 13.7 m. In order to unify the obtained results, it was necessary to calibrate the simulator, i.e., coefficients of the relationship of the received simulator data with the real ship. In practice, for such simulator calibration, one or two datapoints of a specific parameter of a real ship were sufficient. In the article, there were at least 2–3 real results for specific parameters of specified ships, and up to 7–12 such real ship test results were used for individual ships.

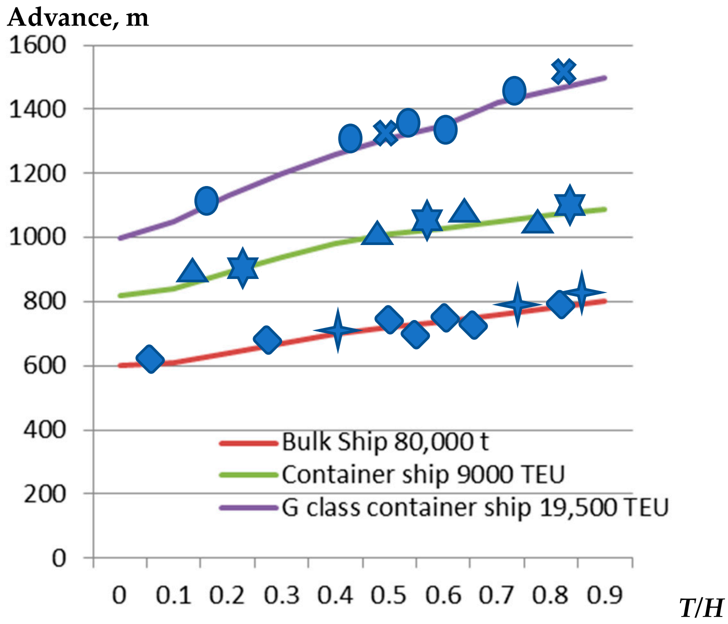

Figure 7. Ships advance on circular trajectory in deep and shallow waters (depending on *T/H*), received by calculation (lines), real ship experiments (G class container ship, container ship 9000 TEU, bulk ship 80,000 t) and calibrated simulator (G class container ship, container ship 9000 TEU, bulk ship 80,000 t).

The accuracy of the real ship test results obtained, necessary for research and simulator calibration using the RTK system, was: ship location—up to 0.1 m; ship speed—up to 0.1 knots; ship angular rotation speed—0.2 degrees per minute. When using the DGPS system, the accuracy of the received data consisted of: the location of the ship—up to 0.5–1.0 m (depending on the distance to the base station); the speed of the ship—up to 0.2 knots; the angular speed of the ship—up to 0.5 degrees per minute.

The study was conducted as presented in Section 3 using the full mission simulator SimFlex Navigator [40] and using real similar ships for experiments. All received data were filtrated by a Kalman filter [53] and the differences between calculated, simulated and real ships' experimental data were analyzed.

The results obtained from the advance calculation and experiments (Figure 7) show that the calculation results using the methodology presented in Section 3 are in high compliance with the results of the real ship experiments and the simulator results.

The results of calculation and experiments (obtained on real ships and with the help of a calibrated simulator) of ships' advance in circulation at a rudder angle of 25 degrees are shown in Figure 7, and the differences (accuracy) at different *T/H* ratios in meters and percentages from the experimental results are shown in Table 4.

The power changes in the main engines of the ships, due to hull longitudinal speed, and additional resistance in shallow waters were calculated according to the methodology presented in Section 3 and verified using a calibrated simulator and the results of real ship experiments under similar conditions (Figure 8).

At least eight types of ships were used to determine the power factor of the ship's main engine, depending on the ship's draft and the depth of the navigation channels, for conducting research and calibrating the simulator. During the experiments, equipment on the ship was used: ship echo sounders were used for depth measurement, the accuracy of which was up to 0.1 m, and the accuracy of the power of the ship's main engine(s) was up to 2% of the engine(s) power. During experiments, the fuel consumption of the real ships was measured by existing sensors in the ship's engine room, the accuracy of which was up to 2–3% of the amount of fuel consumed, and instantaneous fuel consumption sensors, the accuracy of which was about 4%. All data were recorded automatically.

Table 4. The difference (accuracy) between the results of calculation and experiments (obtained on real ships and with the help of a calibrated simulator) of ships' advance in circulation in meters and percentages from experimental results.

Ship	*T/H*	Calculated Advance, m	Difference Advance between Experimental and Calculation, m	Percentages from Experimental Results
G class Container	0.76	1430	30	2.1
G class Container	0.61	1350	48	3.6
G class Container	0.55	1330	32	2.4
G class Container	0.37	1260	22	1.7
G class Container	0.14	1120	18	1.6
Container 9000 TEU	0.73	1050	20	1.9
Container 9000 TEU	0.62	1030	27	2.6
Container 9000 TEU	0.47	1005	31	3.1
Container 9000 TEU	0.13	850	41	4.8
Bulk 80,000 t	0.83	790	22	2.8
Bulk 80,000 t	0.61	740	30	4.1
Bulk 80,000 t	0.31	680	28	4.1
Bulk 8000 t	0.06	603	18	3.0

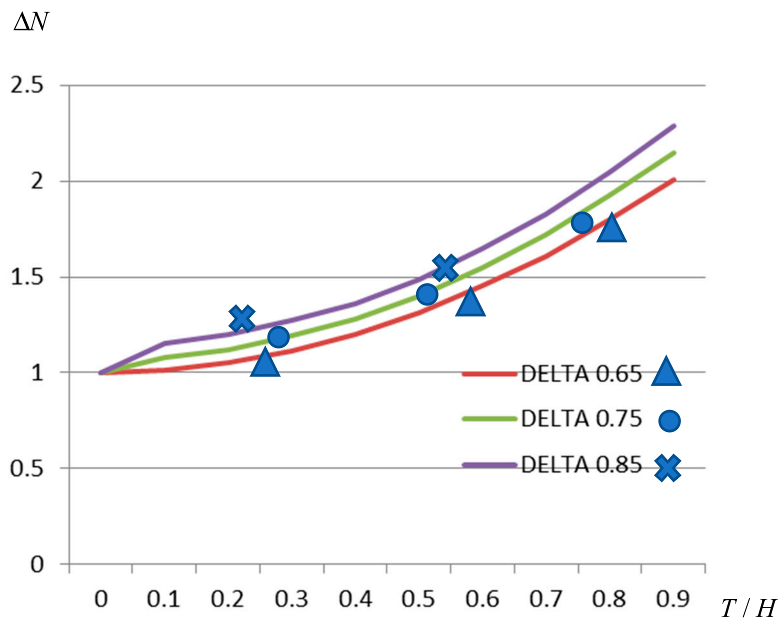

Figure 8. Ship's main engine power coefficient depending on ship's draft and depth ratio (*T/H)* and ship's overall hull fullness factor (DELTA) (calculation and experimental results).

The compliance between the results of the calculations and the experiments is quite high (the difference does not exceed 10 percent (Table 1)) (Figure 8), and therefore it can be concluded that the methodology presented in Section 3 for the calculation of the ship's engine power increasing during sailing at low depths can be used for practical purposes for the assessment of the performance of ships when sailing through channels and other similar locations with low depths.

The port of Klaipeda was chosen for the case analysis. The passage of a standard LNG tanker from the entrance channel to the southern turning basin of the port was analyzed (Figure 9).

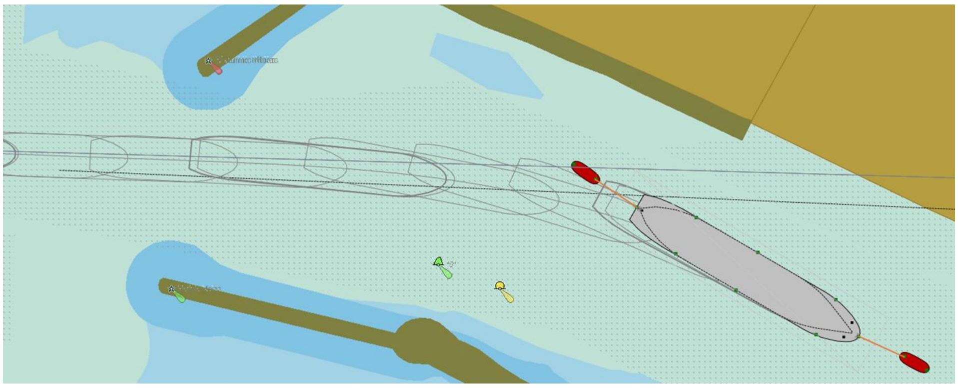

Figure 9. LNG standard tanker sailing trajectory in Klaipeda port.

The main engine power, fuel consumption and emissions of the ships were calculated according to the methodology presented in Section 3. The SimFlex Navigator simulator was used to change the clearance under the hull. Experiments were carried out on real ships (LNG standard tankers, length approx. 290 m, beam approx. 49 m, draft approx. 12 m, overall fullness coefficient approx. 0.75). The speeds adopted and used in the calculations, simulator and actual LNG carriers for the majority of the passage (up to the turning basin) were between 7 and 8 knots.

The calibration of the simulator was carried out by comparing the results of a real ship and a ship in the simulator. The simulator calibration was produced by calibration coefficients for the ship's main engine power, fuel consumption and the ship's speed at high and low depths. Following the simulator calibration, experiments were carried out on the simulator at various depths and speeds in the range from 6 to 10 knots and at characteristic depths in harbor approaches and ports, i.e., a T/H between 0.6 and 0.92.

The main engine power, speed and fuel consumption of the LNG standard tanker in the approach and internal navigational channels of the port of Klaipeda, obtained in a calibrated simulator, are shown in Figure 10.

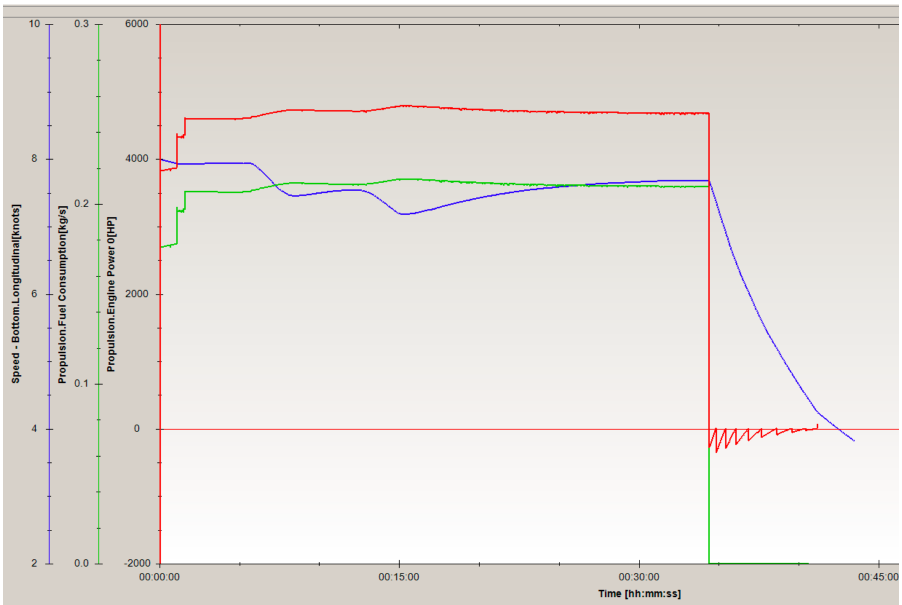

Figure 10. The LNG standard tanker engine power, ship's speed and fuel consumption obtained in a calibrated simulator.

The variation of the main engine power and fuel consumption factors for the LNG standard tanker sailing at a constant speed as a function of the ship's draught/depth ratio, which is characteristic of harbor approaches and internal navigation channels, using the methodology presented in Section 3, and the results obtained on the real ship, are presented in Figure 11.

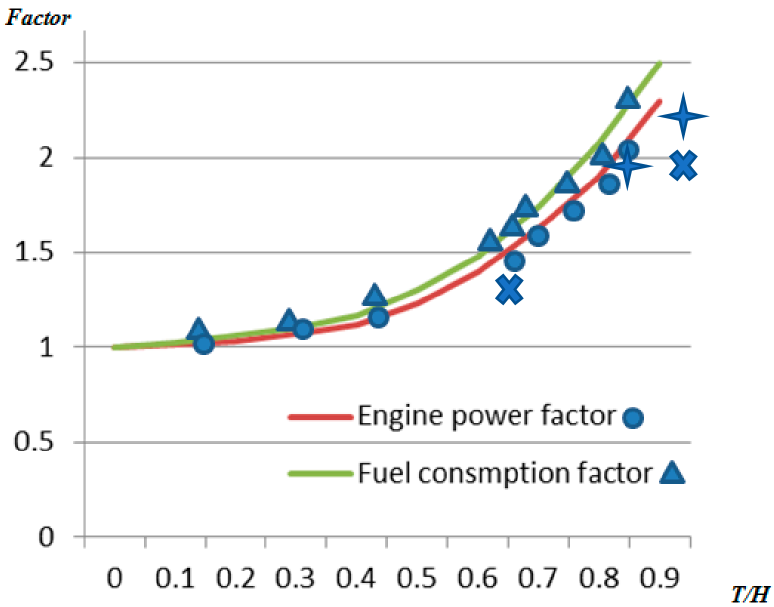

Figure 11. Standard LNG tanker main engine power and fuel consumption factors depending on the ratio of the ship's draft and depth (*T*/*H*) received by the theoretical method (lines) presented in Section 3, and experiments' results of the real ship (fuel consumption factor, engine power factor) and calibrated simulator.

As can be seen from the results obtained, the methodology presented in this article for the estimation of the usable power of a ship's main engine for ships navigating in the port approach and the internal channels can be applied for practical purposes.

The comparative studies of the calculation and experimental results of the received engine power and fuel consumption factors of the ship showed (LNG standard tanker) that the maximum difference between the calculation and experimental results (real ship and calibrated simulator) was up to 0.23, or, as a percentage, up to 9.3 percent.

On the basis of the results obtained, it can be concluded that the methodology presented in Section 3 for the estimation of the fuel consumption of ships in port approach and internal navigation channels can be successfully used for practical purposes and further calculations, for example, for the estimation of generated emissions.

Fuel consumption of the standard LNG tankers while sailing (Figures 9 and 10) at the specified sailing distance using LNG and diesel fuel depending on the ratio of the ship's draft and depth while the ship is sailing at a speed of 7–8 knots obtained by calculation and experimentally are presented in Figure 12.

As can be seen from the obtained calculation results (ship's circulation advance at low depths and ship's main engine(s) factors using the methodology presented in Section 3) and the results of experiments on real ships in corresponding conditions, there is a good correlation between the calculation and experimental results, which allows the use of the methodology developed and presented in this paper for practical purposes. At the same time, it is necessary to appreciate the fact that fuel consumption for ships sailing and maneuvering in ports depends up to 10–12 percent on the qualifications of ship crews and port pilots [15].

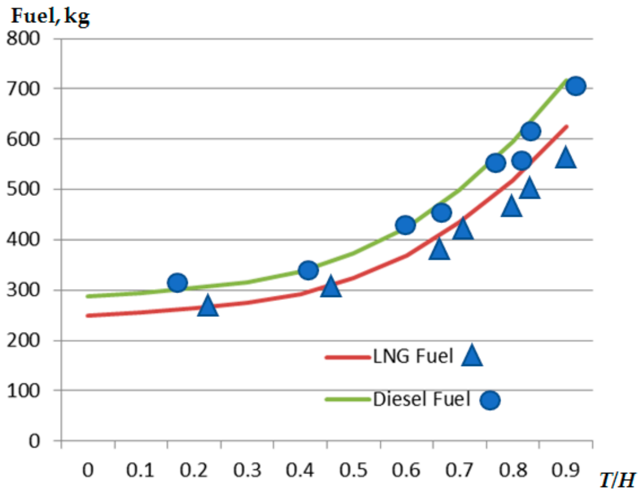

Figure 12. The fuel consumption of a standard LNG tanker sailing at a speed of 7–8 knots at sea and when entering the port of Klaipeda, obtained by calculation and experiments (sailing distance 5 n. miles).

The methodology presented in Section 3 is used to calculate the emissions. Emission values were calculated using petroleum products (diesel) and LNG fuel. The values of CO_2 and SO_x emissions, depending on the amount of fuel used, when sailing from the beginning of the port entrance channel to the turning basin (taking into account the differences in the energy capacity of LNG and diesel) were calculated. When the ship sails at a speed of 7–8 knots and different T/H ratios, the amount of CO, NO_x and PM emissions of a standard LNG tanker, depending on the T/H ratio, was calculated according to the methodology presented in Section 3, based on engine power, engine operating time and the corresponding emission generation factors presented in Tables 1 and 2. The results of generated emissions are presented in Table 5.

Table 5. Standard-LNG-tanker-generated emissions during entrance to Klaipeda port, as shown in Figures 9 and 10.

T/H	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
N, kW	2220	2253	2287	2375	2486	2731	3108	3619	4040	5106
CO_2 (LNG), kg	675	691	716	725	788	872	1000	1175	1399	1688
CO_2 (diesel), kg	922	945	976	1011	1075	1197	1360	1600	1907	2298
SO_x (diesel), kg	0.28	0.29	0.31	0.32	0.34	0.37	0.43	0.50	0.60	0.72
CO (LNG), kg	3.80	3.85	3.92	4.00	4.21	4.62	5.31	6.14	6.91	8.7
CO (diesel), kg	6.40	6.50	6.62	6.90	7.22	7.93	9.01	10.5	11.7	14.8
NO_x (LNG), kg	5.1	5.2	5.3	5.5	5.7	6.3	7.2	8.3	9.3	11.7
NO_x (diesel), kg	12.9	13.1	13.3	13.8	14.2	15.8	18.0	21.0	23.4	29.6
PM (diesel), kg	0.69	0.70	0.71	0.72	0.74	0.82	0.93	1.10	1.21	1.53

The fuel consumption and emissions of the vessels to maintain the same speed in channels and other similar locations at low depths were calculated using the methodology presented in Section 3 and verified with simulators and real vessels under similar sailing conditions. As can be seen from the obtained results, the difference between the calculation and experimental results is not significant (maximum difference of 8 percent) and therefore the calculation methodology presented in Section 3 can be applied to the estimation of fuel consumption and emissions of ships sailing in harbors and other channels at low depths.

5. Discussion

For further studies related to fuel consumption and emissions, it is important to study the power of the ship's main engine when the ship moves at a constant speed, depending on the ratio of the ship's draft to the depth of the channel, which is typical for ships sailing in ports. Research on the variation of the power of the ship's main engine at shallow depths in the evaluation of the fullness factor of the ship's hull should cover a wider range of ship types and designs. In addition, additional aspects of further research such as ships turning in turning basins and ship towing to and from quays, including the performance of tugs at low clearances, are important for finding methods to reduce environmental impact. These could be further directions of research.

The research results presented in the paper are critical because they clearly showed the importance of finding optimal methods for ships to enter and leave ports safely, primarily to ensure the safety of shipping (safety first) and at the same time reduce energy (fuel) demand and emissions. In this way, further complex studies are very important for the safety of shipping in the approaches to ports while constituting as low a possible impact on the environment.

The results of the scientific literature review showed that a specific methodology for assessing the trajectory of a ship's movement in shallow depths is important for predetermining the ship's maneuverability and safe navigation in port entrances and internal port navigation channels. At the same time, in order to reduce non-standard situations as much as possible, especially when ships pass near port infrastructure and ships moored at the quays, further studies of the controllability of ships in difficult conditions, especially regarding the effect of tides on the trajectories of ships, are important.

The change in the power of the ship's engines at shallow depths is important; therefore, the developed methodology for estimating the power of a ship's engines when the ship is sailing at a shallow depth is extremely important in ensuring the safety of shipping in ports. At the same time, for ships with relatively low-power engines, such as some bulkers, a preliminary assessment of the capabilities of such ships and further research is very important. Vessels with relatively weak main engines often have to use maximum or near-maximum main engine power when navigating port navigation channels in bad weather conditions where there is very little clearance, which requires high fuel consumption and generates high emissions. Therefore, according to the authors, similar studies are very important and may be another direction for future research.

The methodology developed to more accurately estimate the fuel consumption and emissions of vessels operating in shallow waters is very important, but further research is needed to determine the optimal safe speed of ships in ports while minimizing fuel consumption and emissions. This is especially important for ports that are within the boundaries of large cities.

6. Conclusions

This article examines the possibility of maneuvering ships sailing in port navigation channels and in the presence of small turns in the channels, and the obtained results allow for increasing the safety of navigation in port approaches and ports. Carrying out studies of the necessary energy (fuel) consumption while maintaining a planned speed is important from the point of view of shipping safety and environmental impact minimization. The results obtained in the article can be applied in the planning of port infrastructure (depths and turns of port navigation channels).

Developed and verified by experiments on real ships and with the help of a simulator, the methodology allows for estimating the power changes of a ship's main engine(s) at low clearances and can be successfully used in port planning and assessing possible emissions changes depending on the clearance. In this way, the methodology developed can help in planning the shipping channels of ports and the environmental impact of ships sailing in them (regarding the amount of pollutants emitted) depending on the depths of the existing or planned shipping channels.

The developed methodologies for evaluating the influence of shallow water on the required power of a ship's main engine, fuel consumption and emissions are important both for ensuring the safety of shipping in ports and for optimizing fuel consumption and reducing emissions in ports.

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