The influence of route choice and operating conditions on fuel consumption and CO_2 emission of ships

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ABSTRACT: The influence of various parameters, such as ship initial speed (full ahead and lower engine loads), loading condition, heading angle and weather conditions on ship fuel consumption and CO_2 emission is presented. A reliable methodology for estimating the attainable ship speed, fuel consumption and CO_2 emission in different sea states is described. The speed loss is calculated by taking into account the engine and propeller performance in actual seas as well as the mass inertia of the ship. The attainable ship speed is obtained as time series. Correlation of speed loss with sea states allows predictions of propulsive performance in actual seas. If the computation is used for weather routing purposes, values for various ship initial speed, loading conditions and heading angles for each realistic sea-state must be provided. The voluntary speed loss is taken into account. The influence of the ship speed loss on various parameters such as fuel consumption and CO_2 emissions is presented. To illustrate the presented concept, the ship speed and CO_2 emissions in various routes of the Atlantic Ocean are calculated using representative environmental design data for the track of the routes where the ship will sail.

Keywords: attainable ship speed, CO_2 emission, fuel consumption, route planning

1 Introduction

Basic characteristics of an efficient transportation are safety, cost effectiveness and friendliness with the environment. According to various environmental impact assessments, ocean-going vessels, as the most important part of maritime transportation industry, will have increasing influence on the global ecosystem in the near future. In the modern approach to ship design the problems related to energy efficiency and environmental protection must not be left aside.

Fortunately, in the majority of the cases, they are related to the ship economic efficiency in a manner that does not require much compromise and measures undertaken are mainly in the same direction. Improving the energy efficiency of the ship means increasing profits and reducing the adverse impact on the environment. From the navigational and marine hydrodynamic point of view, the accurate calculation or at least reliable estimation of the attainable ship speed at the actual sea is essential both from economic and environmental aspects. Reliable ship speed-loss estimation under real environmental and loading conditions allows a more accurate prediction of the power increase and fuel consumption as well as gas emissions from ships. On the other hand, technological enhancements like improved hull designs as well as improvement in power and propulsion systems could potentially reduce CO2 emission up to 35% (IMO, 2009). These measures could effectively be combined with several other operational measures, such as optimal weather routing and voyage planning for ships, in order to ensure that fuel consumption and CO2 emissions from ships are minimized on every voyage.

Nowadays the environmental issue becomes very important because of the problem of global warming. Following the increasing awareness of the environmental and human health concerns of shipping, legislative actions have been taken on global and national levels. The International Maritime Organization (IMO) developed the Energy Efficiency Design Index (EEDI), which expresses the emission of CO2 from a ship under specified conditions (e.g., engine load, draught, wind, waves, etc.) in relation to a nominal transport work rate. The calculation of EEDI is based upon a ship's technical characteristics, such as hull dimensions and form, propeller design, propulsion system, fuel usage, and other factors. The Energy Efficiency Operational Indicator (EEOI) is related more to operational efficiency and changes with operational conditions.

IMO developed EEDI values for the existing international fleet by type of ship. A "reference line value" was determined by fitting a curve through the data for the fleet. The mathematical formula for the curve determines the reference line value. The formula uses the deadweight of the ship and numerical factors based upon the type of ship. The idea of new regulations (IMO, 2012) is to reduce greenhouse gases (GHG) and other air pollution emissions by requiring new ships to stepwise reduce their EEDI (in the period from 1st January 2013 to 2025) from an existing baseline EEDI to a maximum level of 70% compared with the design index of existing ships. Since a reduction of CO2 emission is roughly equivalent to a reduction in fuel consumption, the goal of the future ship design will roughly correspond to 30% reduction in fuel consumption per voyage in normal, average service.

The recent emphasis on reducing greenhouse gases (GHG) emission has resulted in renewed interests for further optimization of ship performance. An IMO MEPC58/INF.21 study (IMO, 2008) indicated that while weather routing can achieve 2-4% reduction in fuel consumption and associated GHG emission, as much as 50% improvement could be achieved through technical and operational measures such as speed management and fleet planning. The benefits of voyage routing optimization with respect to classical weather routing were described and analysed by Chen et al. (1998).

Traditional weather routing (Delitala et al., 2010; Gershanik, 2011) has served its purpose of avoiding bad weather in the past. However, it has reached its limitations as shipping companies attempt to minimize fuel consumption by slow steaming, super slow steaming and virtual arrival approach (Intertanko, 2011). A ship slows down either involuntarily due to increased resistance from the wind and waves, or voluntarily due to navigation hazards or fear of heavy weather damage from excessive ship motions and accelerations, propeller racing, slamming or boarding seas (Kwon, 2008; Minoura and Naito, 2008; Dallinga et al., 2008.; Prpić-Oršić and Faltinsen, 2012).

Knowing ship speed at any heading angle with respect to the current and future sea state is one of the most significant factors of the decision making phase in the entire chain of maritime economy. From optimal routing point of view, precisely estimated ship speed at any weather conditions is essential for minimization of sailing time. Regardless to whether that is necessary for economic-logistical reasons (Wang and Meng, 2012), such as a more precise prediction of the estimated time of arrival to the port, or in order to increase the safety of navigation when dealing with a more precise navigation planning for a safer and more reliable collision avoidance (Tsou et al., 2010.), or because of a more precise fuel consumption calculation for a more ecologically acceptable navigation with decreased GHG emissions (Kim et al., 2012; Qi and Song, 2012), or for completely different reasons, the fact remains that a better prediction of ship speed depending on the external disturbances has a wide range of implementation possibilities in maritime affairs.

The more reliable the weather (wind/waves) forecasts (Vlachos, 2004, Rusu and Guedes Soares 2014) and the performance simulation of ships in a seaway become, the better they serve to identify the best possible route in terms of criteria like estimated time of arrival, fuel consumption, GHG emissions, safety of ship, crew, passengers and cargo, etc. This establishes a multi-objective, non-linear and constrained optimization problem in which a suitable compromise has to be found between opposing targets.

Without modelling the ship performance, it is not possible to minimize the fuel consumption for a given arrival time without exceeding the safe operating limits (Tsujimoto and Hinnenthal, 2008; Panigrahi et al., 2012). Speed, loading and heading should all be integrated into routing optimization, making the problem multi-dimensional (Shao et al., 2012).

2 Estimation of fuel consumption and CO_2 emissions

Introduction of novel ship designs and propulsion systems, together with increased fuel costs and the increasing conscience about environmental protection requires detailed research. Moreover, the necessity for respecting the strict safety requirements and increasingly demanding marine operations to be performed in the heavy sea conditions is growing. The aim of the strategy proposed in this paper is to reduce the GHG emissions from ships by adopting better hull designs, energy efficient technologies and energy efficient operations. The objective is to improve ship design and performance taking into account the environmental issue, creating aforementioned eco-efficient or "green" design.

Within this strategy, several goals need to be accomplished. Since ship operates in weather conditions that could not be predicted with the absolute certainty, the appropriate simulation method of the real weather conditions is essential part of a ship voyage scenario. Another very important segment of the methodology is the short and long-term ship attainable speed estimation, which allows reliable prediction of fuel consumption as well as GHG emissions. The prediction of these values very much depends on the main engine model. Therefore, there is a need for the development of an appropriate dynamic model of the main engine, which could adequately predict fuel consumption and GHG emissions on various sea state conditions. If it is possible to create the more realistic scenario of ship behavior under the real weather conditions, then the ship design and operations can be improved in order to increase ship energy efficiency in "real life". It could be achieved by various concepts such as improvement of the ship hull form taking into account the resistance both in the calm water and under the real environmental conditions, selection of ship's engine/propulsion system, deployment of a novel approach to dynamic and adaptive weather route planning, etc.

2.1 Ship hull design

A ship performance in operational conditions changes significantly under real weather factors. Important factors are significant wave height, wave period, wind speed, ship heading, ship speed and ship particulars (principal dimensions and hull shape, superstructure shape, draught etc.).

The ship hull design is an iterative process in which compromises must be made among various, in most cases conflicting, requirements. The design of a ship hull can be formulated as determination of a set of design variables subjected to certain relations between variables and restrictions of these variables. In general, many factors must be considered and not all of them are hydrodynamic in nature. The optimal design of the hull shape is basically a multi-objective optimization problem since the improvement of a specific aspect of the global design usually causes the worsening for some other. Therefore, the correct approach to the problem must follow the multi-objective optimization theory, involving the modelling, the development and the implementation of algorithms for the hydrodynamic optimization, i.e. the ship hull optimization regarding the calm water as well as added resistance.

2.2 Attainable ship speed

The ship speed, required power and propeller characteristics are usually estimated for calm water conditions. However, during its exploitation, the ship encounters different sea conditions and in many occasions, the seaway influences the resistance and propulsion features. The capability to sustain speed in a seaway is one of the primary objectives in the design of a ship. The added resistance of a ship in a seaway is becoming of great importance because of increasing demand in transportation speed and voyage duration (Guedes Soares et al., 1998) as well as due to increasing conscience of need to reduce emissions from the ships (Prpić-Oršić & Faltinsen, 2009). The added resistance of a ship in waves is mainly a potential flow effect and caused by the ability of the ship to generate waves. When the wavelength of the incident waves are smaller than approximately half the ship length, the wave induced ship motions are small and the added resistance is mainly due to wave diffraction caused by the ship. When the ship motions are significant, they strongly influence the added resistance in waves.

Progress made in seakeeping, in both analytical methods and experimental techniques, makes it possible to determine added resistance with sufficient accuracy for design purposes. However, the accuracy of added resistance calculation depends very much on the accuracy of ship motion predictions. The same is true for the effect of wind loads on speed loss and the effects which lead to voluntary speed reduction based on the ship master judgment (such as slamming, propeller racing, ventilation, excessive accelerations and green water on deck).

2.3 Ship route planning

A very important factor in assessing the cost of travel is the ship route planning. Selecting rational ship routes taking into account weather conditions contributes in not only improving shipping efficiency and in reducing accompanying risks, but also in allowing more precision in predicting ship's estimated time of arrival at destination port. For a selection of the best route from one to the other port, it is necessary to know the ship performance at weather conditions that ship may encounter during voyage. The selection of the best route is influenced by many factors. Primarily, the weather conditions that the ship will, with a certain probability, encounter at the particular segment of the route. Of course, it is crucial to be able to assess the dynamic response of the vessel due to real weather conditions (wind and waves) (Pacheco & Guedes Soares 2007). At lower sea states, decrease of ship speed is related to additional resistance due to waves and wind, while at higher sea states the safety of ship operation depends significantly on weather conditions and the full range of adverse dynamic effects must be taken into account. As the weather conditions deteriorate and significant wave height and wind speed increase, the ship behaviour differs more from that estimated for calm sea condition. Propulsion system: propeller-engine works in conditions, which are significantly different from those for which it is designed, and the efficiency of both propeller and engine is reduced. In addition, the ship can be subjected to bow and stern slamming, green water, excessive accelerations and roll that jeopardize the safety of the ship and people aboard. In such circumstances, a conscientious master will take measures to reduce those dangerous effects: he or she will change the course and/or reduce speed. If possible, the master will try to apply the strategy of avoiding dangerous conditions bypassing the storm or simply wait to pass.

While planning the route all before mentioned must be taken into account. The hydrodynamic performance of the ship affects the added resistance, which has an important effect on ship speed and fuel consumption and related CO2 emissions. The optimal ship speed and heading must be determined, so that fuel consumption is minimized while certain safety constrains are met. The safety constrains could be expressed by limiting values that could not be exceeded. The non-exceedance of these values is ensured by reducing speed and/or changing the course of the ship.

3 Numerical example

The calculations of attainable ship speed, fuel consumption and related CO_2 emission have been performed for the S-175 containership. The main particulars of the ship are given in Table 1. (ITTC, 1978).

3.1 Involuntary and voluntary speed loss

The ship speed under rough weather conditions is not only decreased by the natural increase of resistance, but also may be reduced for safety concerns such as avoiding excessive accelerations, slamming, propeller racing and other dangerous effects. The instantaneous ship speed is calculated by taking into account propeller in-and-out-of-water effect on ship propulsion and the effect of mass inertia (Prpić-Oršić and Faltinsen, 2012). As the propulsion factors are dependent on the waves the irregular sea can be handled as series of regular waves with different amplitudes and frequencies. The procedure is proposed by Faltinsen et al. (1980) and proceeds as follow: from chosen sea spectrum the time domain wave trace can be obtained for specific sea state. This time series can be decomposed in regular waves by locating the zero-upcrossing (or downcrossing) points. The time between two zero-upcrossing points is taken as wave period and the half distance between two maxima inside this time period is taken as wave amplitude. The waves characteristics obtained in that way are considered as regular waves in seakeeping calculation. In that way the slowly varying time trace of ship speed is obtained as a result.

The constant propeller torque condition is assumed. The total resistance is composed of still water resistance, added resistance in waves and wind resistance. The still water resistance is calculated according to Holtrop & Mannen method (Holtrop & Mannen 1982, Holtrop 1984), an approximate procedure which is widely used at the initial design stage of a ship. The method is based on regression analysis of random model experiments and full-scale data, available at the Netherlands Model Basin.

The calculation of added resistance in waves is partly carried out according to the direct pressure integration procedure developed by Faltinsen et al. (1980). As an example only the cases of head and following waves at different ship speeds (Froude numbers) and for full loaded conditions are reported in Fig.1. The method predicts added resistance, transverse drift force and mean yaw moment on a ship in regular waves of any wave direction. It is not applicable for short wave lengths (when wave length to ship length ratio is lower than 0.5). For the case of short waves the asymptotic theory developed by the same authors give reliable results for moderate Froude numbers and common hull forms. A comparison of this method with other and with experiments can be found in Matulja et al. (2011). The problem of are unrealistic high values of added resistance for very low encounter frequencies is, in practice, solved by artificially forcing wave loads to go on zero value.

For a diesel engine, it is mostly accepted that the propeller torque remains constant at an increasing loading. In practice, there are some deviations from this assumption, but for a practical purpose of speed calculations, this assumption seems to be sufficiently accurate.

The numerical model used for main propulsion engine modelling is based on a zero-dimensional model of an internal combustion engine. A number of control volumes interconnected with links for mass and energy transfer between them (Medica & Mrakovčić, 2002), represents the main propulsion engine. This model provides satisfactory prediction of engine dynamic response during transients with rather short computational time. In addition, engine fuel consumption can be precisely determined, which represents the basic presumption for estimation of carbon-dioxide emission. Furthermore, use of such a model can be extended to determination of the lowest fuel oil consumption strategy for given sea condition and ship speed with resulting lowest possible CO_2 emissions.

The relation between the thrust required by the propeller and the number of revolution for several speeds are obtained by using the torque characteristics of an assumed B-series propeller behind the ship and a wake fraction. The open water propeller characteristics are obtained by Oosterveld & Oossanen method (1975). The relationship between torque delivered by the engine and the number of revolutions can be calculated from the engine characteristics and shaft losses. The sustainable speed for any particular time fraction is calculated from the equilibrium of ship inertia, calculated total resistance and required thrust at given condition taking into account thrust deduction fraction and the loss coefficient due to in-and-out-of-water effect. The time simulation of force equilibrium within one wave period has been done using the fourth order Runge-Kutta method starting with the mean values form the previous wave period.

The thrust loss coefficient values, as function of relative shaft speed n/n_{bp} and relative submergence h/R, are estimated from a simplified ventilation thrust loss model, which is obtained by utilizing known experimental data (Smogeli, 2006). After defining the model, the effect can be estimated knowing the propeller emergence and number of shaft revolutions. A fixed pitch propeller of 5.6 meter diameter with 6 blades is used in the numerical example.

The wave realization is obtained from the two parameter ITTC spectrum (ITTC, 1978). The definition of wave direction follows the common practice. Angle 0° refers to following waves and it increases till 180° which identify head waves. The same definition is used for the wind. In calculation we considered waves and wind coming from the same direction. The wind resistance coefficients are calculated according Blendermann (1996) model (Fig. 2.). The coefficient Cxw represent wind resistance coefficient, e.g. it is positive for head wind (waves) and negative for head wind (waves). The total wind velocity is a combination of a steady-state or mean velocity and a turbulent (gust) velocity. The mean speed is calculated as a function of significant wave height according to the spectrum. The gust component is a random process with zero mean and a spectrum called the gust spectrum which could be calculated according to Harris (1971). The wind direction is assumed to be the same as wave direction. The mean speed loss, obtained as the average value during the time simulation, represents the reduction from 21.8 kn speed and includes voluntary speed loss in severe seas. In this particular calculation the criteria used for voluntary speed reduction are: slamming, deck wetness, bow acceleration and propeller emergence. There is no strict rule that determines under which conditions the shipmaster would reduce the speed, so various authors have proposed different criteria (Faltinsen & Svensen, 1990; Prpić-Oršić et al. 2014b). Limiting values for slamming, deck wetness and propeller emergence are taken as probability 0.01, 0.05 and 0.1, respectively. For the vertical acceleration, the adopted limiting rms value is 0.215 times gravity acceleration. Values of mean speed loss, both involuntary and voluntary, are obtained for significant wave height from zero to 12 m and the whole range of wave periods and heading angles.

For an accurate estimation of ship efficiency on a seaway it is thus important to reliably assess the effect of all the factors that cause an increased resistance, as depicted in Fig. 3. The wider explanation of methodology can be found in Prpić-Oršić et al. (2013).

The attainable speed calculated for head and following wind and waves obtained for the most probable zero crossing periods related to specific sea states using ITTC spectrum are shown in Fig. 4 and Fig. 5. The curves refer to the case of involuntary (full line) and voluntary speed reduction (dashed line).

The results of attainable ship speed for head sea defined by significant wave height higher than 8 m need particular attention. The Fig. 4 shows that the attainable ship speed estimated for sea states with significant wave height from 8 to 12 m is nearly constant, while for following seas the value of speed drop will continue to grow slowly. This trend could be explained by the fact that the one-parameter wave spectrum is used. So, for very high significant wave height it give back a sea-state characterized by very long waves (high zero crossing period), thus there are almost no relative motions. It can also be assumed that is impossible to obtain reliable values of ship speed for such adverse weather conditions where the ship dynamics is affected by many highly nonlinear effects. However, the inaccuracy of those results will not significantly affect the results of mean ship speed for the whole voyage because such extremely high sea states are very rare, and even if the ship is going toward such storm, the master will certainly try to avoid it (Prpić-Oršić et al. 2014a).

Fig. 6 and Fig. 7 show the attainable speed calculated for heading angles from 0 to 180 degrees obtained for three different sea state defined by the most probable zero crossing periods related to significant wave height of 1 m, 4 m and 8 m. Fig. 6 refers to the case of involuntary speed reduction while Fig. 7 refers to voluntary speed reduction.

3.2 Fuel consumption and CO2 emissions

The estimation of fuel consumption and related CO_2 emissions from the main engine of a containership on North Atlantic routes is based on the mean speed drop for the constant torque conditions. Fig. 8 and Fig. 9 show the fuel consumption (FOC) and CO_2 emission expressed in kg per kilometre of voyage in head and following waves for the whole range of different sea states.

The fuel consumption is assumed to be related to ship speed as estimated in Prpić-Oršić et al. (2013). The emission factors used in the calculations, 3173 g CO_2/ kg fuel, named CORINAIR (CORe Inventories AIR), are based on the emission factors presented in the guidebook from EMEP/CORINAIR (CORINAIR, 1999).

Fig. 9 to Fig. 13 show fuel consumption (FOC) and CO_2 emission expressed in kg per kilometre of voyage calculated for heading angles from 0 to 180 degrees obtained for three different sea state defined by the most probable zero crossing periods related to significant wave height of 1 m, 4 m and 8 m. It can be noticed that for sea states with significant wave height higher than 3 m the FOC and CO_2 emission increase both for head and following seas. The absolute fuel consumption decreases for the case of voluntary speed reduction and the minimum value is in approximately 4 m of significant wave height. The reason for this trend is the fact that the main engine is not working in the same efficiency regime. Since absolute fuel consumption is lower for the case of voluntary speed reduction the same stands for CO_2 emission. The CO_2 emission significantly increase for the higher sea states, so for the head sea states specified by significant wave height of 7 m is more than double the value for calm sea. Fig. 10 and Fig. 12

refer to the case of involuntary while Fig. 11 and Fig. 13 refer to voluntary speed reduction.

As expected, the trends of fuel consumption and CO_2 emissions follow the speed loss trend. It can be noticed that for sea states with significant wave height higher than 4 m, the speed loss significantly increases as well as the fuel consumption and CO_2 emission.

3.3 Effect of different initial speed and loading condition

During ship exploitation the loading conditions are constantly changing due to loading/unloading of cargo and supply utilization. In addition, the ship master may for various reasons (other than the so called voluntary speed reduction) change the initial speed of the ship. These reasons, in addition to preserving the safety of the ship (voluntary speed reduction) may be related to fuel economy, the default schedule of arrival in the port and other reasons relating to the navigation constrains. Fig. 14 and Fig. 15 present the speed reduction in knots and percentage for three different loading cases (drafts 7.5 m, 8.5 m and 9.5 m) and for the range of initial ship speed from 12 to 24 knots.

The results are obtained as a weighted average of the values referred to the specific condition (sea state and heading) and the relative probability of occurrence. For the heading a uniform probability is assumed, while for the sea-states it is considered the wave climate of the North Atlantic sub-basin given by the scatter diagram recommended by the International Association of Classification Societies (IACS, 2000).

One trend is obvious – the loading case with draft value of 8.5 m is the most favourable from the fuel consumption/CO_2 emission point of view. The speed loss is higher for the case with lower and higher draft value, 7.5 m and 9.5 m, at the whole range of initial ship speed. It seems that the loading case with the lowest draft value (7.5 m) is the most unfavourable – for example, for the initial ship speed of 24 kn, the speed reduction is approximately 6 % to 8 % higher than for the other two cases. The reason of this trend is the poor seakeeping performance and propeller efficiency of such loaded ship (involuntary speed reduction) combined with the excessive motion which would lead to master decision to reduce the ship speed (voluntary speed reduction). Although that is not very

realistic to expect this loading case to happen, the mentioned trend shows that the change of draft value could significantly affect the attainable ship speed.
Fig. 18 and Fig. 19 show speed reduction and percentage of speed reduction vs. draft (loading condition) for three different initial speeds (24 kn, 18 kn and 12 kn - full ahead and lower engine loads). The above mentioned statement that the draft of 8.5 m is the most favourable for the fuel economy could be clearly seen. Fig. 17 shows that the absolute values of speed loss due to weather conditions are higher for higher initial speed values, while, considering percentage values, the relative speed loss is higher for the lower values of initial ship speeds.
Considering the ship draft vs. speed loss for different initial speed of the ship, it is evident that the percentage of speed drop is more pronounced for lower speeds.
This statement is even more apparent for voluntary speed reduction where there is, at lowest speed (12 kn), noticeable decrease speed rate of 40% for the draft values of 7.5 m and 9.5 m.

3.4 Effect of choosing different ship route

The tracks of the main North Atlantic routes were identified by Vettor & Guedes Soares, (2015) by means of the Voluntary Observing Ship (VOS) database following the area with a higher density of reports and with some consideration of global economy and geography.

The following six principal trans-oceanic passages were detected and depicted in Fig. 18:

- Route 1: Channel - Puerto Rico (North), [Ch_PR1]
- Route 2: Channel - Puerto Rico (South), [Ch_PR2]
- Route 3: Channel – Virginia, [Ch_VA_total]
- Route 4: Strait - Virginia (North), [St_VA1_total]
- Route 5: Strait - Virginia (South), [St_VA2]
- Route 6: Strait – Miami, [St_MIA]

It was shown that the most travelled route is the one from Northern Europe (the Channel) to the Caribbean Sea (routes 1 and 2) with 36% of the traffic in the considered areas (higher percentages in winter). More than one-third of these ships prefer the northern and shorter orthodrome; in August this percentage rises to 43%.

The transport stream between the Strait of Gibraltar and the North-East Coast of USA (routes 4 and 5) denote a similar concentration with about 32% of the trades, while the routes from the Channel to the Virginia area (route 3) and from Gibraltar to Miami (route 6) contribute 21% and 10% respectively.

When effects such as ship motions, speed loss, fuel consumptions and CO_2 emissions have to be analysed in the long-term period, the sea-state probability in terms of the join probability of significant wave height wave periods and relative wave heading probability is essential.

The initial wave databases of the oceans were constructed from visual observations that were collected in relatively large areas over which statistics were given. More modern databases can be obtained from phase averaging models that predict the spatial and temporal evolution of the directional spectrum solving the spectral energy equation.

One such hindcast data set that was produced in the EU project HIPOCAS (Guedes Soares, 2008) includes a 44 years database (January 1958 to December 2001) of wave, wind and sea level data for the Atlantic Ocean and all seas around Europe. This dataset, which is adopted in this study, consists of 3-hourly fields with a 2.0°x2.0° grid resolution over the North Atlantic The initial wind forcing was from the NCEP reanalysis, which was used to force a regional wind model (REMO), which finally forced the WAM wave model. The data was validated with buoy measurements establishing its general adequacy (Pilar et al., 2008).

All the grid points contained in a squared area of 2°x2° (Fig. 18.) around a number of previously defined route points are taken into account for each route. From those grid points the wave data have been extracted to compute the specific scatter diagram of each route.

To illustrate the presented concept, the mean fuel consumptions and CO_2 emission increase for the six different North Atlantic routes were calculated, as well as increase in CO_2 emission relative to calm sea (Dolinskaya et al., 2009). The time percentage of ship operation in each zone is estimated according to the fraction of route distance in each zone (Guedes Soares and Moan, 1991).

In order to compare the fuel consumption and CO_2 emissions on different routes of the North Atlantic the most likely mean values are calculated.

For this purpose, the calculated mean ship speed for a wide range of different sea states (combinations of significant wave heights and zero crossing periods) and heading angles are used.

The appropriate values of ship speed, fuel consumption and CO_2 emissions for calm water conditions are shown on Table 2.

The values of route length, voyage time, average fuel consumption and CO_2 emission for ship sailing on calm water is calculated for different routes as are shown on Table 3. On real weather conditions speed decreases due to involuntary (Table 4) and voluntary (Table 5) speed reduction. Fig. 20 and 21 show sailing time and CO_2 emission increase in percentage caused by waves and wind.

The values of fuel consumption and CO_2 emission for ship sailing on real weather conditions is calculated for different routes in Eastward and Westward direction as are shown on Table 6 to Table 9. On real weather conditions speed decrease due to involuntary (Table 6 and Table 8) and voluntary (Table 7 and Table 9) speed reduction. Fig. 22 to 25 show sailing time and CO_2 emission increase in percentage because of the influence of waves and wind for Eastward and Westward direction. It is interesting to note that Route 4 is more convenient in the Westward then Eastward direction while time of sailing on Route 5, which connect the same points of America and Europe, is shorter in the Eastward then in Westward direction.

With the reliable weather (wind/waves) data and the performance simulation of ships in a seaway, it is possible to decrease fuel consumption and CO_2 emission by identifying the best possible route. It has to be done by taking into account other criteria like estimated time of arrival, safety of ship, crew, passengers and cargo, etc. The optimization problem is obviously multi-objective, non-linear and constrained and a suitable compromise has to be found between opposing targets.

4 Conclusions

Relative emissions of greenhouse gases from ships (kg/tonne-km) are very sensitive to capacity utilization of the vessel, and thus to transport efficiency. One of the potential for reducing emissions is through vessel route planning for increased transport efficiency. Knowing mean attainable ship speed in a specific sea state and heading angle, the prediction of speed loss and CO_2 emissions during the whole route and under various weather and load conditions can be estimated.

In this paper a procedure is proposed to calculate attainable ship speed as well as fuel consumption and CO_2 emission from main engine at the whole range of sea states and heading angles with regards to propulsive performance in actual seas when the ship could be subjected to severe dynamic effects. The influence of loading condition and initial ship speed on attainable ship speed is analysed. The change of loading conditions means the change of wetted hull surface (and above water area) and affects all aspects of the attainable ship speed calculation: estimation of still water and added resistance, wind loads, seakeeping performance (absolute and relative motions), propulsive performance, etc. It is shown that the small change of draft could significantly affect the speed loss under real weather conditions. The analysis of the speed loss percentage for different initial ship speed (full ahead and lower engine loads) shows that lowering the ship speed does not always mean economic voyage, especially considering various loading conditions. In fact, the percentage of speed loss could be doubled or tripled for lower speed values as showed for the case of 12 kn and 24 kn at ship draft of 9.5 m.

The mean results for the six main North Atlantic routes are analysed for the case of involuntary and voluntary speed reduction. The results are showed for Eastward and Westward directions. The percentage of voyage time increase compared to still water is approximately doubled when considering voluntary speed reduction. For the selected ship the most northern route (Route 3: Channel to Virginia) seems to be the most demanding from that point of view and at this route "real-weather" voyage duration increased by almost 13% compared to time needed in "calm-weather" conditions. At the same time fuel consumption decreases by 8% as well as CO_2 emission.

Knowing the mean values of speed loos, fuel consumption and CO_2 emission for the whole range of different ship loading cases and service speeds the ship owner would be able to estimate the economic benefit of various voyage regimes taking into account ship safety and, of course, the ship mission.

The proposed method allows reliable prediction of voyage duration and fuel consumption as well as CO_2 emissions from main engine. It allows considering various strategies and scenarios of voyage and selection of the optimal one taking into account ship safety and operability as well as economic and environmental aspects. Possible cost functions could be: fuel (power) consumption, concentration and amount of selected GHG gasses (CO_2, NO_x, …), environmental loads (wind, waves, ocean currents) in weathervaning, etc. Constraints will be seaway paths and navigational constraints for determination of the route domain, surrounding seas according to weather forecasts (avoiding heavy seas and storms), etc. Additional objectives could take into account slow steaming and super slow steaming approach for reducing fuel consumption and GHG emissions, as well as determination of slow steam ship speed in some optimal sense (decrease of fuel consumption with fulfilment of predetermined constraints and limitations, e.g. estimated time of arrival, waypoints correction, navigational rules, weathervane, etc.).

The results of proposed strategy will improve a very important segment of maritime transport technology, i.e. green ship design and shipping which assumes decreasing of fuel consumption and GHG emissions and at the same time much safer navigation for crew, passengers and the ship herself.

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References

Blendermann, W. (1996). Floating docks: prediction of wind loads in extreme winds. *Schiff und Hafen* 48, 4

Chen, H., Cardone, V., Lacey, P. (1998). Use of Operation Support Information Technology to Increase Ship Safety and Efficiency. *SNAME Transactions* 106, pp. 105-127.

Dallinga, R., Flikkema, M., Grin, R. (2008). Challenging wind and waves - their impact on fuel consumption. *MARIN report* 94, pp. 1-3.

Delitala, A.M.S., Gallino, S., Villa, L., Lagouvardos, K., Drago, A. (2010). Weather routing in long-distance Mediterranean routes. *Theoretical and Applied Climatology* 102 (1-2), pp. 125-137.

Dolinskaya, I.S., Kotinis, M., Parsons, M.G., Smith, R.L., (2009). Optimal Short-range Routing of Vessels in a Seaway, *J. Ship Research*, Vol. 53, No. 3, pp. 121-129.

EMEP/CORINAIR (1999). EMEP Co-operative Programme for Monitoring and Evaluation of the Long Range Transmission of Air Pollutants in Europe, The Core Inventory of Air Emissions in Europe, September 1999. *Atmospheric Emission Inventory Guidebook*, Second Edition.

Faltinsen, O.M. Minsaas, K.J. Liapis, N. Skjordal, S.O. (1980). Prediction of Resistance and Propulsion of a Ship in a Seaway*, Proc. 13th Symposium on Naval Hydrodynamics*, pp. 505-529.

Faltinsen, O.M. Svensen, T. (1990). Incorporation of Seakeeping Theories in CAD. CFD and CAD in Ship Design, Elsevier Science Publishers B. V.

Gershanik, V.I. (2011). Weather routing optimisation - challenges and rewards. *Journal of Marine Engineering and Technology* 10 (3), pp. 29-40.

Guedes Soares, C. (1990). Effect of Heavy Weather Maneuvering on the Wave Induced Vertical Bending Moments in Ship Structures. *Journal of Ship Research.* 34(1):60-68.

Guedes Soares, C. (2008). Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe. *Coastal Engineering*; 55(11):825-826.

Guedes Soares, C. and Moan, T. (1991). Model Uncertainty in the Long Term Distribution of Wave Induced Bending Moments for Fatigue Design of Ship Structures. *Marine Structures*. 4, pp. 295-315.

Guedes Soares, C., Fonseca, N., Ramos, J. (1998). Prediction of Voyage Duration with Weather Constraints. *Proceedings International Conference on Motions and Manoeuvrability*, Royal Institute of Naval Architects, London.

Harris, R.I. (1971). The Nature of the Wind,the Modern Design of Wind Sensitive Structures. Const. *Ind. Res. & Inf. Assn.*, London

Holtrop, J. A. & Mennen, G.G.J. (1982). An Approximate Power Prediction Method. *International Shipbuilding Progress*, Vol. 29, pp. 166-170.

Holtrop, J. A. (1984). Statistical Reanalysis of Resistance and Propulsion Data. *International Shipbuilding Progress*, Vol. 31, pp. 272-276.

IACS (2000). Standard Wave Data. International Association of Classification Societies, Rec. No. 034.

ITTC, 1978. Report of the Seakeeping Committee. In: Proceedings of the 15th International Towing Tank Conference, Vol. 1. The Hague, Netherlands

IMO (2008). Prevention of Air Pollution from Ships - Opportunities for Reducing Greenhouse Gas Emissions from Ships. *MEPC 58/INF.21*, International Maritime Organization.

IMO (2009). Prevention of Air Pollution from Ships – Second IMO GHG study. *MEPC 59/INF.10*, International Maritime Organization.

IMO (2012). Prevention of Air Pollution from Ships, IMO GHG study. *MEPC 63 and 64*, International Maritime Organization.

Intertanko (2011). Virtual Arrival - Optimising Voyage Management and Reducing Vessel Emissions - an Emissions Management Framework. *2nd Ed., Oil Companies International Marine Forum (OCIMF)*, London, UK.

Kim, H.J., Chang, Y.T., Kim, K.T., Kim, H.J. (2012). An epsilon-optimal algorithm considering greenhouse gas emissions for the management of a ship's bunker fuel. *Transportation Research Part D - Transport and Environment* 17 (2), pp. 97-103.

Kwon,Y.J. (2008). Speed Loss Due to Added Resistance in Wind and Waves. *The Naval Architect, RINA (U.K.),* pp. 14-16.

Matulja, D., Sportelli, M.; Guedes Soares, C., and Prpić-Oršić, J. (2011). Estimation of Added Resistance of a Ship in Regular Waves. *Brodogradnja* , Vol. 62, No. 3, pp 259-272.

Medica, V., Mrakovčić, T. (2002). Compressor map representation in numerical simulations of turbocharged diesel engine steady and transient operation, *Proceedings of the Symposium Motors and Vehicles*, Zagreb, pp. 1-10

Minoura, M., Naito, S. (2008). Statistical Estimation of Ship Speed Loss by Monitoring Data. *Proceedings of the 6th Osaka Colloquium on Seakeeping and Stability of Ships*, Osaka, Japan, pp. 37-42.

Oosterveld, M.W.C. & van Oossanen, P. (1975). Further Computer-Analyzed Data of Wageningen B-Screw Series. *International Shipbuilding Progress*, Vol. 22, No. 251, pp. 3-14.

Pacheco, M.B. and Guedes Soares, C. (2007). Ship Weather Routing Based on Seakeeping Performance. *Advancements in Marine Structures*. Guedes Soares, C. & Das, P.K. (Eds.), London, U.K.: Taylor & Francis Group; pp. 71-78.

Panigrahi, J.K., Padhy, C.P., Sen, D., Swain, J, Larsen, O., (2012). Optimal ship tracking on a navigation route between two ports: A hydrodynamics approach. *Journal of Marine Science and Technology* 17 (1), pp. 59-67.

Pilar P., Guedes Soares C., Carretero J.C. (2008). 44-year wave hindcast for the North East Atlantic European coast. *Coastal Engineering* 55, pp. 861–871.

Prpić-Oršić, J., Faltinsen, O.M., (2009). Speed loss calculation in a Seaway. *The 13th Congress IMAM 2009*., pp. 393-400, Istanbul, Turkey

Prpić-Oršić, J., Faltinsen, O.M. (2012). Estimation of Ship Speed Loss and Associated CO_2 Emissions in a Seaway. *Ocean Engineering*, Vol. 44, No 1, pp. 1-10.

Prpić-Oršić, J., Faltinsen, O.M., Mrakovčić, T. (2013) Influence of ship behaviour in a seaway on CO_2 emissions. *Proceedings of the 32nd International Conference on Ocean, Offshore and Arctic Engineering* (DVD)**,** OMAE 2103, pp. 1-8, Nantes, France

Prpić-Oršić, J., Vettor, R., Faltinsen, O.M., Guedes Soares, C. (2014a). Influence of ship routes on fuel consumption and CO_2 emission. *The 2nd Congress Maritime Technology and Engineering - MARTECH 2014*., pp. 857-864, Lisabon, Portugal

Prpić-Oršić, J., Parunov, J., Šikić, I. (2014b) Operation of ULCS - real life. *International Journal of Naval Architecture and Ocean Engineering*, Vol. 6, No 6, pp. 1014-1023

Qi, X.T., Song, D.P. (2012). Minimizing fuel emissions by optimizing vessel schedules in liner shipping with uncertain port times. *Transportation Research Part E - Logistics and Transportation Review* 48 (4), pp. 863-880.

Rusu, L. and Guedes Soares, C. (2014). Forecasting container-ship responses in the Azores Archipelago. Guedes Soares, C. & Lopez Pena F., (Eds.). *Developments in Maritime*

Transportation and Exploitation of Sea Resources. Francis & Taylor Group London, UK; pp. 987-994

Shao, W., Zhou, P.L., Thong, S.K. (2012). Development of a novel forward dynamic programming method for weather routing. *Journal of Marine Science and Technology* 17 (2), pp. 239-251.

Smogeli, O.N. (2006). Control of Marine Propellers - From Normal to Extreme Conditions. PhD-thesis 2006:187, Faculty of Engineering Science & Technology, Trondheim

Tsou, M.C., Kao, S.L., Su, C.M. (2010). Decision Support from Genetic Algorithms for Ship Collision Avoidance Route Planning and Alerts. *Journal of Navigation* 63 (1), pp. 167-182.

Tsujimoto, M, Hinnenthal, J. (2008). Optimum Navigation for Minimizing Ship Fuel Consumption - Investigation of Route, Speed and Seakeeping Performance. *Proceedings of the 6th Osaka Colloquium on Seakeeping and Stability of Ships*, Osaka, Japan, pp. 43-50.

Vettor, R., Guedes Soares, C. (2015). Detection and analysis of the main routes of voluntary observing ships in the North Atlantic, Journal of Navigation, *68 (2015) 397*

Vlachos, D.S. (2004). Optimal Ship Routing Based on Wind and Wave Forecasts. *Applied Numerical Analysis & Computational Mathematics* 1 (2), pp. 547-551.

Wang, S.A., Meng, Q. (2012). Liner ship route schedule design with sea contingency time and port time uncertainty. *Transportation Research Part B – Methodological* 46 (5), pp. 615-633.

Figures

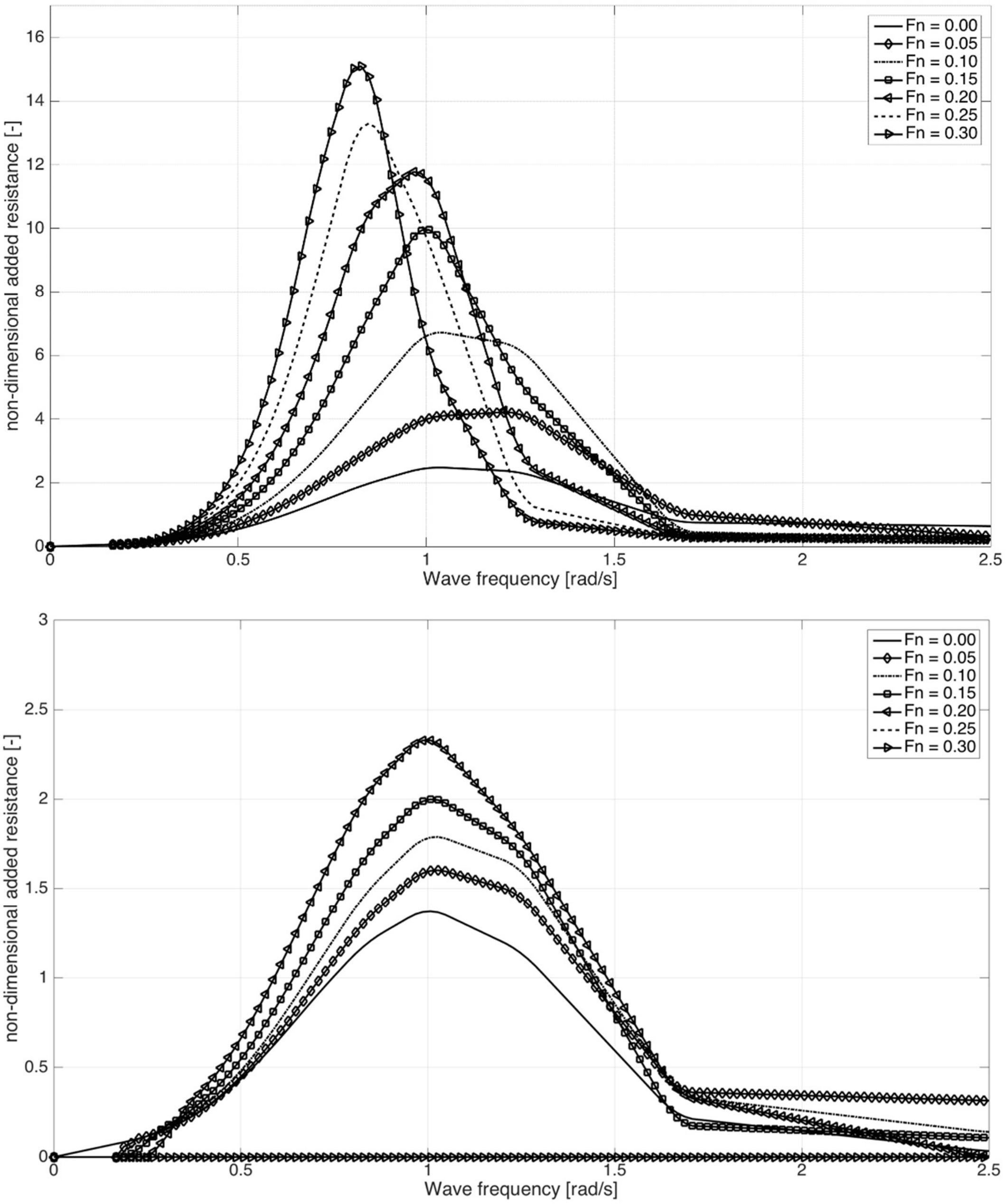

Figure 1. Added resistance for head and following waves

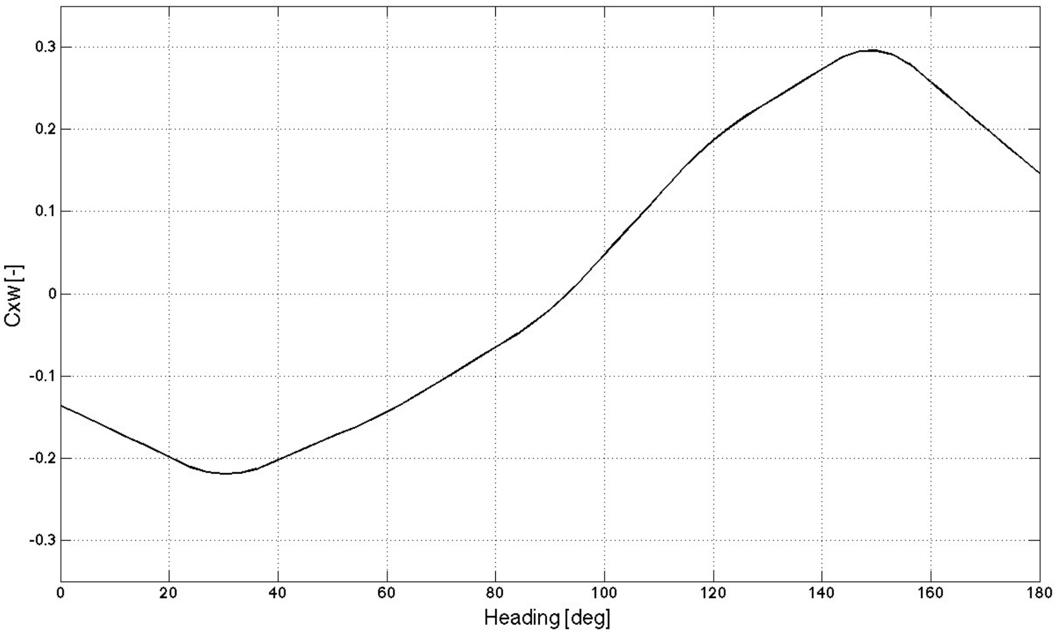

Figure 2. The wind load coefficients

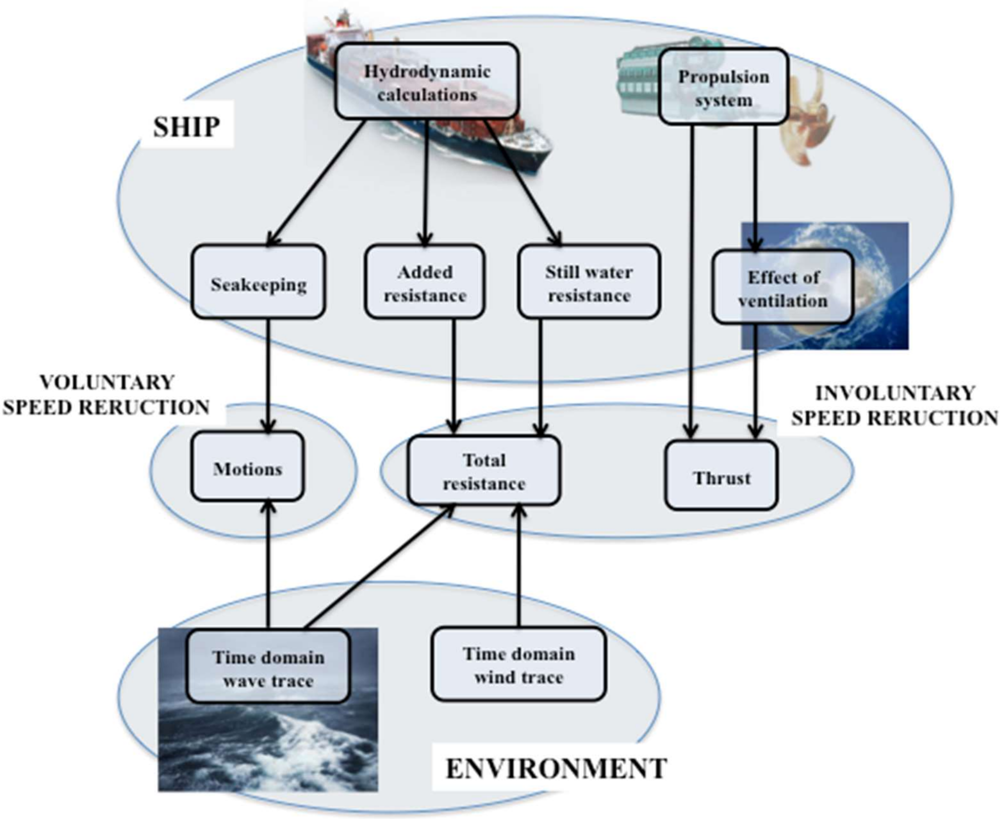

Figure 3. Scheme of the program

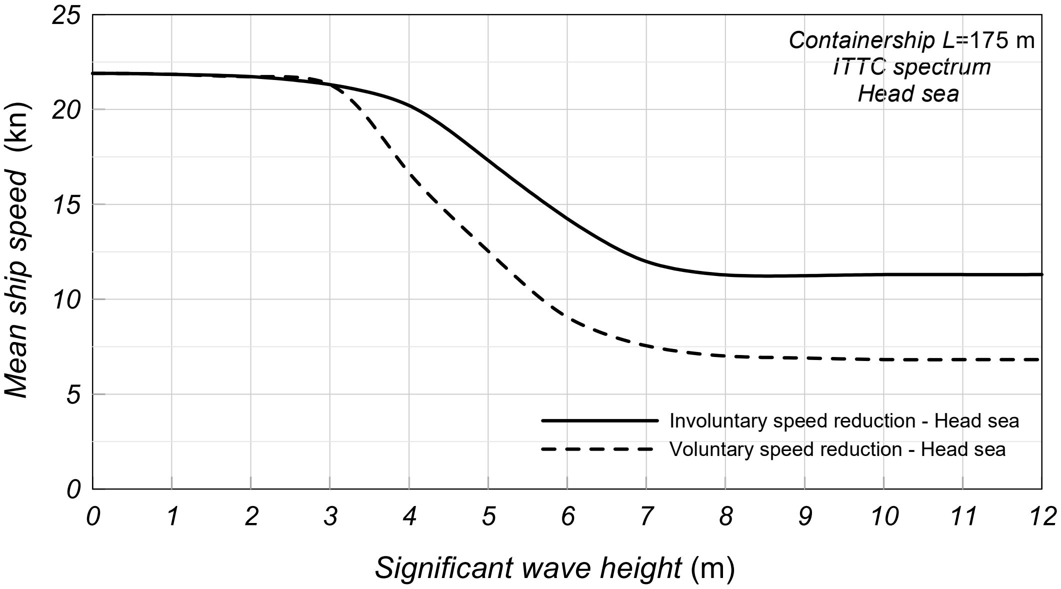

Figure 4. Ship speed loss for head sea

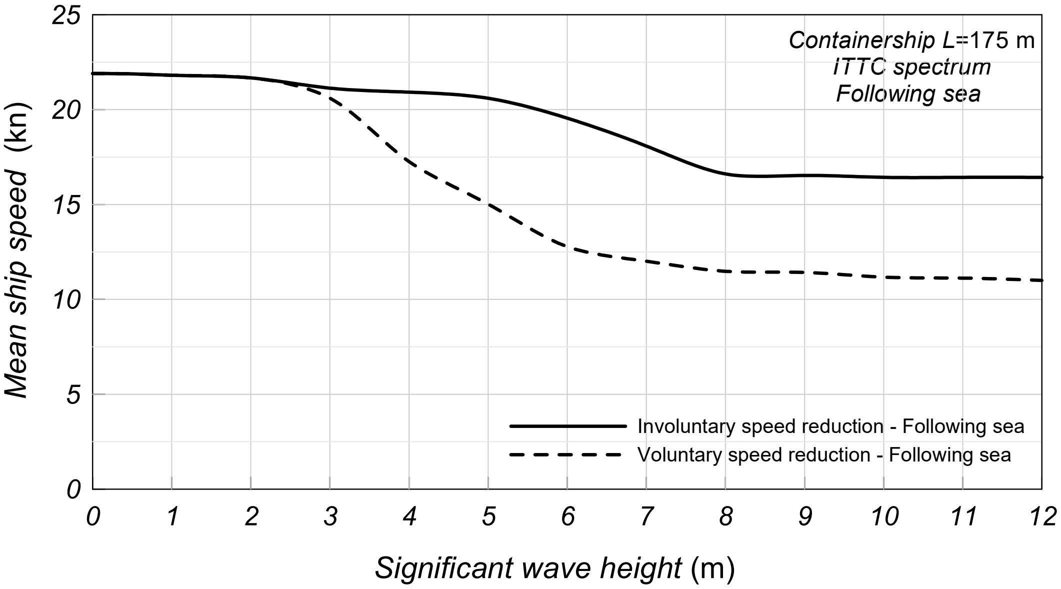

Figure 5. Ship speed loss for following sea

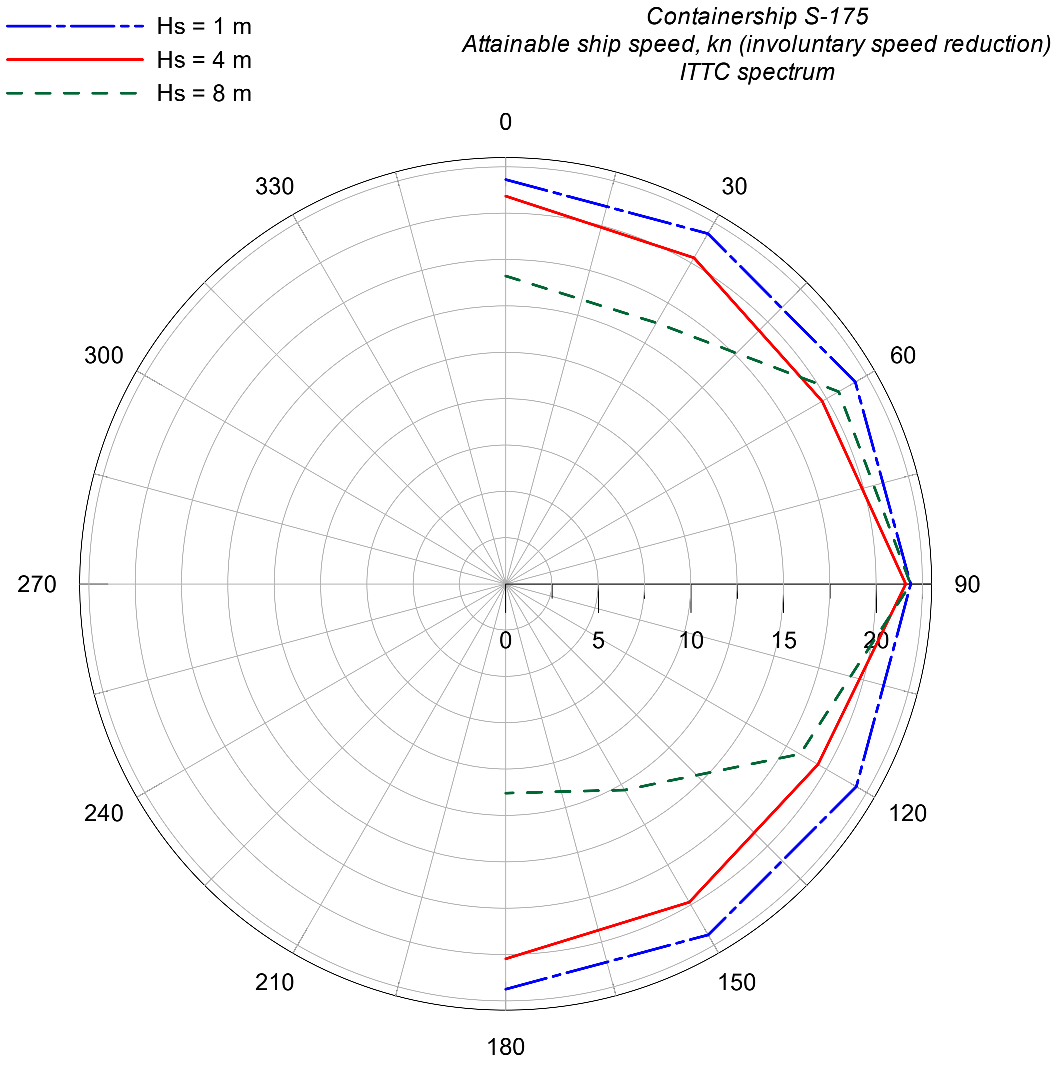

Figure 6. Attainable ship speed for involuntary speed reduction

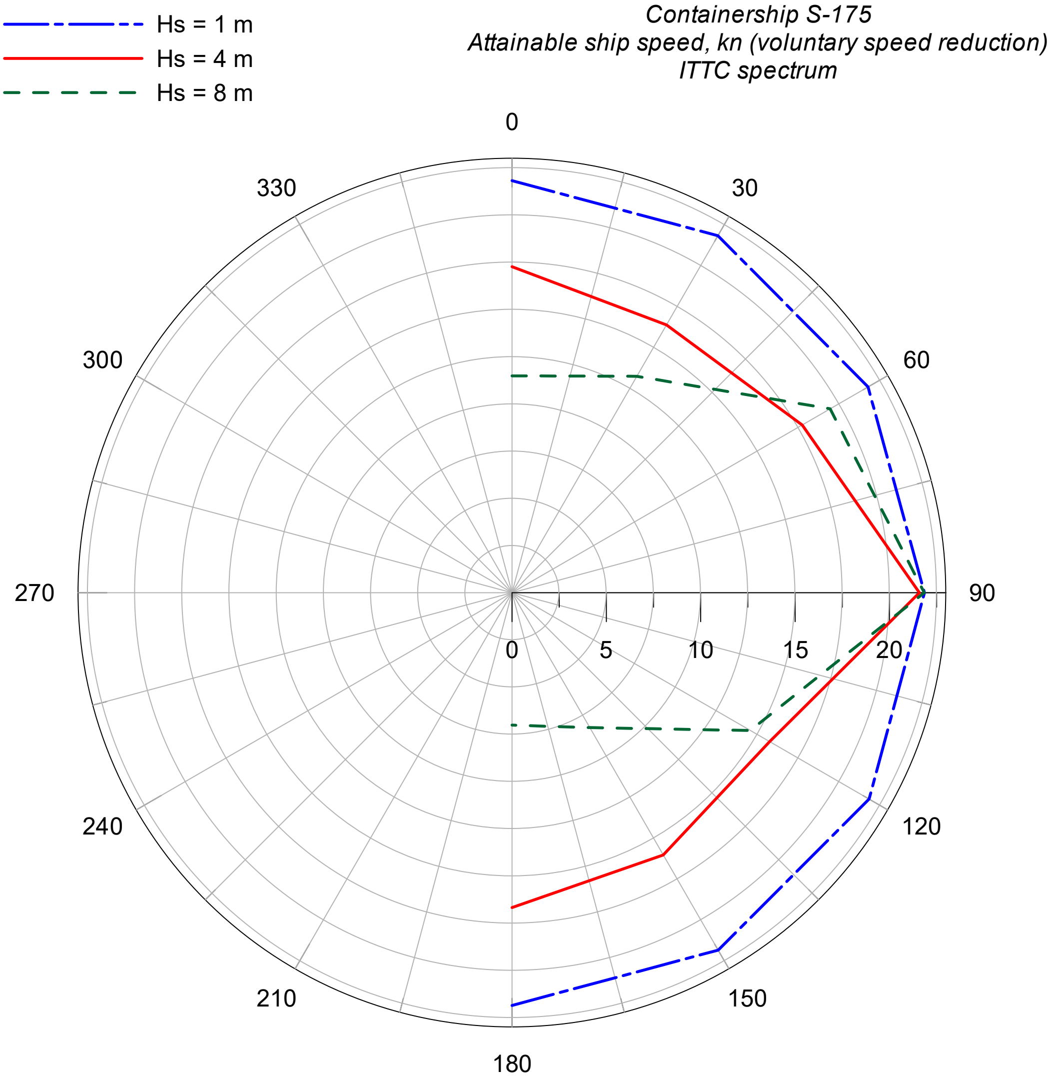

Figure 7. Attainable ship speed for voluntary speed reduction

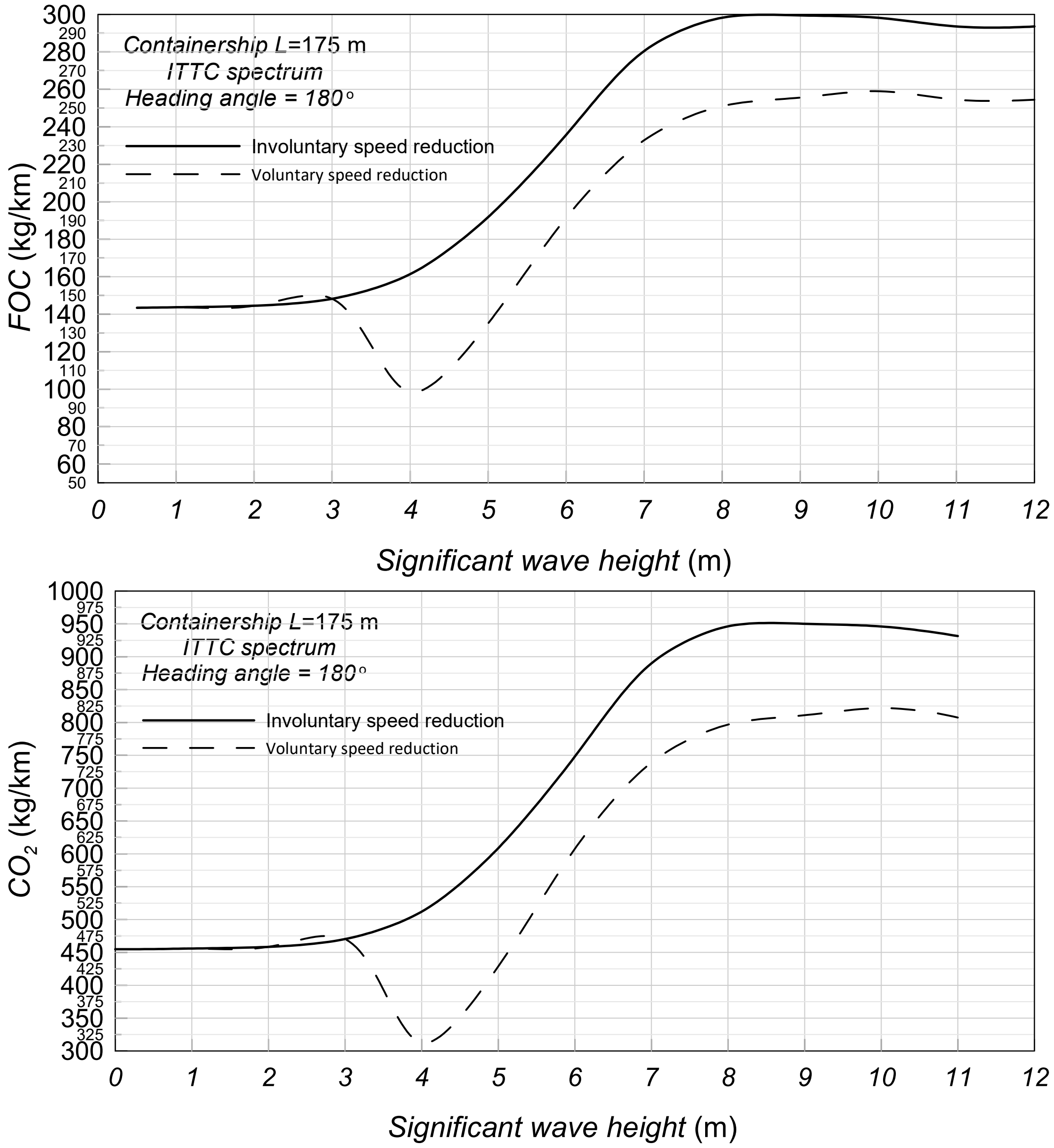

Figure 8. Fuel consumption (FOC) and CO_2 emissions for head sea

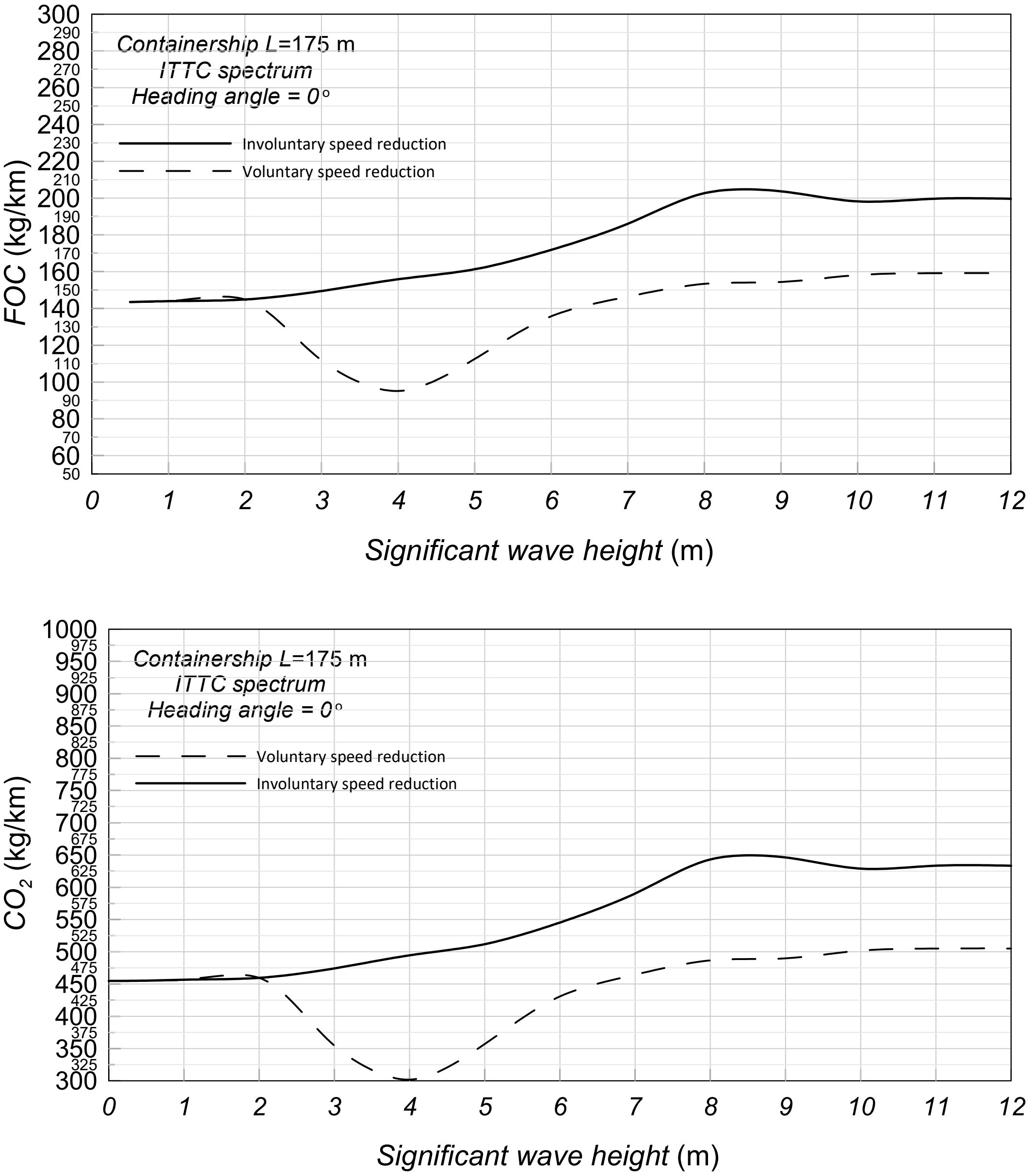

Figure 9. Fuel consumption (FOC) and CO_2 emissions for following sea

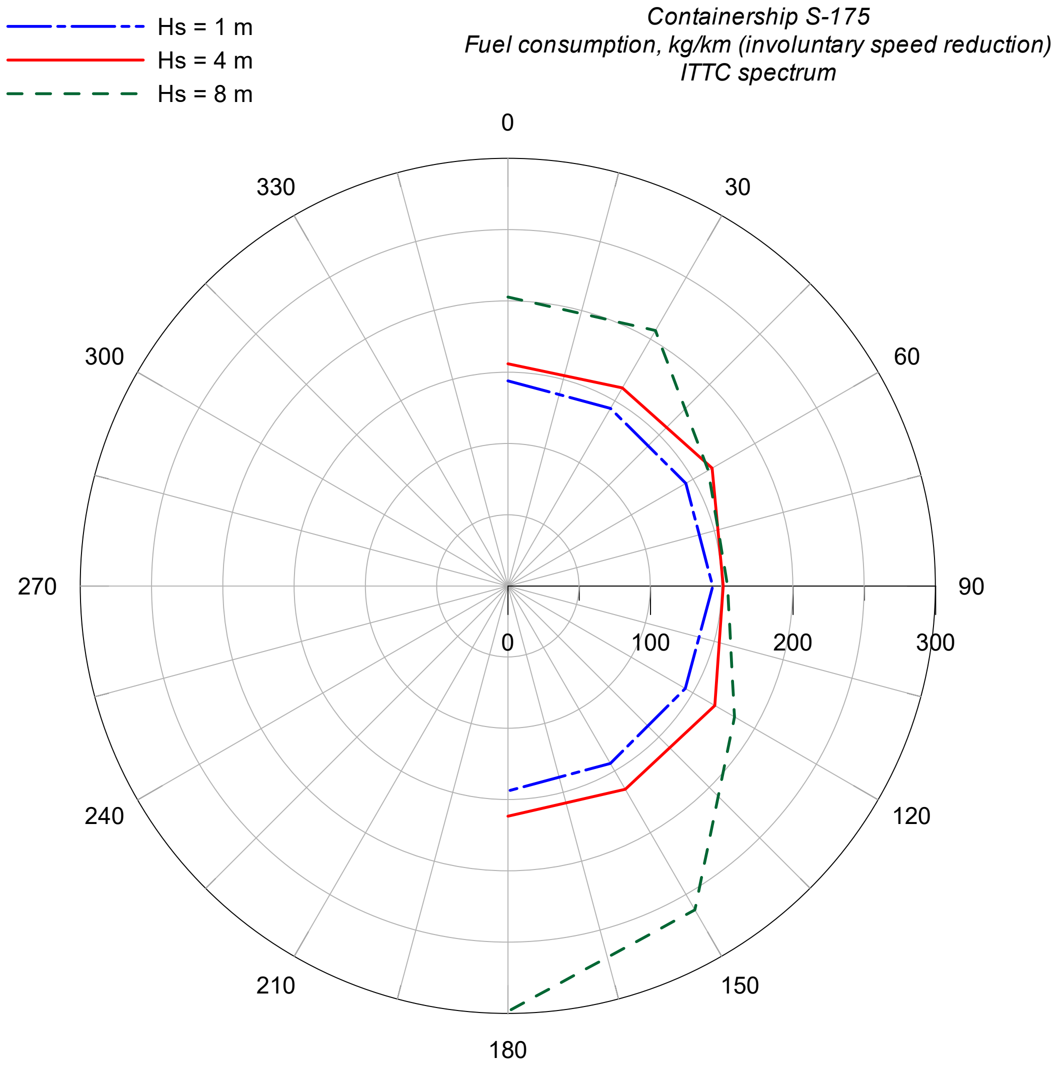

Figure 10. Fuel consumption for involuntary speed reduction.

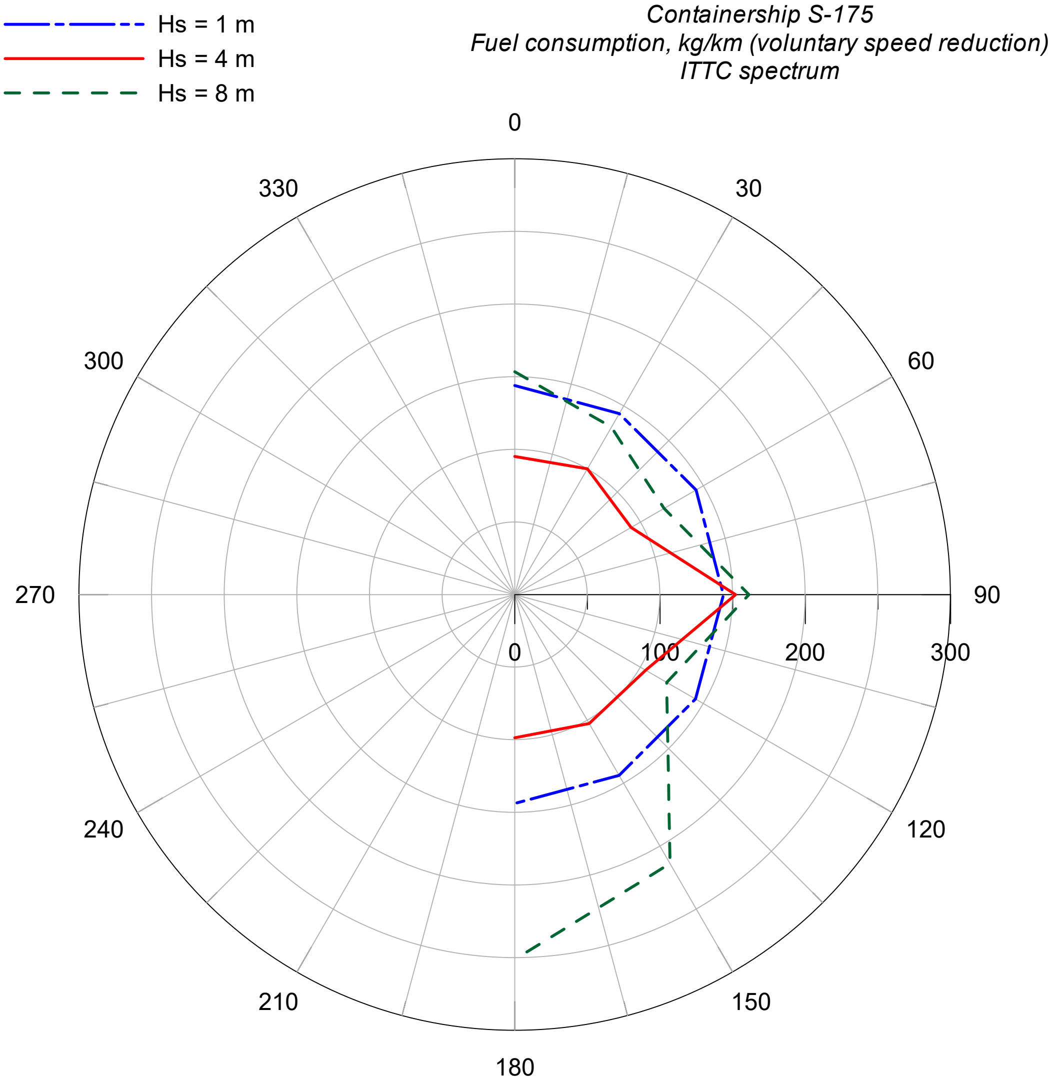

Figure 11. Fuel consumption for voluntary speed reduction.

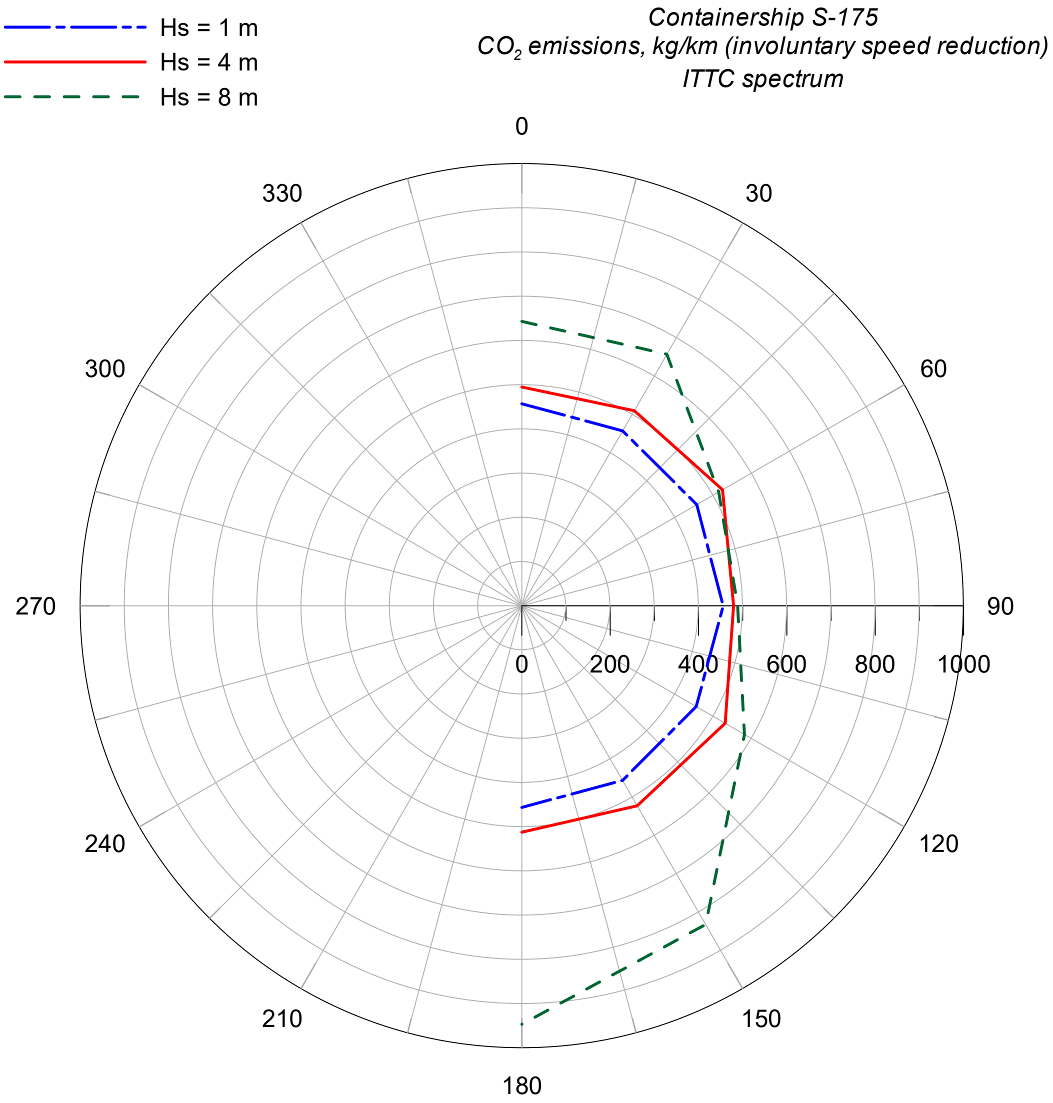

Figure 12. CO_2 emissions for involuntary speed reduction.

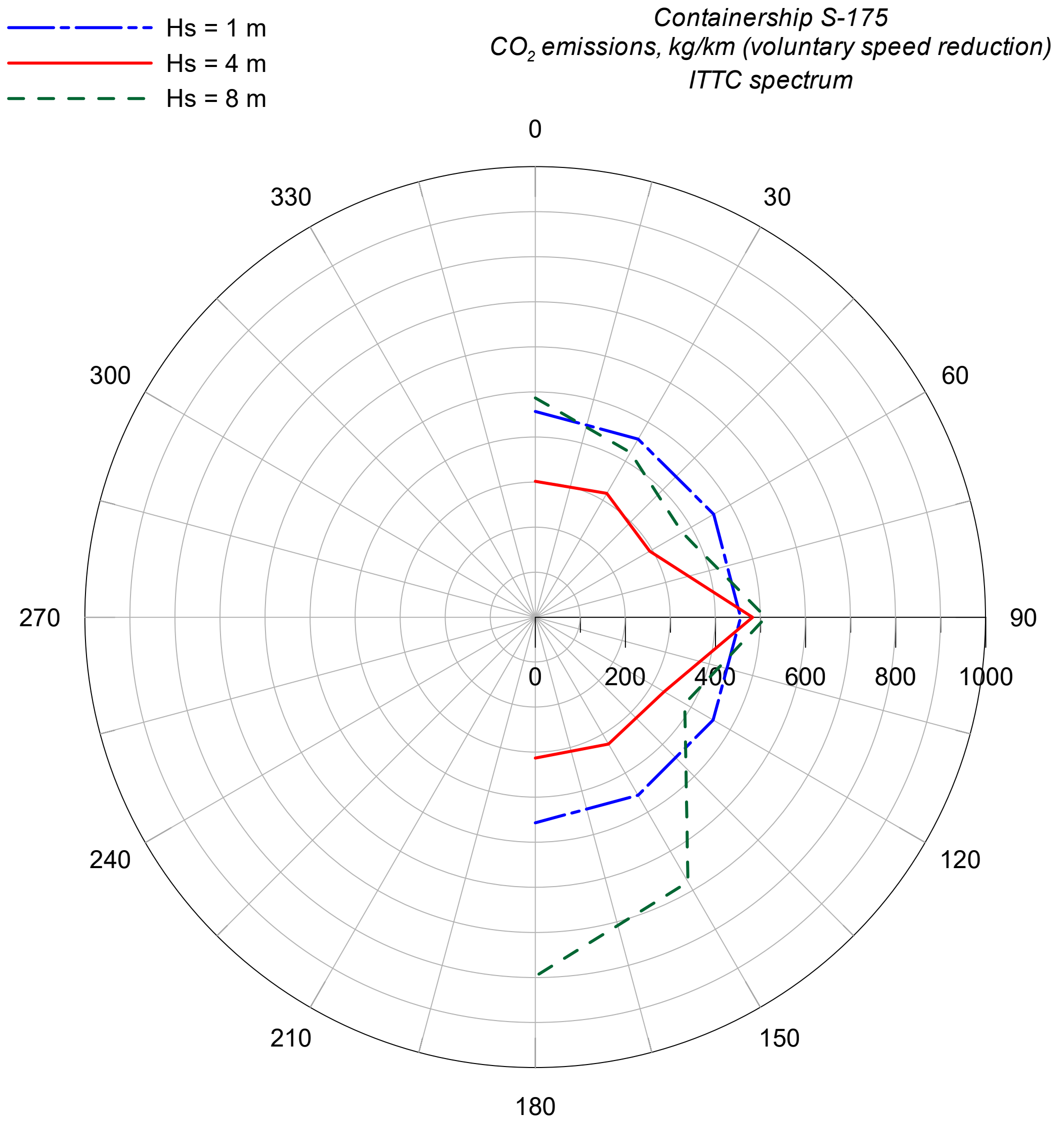

Figure 13. CO_2 emissions for voluntary speed reduction.

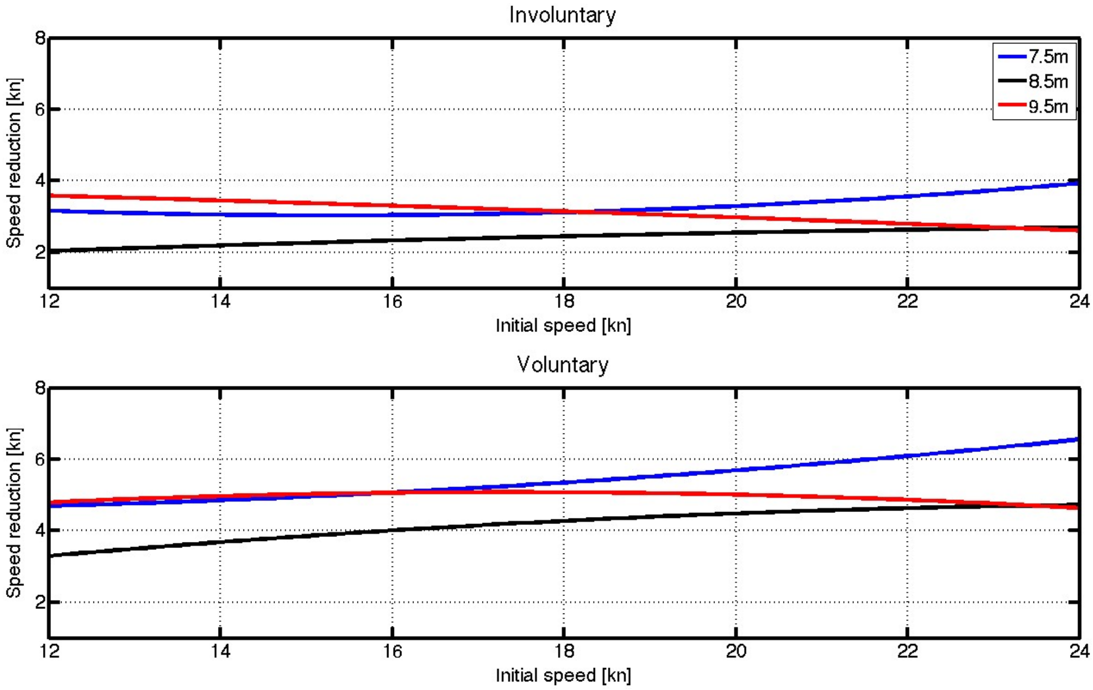

Figure 14. Speed reduction vs. initial speed for different loading conditions.

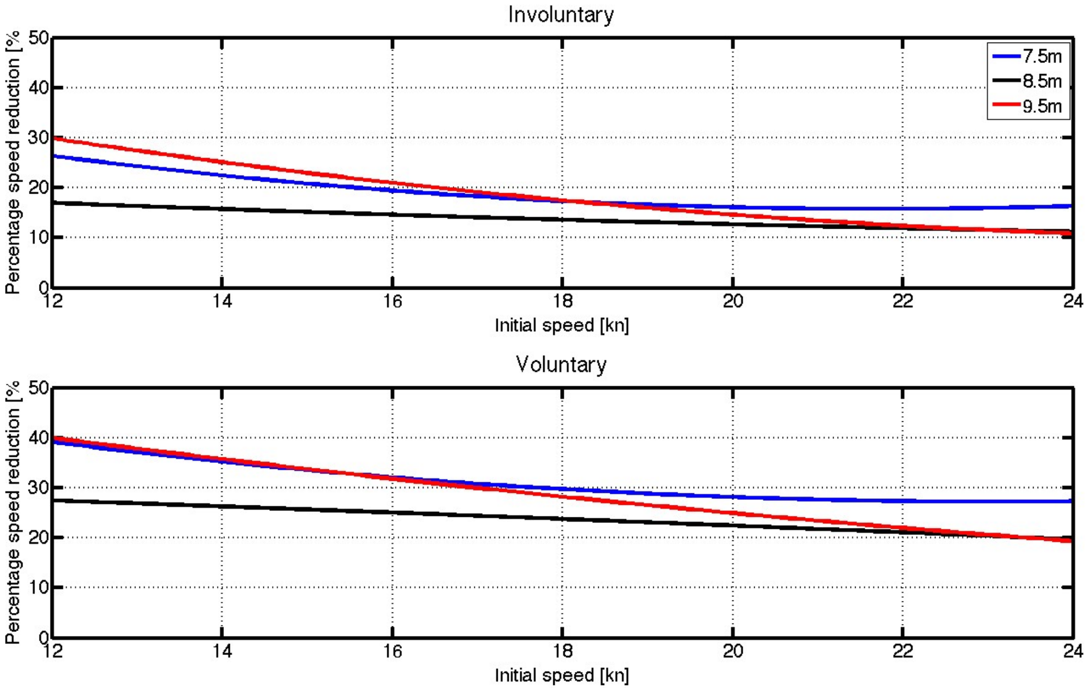

Figure 15. Percentage of speed reduction vs. initial speed for different loading conditions.

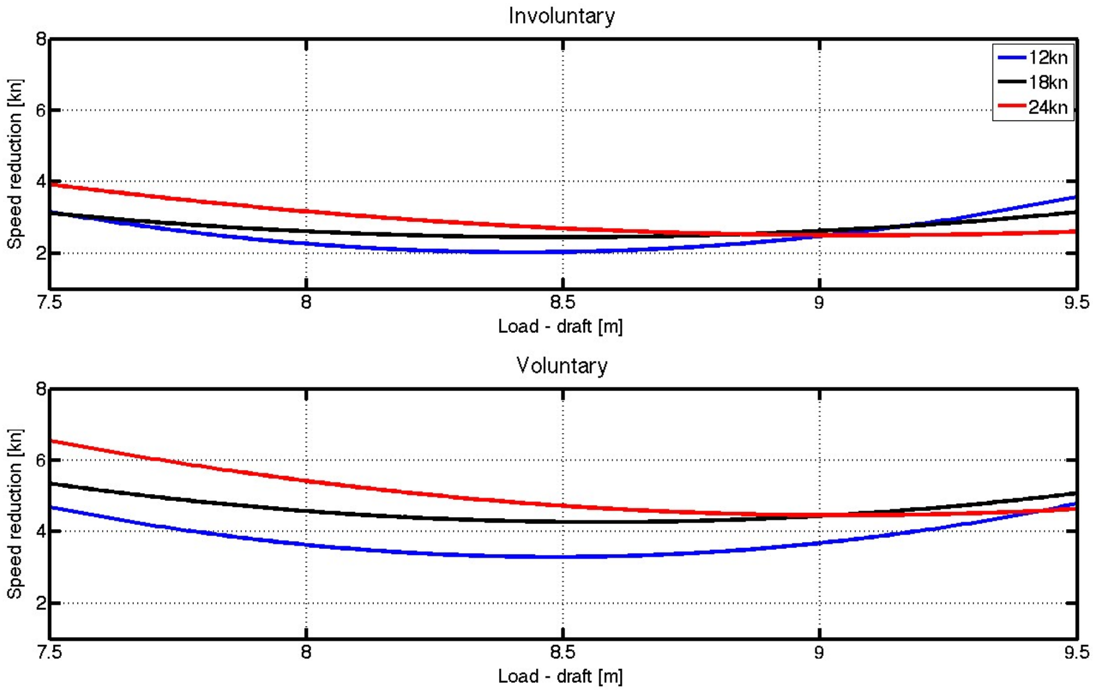

Figure 16. Speed reduction vs. draft (loading condition) for different speeds.

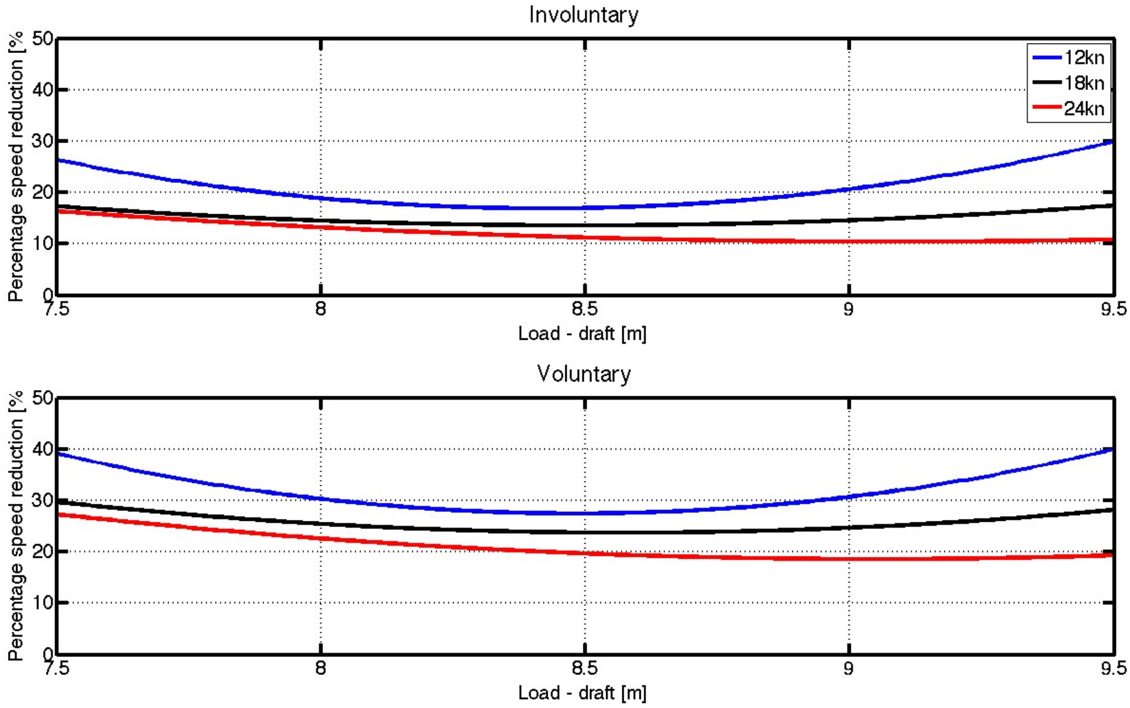

Figure 17. Percentage of speed reduction vs. draft (loading condition) for different speeds.

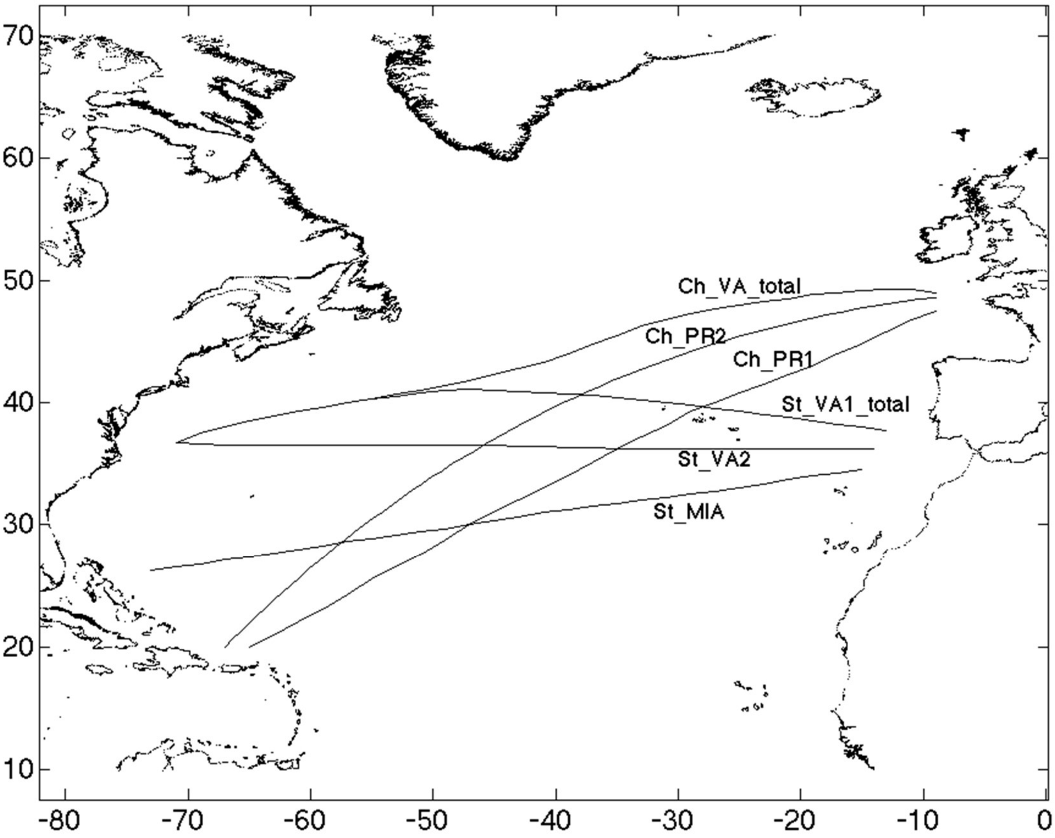

Figure 18. Main North Atlantic trans-oceanic routes.

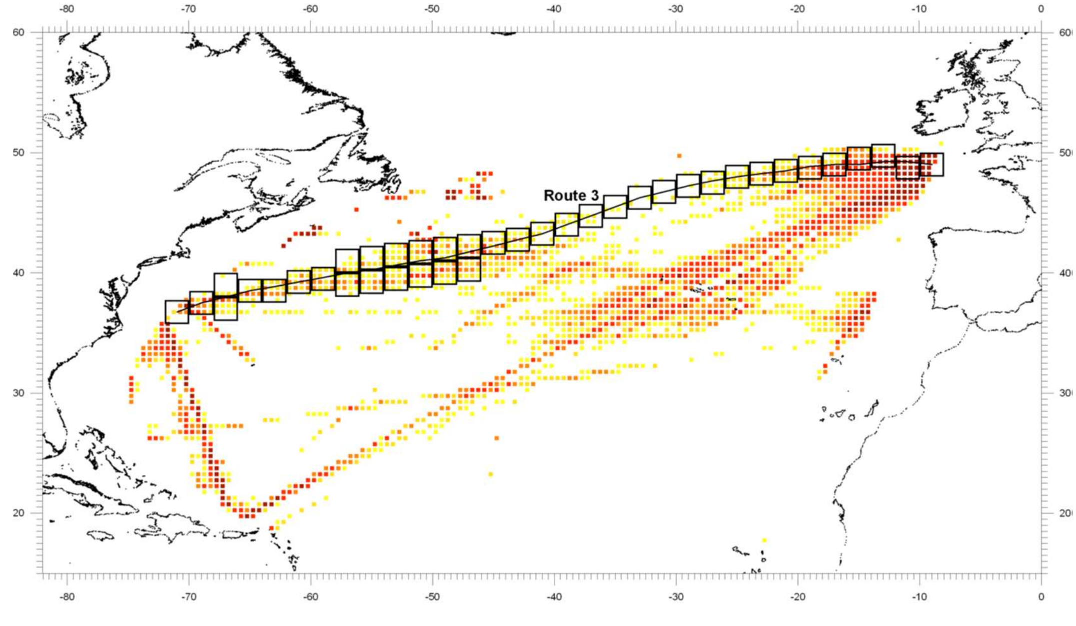

Figure 19. Example of route panels.

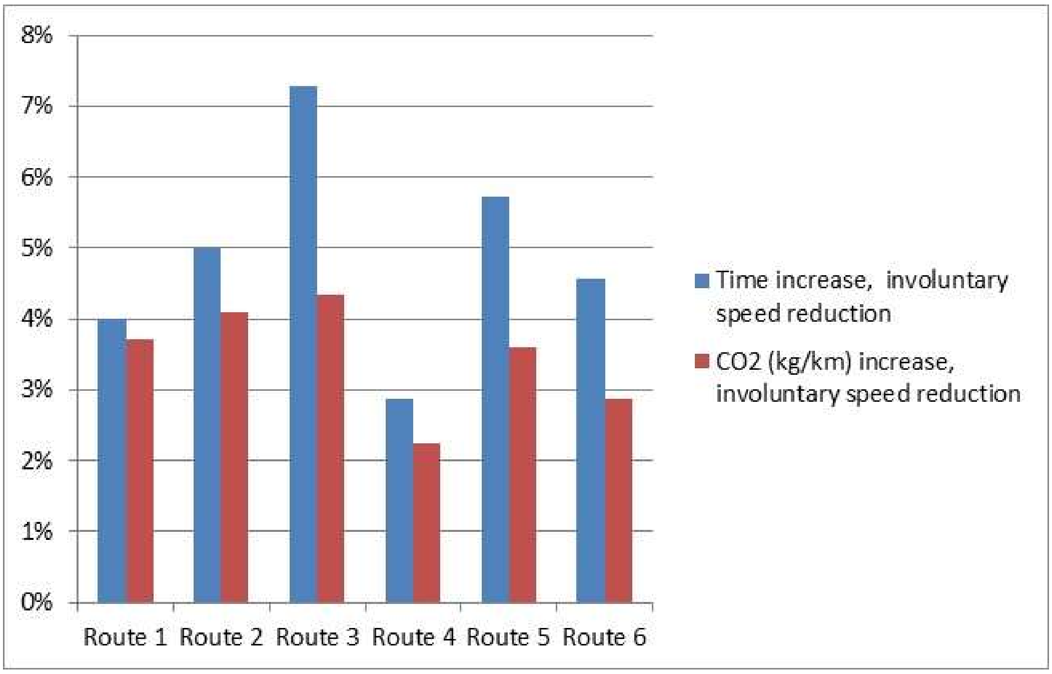

Figure 20. Time increase and CO_2 emmission increase (involuntary speed reduction).

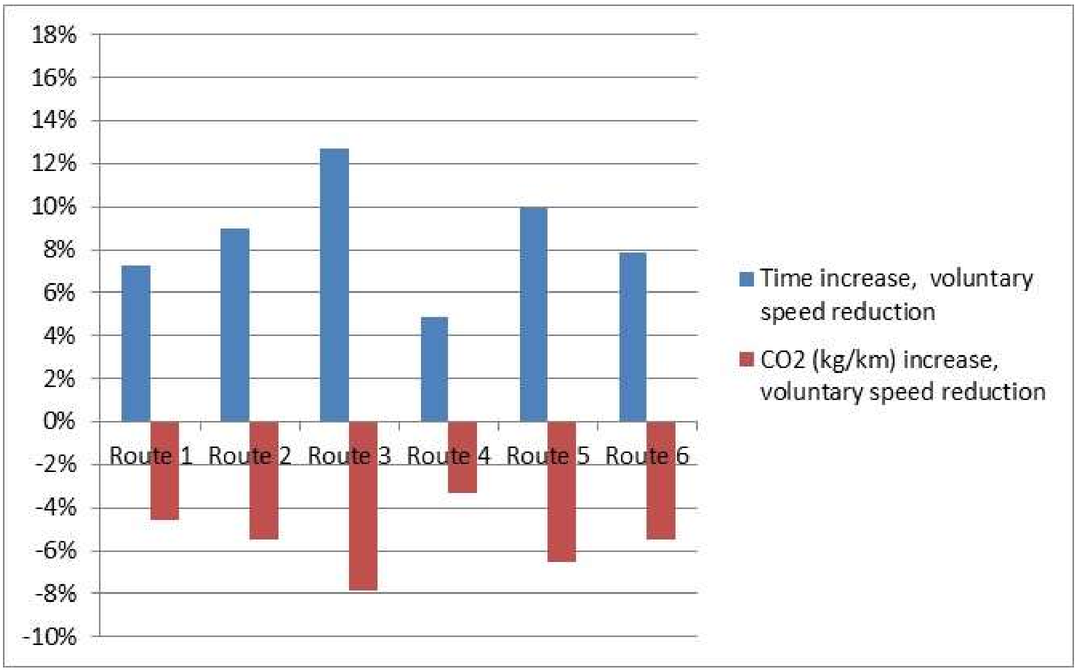

Figure 21. Time increase and CO_2 emmission increase (voluntary speed reduction).

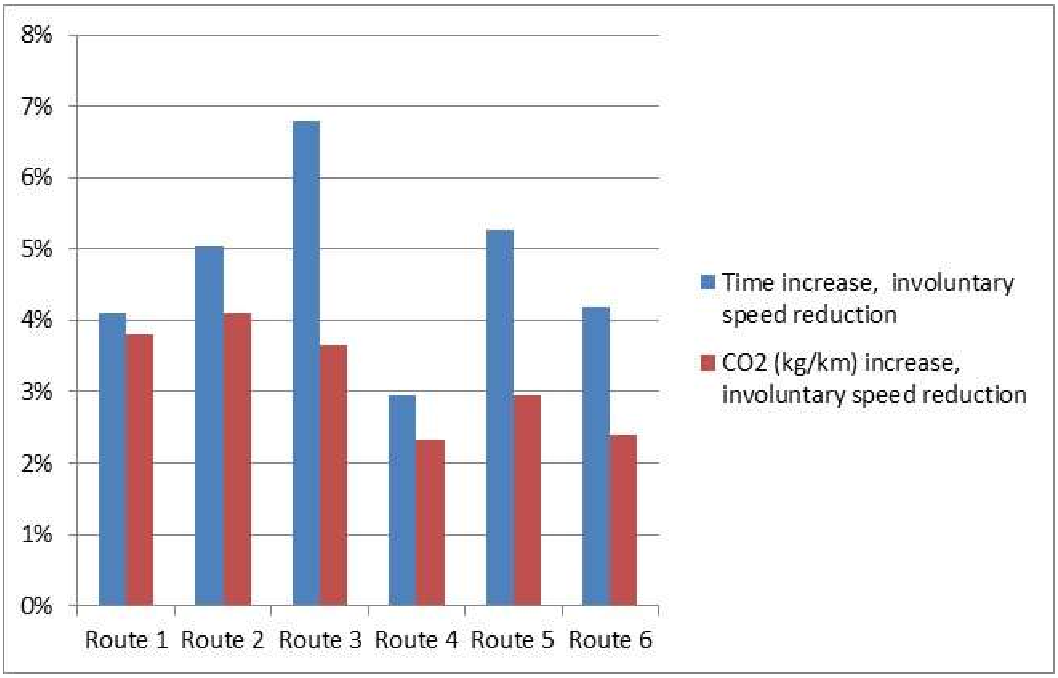

Figure 22. Time increase and CO_2 emmission increase (Eastwards - involuntary speed reduction).

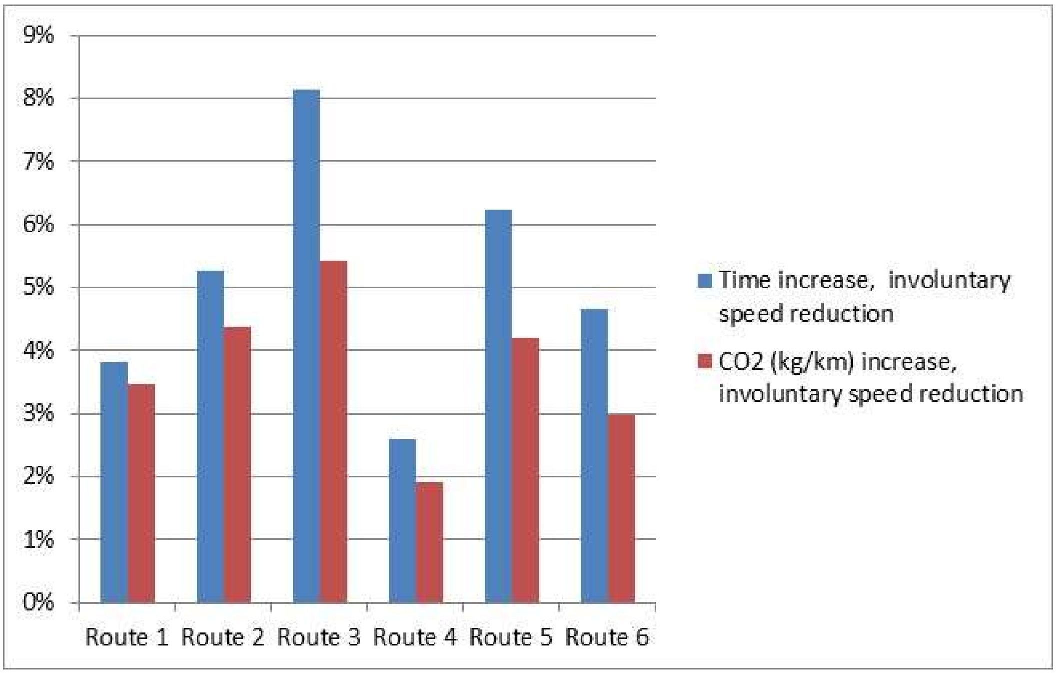

Figure 23. Time increase and CO_2 emmission increase (Westwards - involuntary speed reduction)

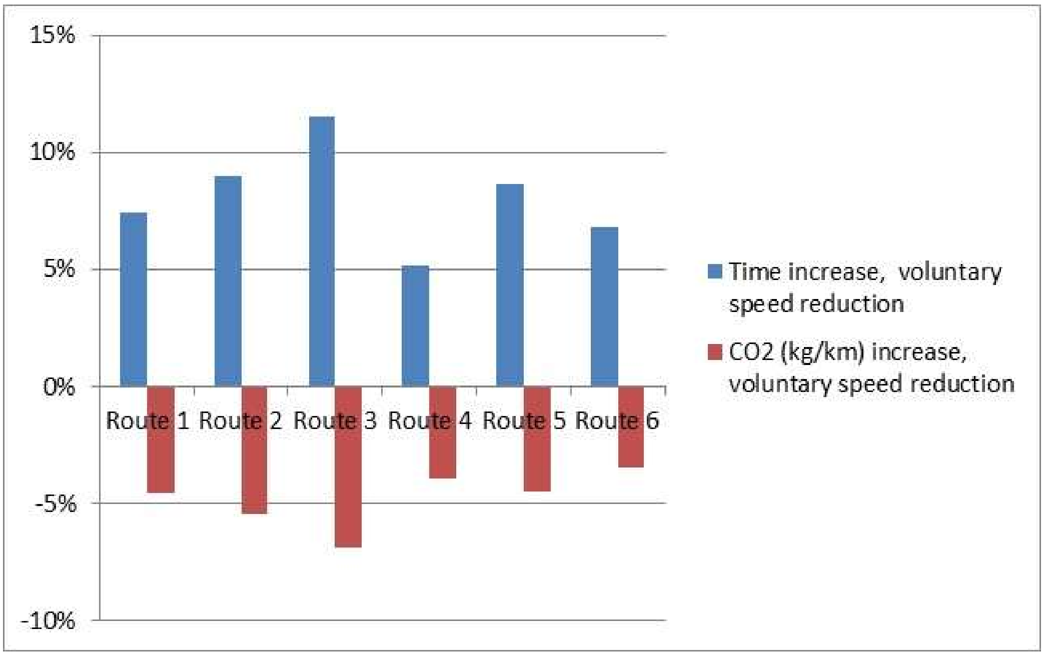

Figure 24. Time increase and CO_2 emmission increase (Eastwards - voluntary speed reduction).

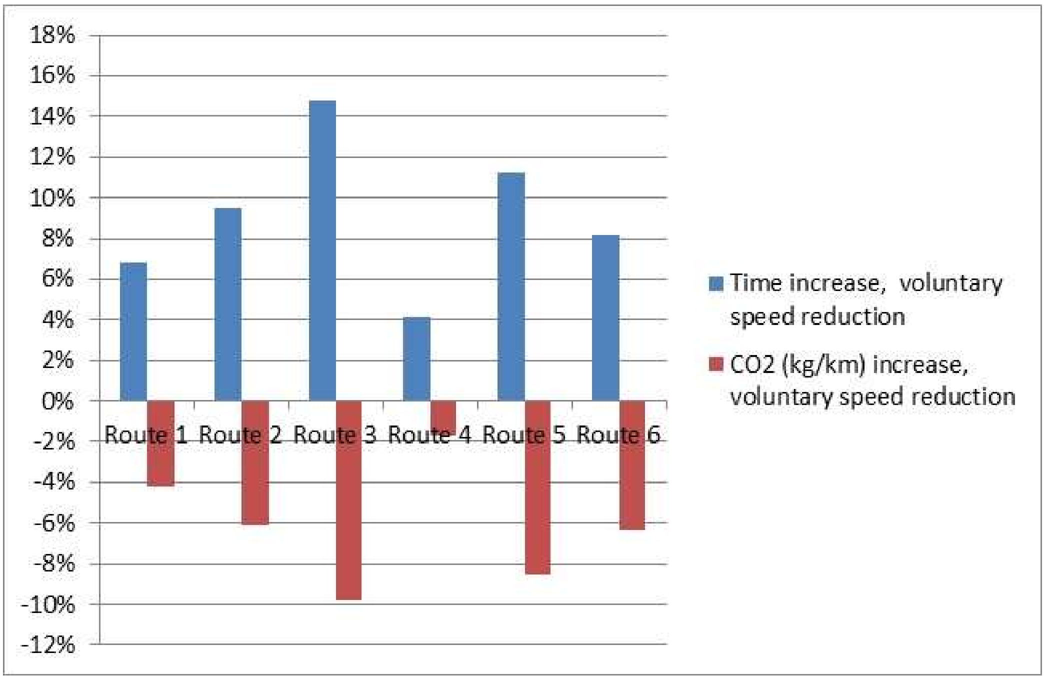

Figure 25. Time increase and CO_2 emmission increase (Westwards - voluntary speed reduction).

Tables

Table 1. Main particulars of the S-175 container ship

Length between perpendiculars	175.0 m
Breadth moulded	25.4 m
Design draft	9.5 m
Freeboard	7.0 m
Displacement	24272 tonnes

Table 2. Calm water condition main parameters.

Power [kW]	26000
SFOC [g/kWh]	171
Speed [kn]	21.9
FOC [kg/km]	143.36
CO_2 [g/km]	454.88

Table 3. Absolute fuel consumption during voyage (calm weather condition).

		Route 1	Route 2	Route 3	Route 4	Route 5	Route 6
Length	[nmi]	3210	3253	2811	3048	2740	2762
Time	[h]	146.59	148.55	128.37	139.19	125.12	126.13
FOC	[t]	852.26	863.68	746.33	809.25	727.48	733.32
CO_2	[kg]	2704.23	2740.45	2368.09	2567.75	2308.28	2326.81

Table 4. Fuel consumption and CO_2 emissions (real weather conditions –involuntary speed reduction)

		Route 1	Route 2	Route 3	Route 4	Route 5	Route 6
Speed	[kn]	21.06	20.86	20.41	21.29	20.72	20.94
Time	[h]	152.47	155.97	137.71	143.18	132.28	131.90
	% increase	4.01	5.00	7.28	2.87	5.72	4.57
FOC	[kg/km]	148.68	149.23	149.58	146.56	148.50	147.47
	% increase	3.71	4.09	4.34	2.23	3.59	2.87
CO_2	[g/km]	471.75	473.49	474.62	465.02	471.20	467.93
	% increase	3.71	4.09	4.34	2.23	3.59	2.87

Table 5. Fuel consumption and CO_2 emissions (real weather conditions – voluntary speed reduction).

		Route 1	Route 2	Route 3	Route 4	Route 5	Route 6
Speed	[kn]	20.42	20.10	19.43	20.88	19.92	20.30
Time	[h]	157.24	161.86	144.70	146.01	137.60	136.05
	% increase	7.27	8.96	12.73	4.90	9.97	7.86
FOC	[kg/km]	136.78	135.49	132.10	138.56	133.96	135.52
	% increase	-4.59	-5.49	-7.86	-3.35	-6.56	-5.47
CO_2	[g/km]	433.99	429.91	419.15	439.66	425.06	429.99
	% increase	-4.59	-5.49	-7.86	-3.35	-6.55	-5.47

Table 6. Fuel consumption and CO_2 emissions (real weather conditions –involuntary speed reduction – Eastwards).

		Route 1	Route 2	Route 3	Route 4	Route 5	Route 6
Speed	[kn]	21.04	20.85	20.51	21.27	20.81	21.02
Time	[h]	152.59	156.03	137.09	143.30	131.70	131.42
	% increase	4.09	5.03	6.79	2.96	5.25	4.19
FOC	[kg/km]	148.81	149.23	148.59	146.70	147.61	146.80
	% increase	3.81	4.09	3.65	2.33	2.96	2.40
CO_2	[g/km]	472.19	473.50	471.48	465.49	468.36	465.78
	% increase	3.81	4.09	3.65	2.33	2.96	2.40

Table 7. Fuel consumption and CO_2 emissions (real weather conditions –voluntary speed reduction – Eastwards).

		Route 1	Route 2	Route 3	Route 4	Route 5	Route 6
Speed	[kn]	20.39	20.10	19.63	20.83	20.16	20.51
Time	[h]	157.42	161.89	143.19	146.33	135.96	134.69
	% increase	7.39	8.98	11.55	5.13	8.66	6.79
FOC	[kg/km]	136.81	135.55	133.55	137.78	136.94	138.44
	% increase	-4.57	-5.45	-6.84	-3.89	-4.48	-3.43
CO_2	[g/km]	434.09	430.11	423.77	437.19	434.50	439.27
	% increase	-4.57	-5.45	-6.84	-3.89	-4.48	-3.43

Table 8. Fuel consumption and CO_2 emissions (real weather conditions –involuntary speed reduction – Westwards).

		Route 1	Route 2	Route 3	Route 4	Route 5	Route 6
Speed	[kn]	21.09	20.81	20.25	21.35	20.62	20.92
Time	[h]	152.20	156.36	138.82	142.79	132.93	132.02
	% increase	3.83	5.25	8.15	2.59	6.23	4.67
FOC	[kg/km]	148.33	149.63	151.11	146.10	149.39	147.63
	% increase	3.46	4.38	5.41	1.91	4.21	2.98
CO_2	[g/km]	470.64	474.79	479.48	463.56	474.02	468.43
	% increase	3.47	4.38	5.41	1.91	4.21	2.98

Table 9. Fuel consumption and CO_2 emissions (real weather conditions –voluntary speed reduction – Westwards).

		Route 1	Route 2	Route 3	Route 4	Route 5	Route 6
Speed	[kn]	20.51	20.00	19.09	21.02	19.69	20.25
Time	[h]	156.56	162.65	147.29	145.00	139.20	136.38
	% increase	6.80	9.49	14.74	4.17	11.25	8.12
FOC	[kg/km]	137.37	134.60	129.28	140.95	131.07	134.29
	% increase	-4.18	-6.11	-9.82	-1.68	-8.57	-6.33
CO_2	[g/km]	435.89	427.10	410.19	447.24	415.88	426.10
	% increase	-4.18	-6.11	-9.82	-1.68	-8.57	-6.33