

Reductions in greenhouse gas emissions and cost by shipping at lower speeds

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ARTICLE INFO

Article history:

Received 5 October 2010

Accepted 17 March 2011

Available online 19 April 2011

Keywords:

Maritime transport

Speed reductions

Greenhouse gas emissions

ABSTRACT

CO₂ emissions from maritime transport represent a significant part of total global greenhouse gas (GHG) emissions. According to the International Maritime Organization (Second IMO GHG study, 2009), maritime transport emitted 1046 million tons (all tons are metric) of CO₂ in 2007, representing 3.3% of the world's total CO₂ emissions. The International Maritime Organization (IMO) is currently debating both technical and market-based measures for reducing greenhouse gas emissions from shipping. This paper presents investigations on the effects of speed reductions on the direct emissions and costs of maritime transport, for which the selection of ship classes was made to facilitate an aggregated representation of the world fleet. The results show that there is a substantial potential for reducing CO₂ emissions in shipping. Emissions can be reduced by 19% with a negative abatement cost (cost minimization) and by 28% at a zero abatement cost. Since these emission reductions are based purely on lower speeds, they can in part be performed now.

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0. Introduction

Anthropogenic emissions of greenhouse gases contribute to global warming, and augmentations in temperature to more than 2 °C above pre-industrial levels are likely to have catastrophic consequences at a global level (Walker and King, 2008). These implications are well documented by IPCC and acknowledged by our politicians. It is estimated that greenhouse gas emissions need to be reduced by around 50–85% in 2050, compared with current levels, in order to achieve a stabilization of the temperature at 2 °C above pre-industrial levels (IPCC, 2007).

While the marine sector has a non-binding commitment under the current Kyoto protocol regime, Article 2.2 of the former invites Annex I countries to the protocol to pursue the limitation or reduction of greenhouse gas emissions from shipping through the IMO. So far, however, the Annex I countries have had little success in limiting or reducing greenhouse gas emissions from international maritime transport. The main reason seems to be differences in the views of Annex I and non-Annex I countries when it comes to the interpretation of Article 2.2 and regarding the applicability of the IMO's principle of a non-discriminatory regulation of all ships engaged in international trade to a climate policy instrument (Faber et al., 2009). However, IMO has made some progress and the current debate is addressing how much

the sector can be expected to reduce emissions, and should be obliged to reduce, as well as in what manner these diminutions can be achieved.

According to the IMO (Second IMO GHG study, 2009), maritime transport emitted 1046 million tons of CO₂ in 2007, representing 3.3% of the world's total emissions. These emissions are assumed to increase by 150–250% in 2050 if no action is taken (i.e., business as usual scenarios with a tripling of world trade). Similar growth prospects have also been reported by OECD (2010) and Eyring et al. (2009). These greenhouse gas emission growth figures stand in sharp contrast to the required total global reductions (IPCC, 2007). Nevertheless, it is a controversial issue how the annual greenhouse gas reductions shall be taken across sectors. Given a scenario where all sectors accept the same percentage reductions, the total shipping emissions in 2050 may be no more than 15–50% of current levels based on the required 50–85% reduction target set by the IPCC (2007). Moreover, provided that the demand for sea transport follows the predicted tripling of world trade, it can easily be deduced that the amount of CO₂ emitted per ton nautical mile (1 nm = 1.852 km) will then (as a minimum) have to be reduced from 25 to 4 g of CO₂ per ton nautical mile by 2050.

This is a reduction by a factor of 5 and a seemingly substantial challenge. The question is thus how to make it come about. There is indeed a documented potential to reduce greenhouse gas emissions in a cost-effective manner. In other words, emissions can be cut with net cost savings (DNV, 2009; Longva et al., 2010). Ships have typically been built to operate at a specific design speed: for large dry bulk vessels this speed is 13–16 knots, while large container vessels have service speeds of 24–26 knots.

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Nomenclature

B	vessel beam (maximum width) of the vessel at the waterline, m
C	cost per freight unit, USD/ton nautical mile
C_{HFO}	cost for heavy fuel oil per ton, USD/ton
C_{IR}	the annual interest rate as calculated by industry or financial institutions, %
C_M	export value per ton of transported cargo, USD/ton
C_{MDO}	cost of marine diesel oil per ton, USD/ton
D	roundtrip distance (1 nm=1.852 km), nautical miles (nm)
C_{aw}	drag coefficient for the wave resistance, non-dimensional
C_T	total drag coefficient, non-dimensional
ε	the amount of CO ₂ emitted per million ton nautical mile, ton
F	fuel consumption F for a roundtrip, ton
F_s	fuel used during sailing F_s , ton
$F_{p\&s}$	fuel used in port and slow zones (canals and in and out of ports), ton
g	the gravity force, m/s ²
$H_{1/3}$	significant wave height, m
j	propeller constant that is speed independent, non-dimensional

k	propeller constant that is speed dependent, non-dimensional
K	propeller (propulsion) efficiency as a function of the vessel speed, non-dimensional
$K_e=3, 17$	emitted CO ₂ when one unit of fuel is burnt, based on Endresen et al. (2007), g/g = 1
$K_f=190$	the amount of fuel used per work unit produced, g/kWh
L	length of the ship at the waterline, m
M	weight (in tons) of the cargo onboard the vessel, ton
P	total power required, kWh
P_{aux}	power required for auxiliary machines, kWh
P_s	power required for still water, kWh
$P_{p\&s}$	power requirement in port and slow zones, kWh
P_w	additional power required for waves, kWh
ρ	density of water, kg/m ³
S	wetted surface of the vessel, m ²
T	time used per roundtrip (days, hours, min)
TC	time charter cost of the vessel per day, USD/day
u	wave speed in relation to vessel speed (1 knots=1852 m/h), knots
v	vessel speed (1 knots=1852 m/h), knots
v_d	the design speed for which the vessel is optimized (this speed is usually 90–95% of the maximum speed), knots

The core insight is straightforward: the power output required for propulsion is a function of the speed to the power of three. Hence, in very simple terms, when a ship reduces its speed, its fuel consumption is reduced. For this reason, several authors have incorporated speed optimization when optimizing fleet scheduling (Bausch et al., 1998; Fagerholt, 2001; Norstad et al., in press).

Ship scheduling and routing concerns the optimal assignment of available cargoes to a set of ships in the fleet, where “optimal” signifies either lifting (transporting) all cargoes while minimizing costs or maximizing profit by only assigning profitable cargoes. Speed reductions also affect the size and mix of a fleet of vessels serving a liner network, and this is known as fleet size mix and routing problems (Christiansen et al., 2007; Fagerholt and Lindstad, 2000). Here, the objective is to find the number and types of vessels as well as a set of feasible routes in order to minimize the total costs.

While the above-mentioned studies have been motivated by the opportunity for cost savings or profit maximization, there has emerged a growing interest in the relationship between speed and emission reductions. Corbet et al. (2009) considered whether the lowering of speed can be a potentially cost-effective CO₂ mitigation option for ships calling at US ports. They found that a fuel tax of about 150 USD/ton would lead to average speed-related CO₂ reductions of approximately 20–30%. Moreover, Sea at Risk and CE Delft (2010) primarily investigated how the overcapacity in major shipping markets in 2009 could be utilized for slow steaming and hence emission reductions. It was estimated that emissions of dry bulk, tanker and container vessels can be reduced by about 30%, relative to the situation in 2007, by employing an oversupply to reduce the speed.

Psaraftis and Kontovas (2010) studied the implications of various emission reduction policies for maritime logistics, and the slow steaming of container vessels in particular. They concluded that lower speeds have environmental benefits, but if the value of the goods is high, its capital cost in addition to the potential loss of sales would favor higher speeds. The modeling approach used in these studies (Corbet et al., 2009; Sea at Risk

and CE Delft, 2010; Psaraftis and Kontovas, 2010) has involved the assumption of constant total transport volumes. This implies that when speed is reduced, additional vessels will be required to maintain the annual transport capacity. While there are some differences regarding which cost elements that are included, the basic method consists in calculating the fuel savings when speed is reduced versus the cost for additional vessels to maximize profit or minimize cost. In this study, both the cost of the shipping lines and that for the cargo owners, including the capital cost for the goods transported has been calculated. The additional value of including both these parameters is to obtain an enhanced understanding of the speed preferences of a cargo owner versus a shipping line.

The fuel and emission calculations in these studies (Corbet et al., 2009; Sea at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010) have been based on still water conditions. In the present study, the added resistance created by wave and wind (sea state) has been included in the power model to reflect the realities from very low speeds up to the design speed, which usually is 90–95% of the maximum speed. This enables the model to calculate the potential emission reductions that can be achieved as a function of speed, dictated by various priorities such as operation at the designed service speed, cost minimization and emission minimization for the various ship classes.

Furthermore, these results have been combined to provide an assessment of the overall potential for short and long term emission reductions through changes in the operation of the global maritime fleet. The employed model is described in Section 1, its application and the data are presented in Section 2, and the obtained results are discussed in the final section with respect to their implications to design policy.

1. Model description

The main objective of the developed model is to calculate costs and emissions for individual ship classes as a function of speed,

dictated by various priorities such as operation at the designed service speed, as well as cost and emission minimizations. The system boundaries focus on the vessels and their use, for which reason the landside of the terminal and the port is excluded. The model consists of four main equations, of which the power Eq. (1) is the most important. It describes the power requirement as a function of vessel speed, hull, propeller and sea state. Traditionally, research on hull shapes and propellers has designed them for still-water, design cargo loads and design speed conditions (Faltinsen et al., 1980), and this despite that a calm sea is quite the exception in shipping. Lloyd (1998) has studied how additional wind and wave resistance increases the power needed as compared to what is required for calm water conditions. The results showed that the resistance rises rapidly with a significant wave height, that the greatest increase relative to the calm water resistance occurs at low speeds and that the contribution from wind is quite small in comparison to the effect of waves.

Based on the above considerations, the power model developed takes into account the propeller efficiency, the power needed for still water conditions, the additional power required for waves and that needed for the auxiliary engines (independent of vessel speed), as expressed by Eq. (1). Comparing this formula to well-established practice, the still water power is calculated in a standard manner (Lewis, 1988), the additional power for waves (Lloyd, 1998) has been modified to enable calculation of the additional average resistance for a full year (the factor $\frac{1}{2}$) and the auxiliary is in standard form. On the contrary, a new notation based on the work by Minsaas (2006) and Lloyd (1998) was required to give a good representation of propeller efficiency from zero speed up to service speed, which is usually 90–95% of the maximum speed

$$P = \underbrace{\frac{1}{\eta(j+k\sqrt{v/v_d})}}_K \left(\underbrace{\left(\frac{\rho C_T S v^3}{2} \right)}_{P_s} + \underbrace{\left(\frac{1}{2} \frac{C_{aw} \rho g (H_{1/3}/2)^2 B^2}{L} (v+u) \right)}_{P_w} \right) + \underbrace{P_{aux}}_{P_{aux}} \quad (1)$$

Here, K gives the propeller (propulsion) efficiency as a function of the vessel speed and η gives the efficiency at the design speed v_d . Typically, η values will reside in the range from 0.6 to 0.7. When speed v is reduced, the propeller efficiency K drops according to the constants j and k (where $j+k=1$). The still water power is given by P_s , where ρ is the density of water, C_T is the total drag coefficient, S is the wetted surface and v is the speed. The wave power is given by P_w , where the $\frac{1}{2}$ expresses the average wave force working on a vessel during a typical roundtrip for which the voyage consists of parts with head waves, side waves and aft waves and where the effect of the aft waves has a small positive contribution to the forward speed compared to the added resistance created by the head waves. In its formula, ρ is the density of water, C_{aw} is the drag coefficient for the wave resistance, g is the vertical force, $H_{1/3}$ is the significant wave height for which the amplitude is half of the height, B is the width of the ship at the waterline, L is the length of the ship at the waterline, v is the vessel speed and u corresponds to the speed of the waves in relation to that of the vessel. The auxiliary power needed for running pumps and for producing electricity for lighting as well as all the supporting systems of the ship, P_{aux} , is a function of the vessel type and size, and also of the cargo it carries. Moreover, it is generally independent of vessel speed.

The fuel consumption F for a roundtrip involves the fuel used during sailing F_s and fuel used in port and slow zones $F_{p\&s}$, as expressed by

$$F = F_s + F_{p\&s} = K_f \left(\left(\frac{PD}{v} \right) + (P_{p\&s} T_{p\&s}) \right) \quad (2)$$

Here, P represents the required power, D is the roundtrip distance, v is the actual vessel speed and K_f is the amount of fuel (in grams) per produced kWh. Moreover, $P_{p\&s}$ corresponds to the power requirement in port and slow zones and $T_{p\&s}$ is the time in port and slow zones per roundtrip. The difference compared to Second IMO GHG study (2009) is that the formula calculates the fuel as a function of speed where the added resistance from waves and efficiency of propulsion has been included in addition to the calm water resistance.

The amount of CO₂ emitted per ton nautical mile ε is calculated as follows (Second IMO GHG study, 2009):

$$\varepsilon = \left(\frac{F}{DM} \right) K_e \quad (3)$$

where F is the total amount of fuel consumed during the roundtrip as described in Eq. (2), K_e is the emitted CO₂ per unit of fuel burnt and DM is the freight service in distance-weight units (ton nautical mile), for which D is the distance and M is the average weight (tons) of the cargo on a given roundtrip.

The cost per ton nautical mile, C , comprise the fuel cost, the time charter cost of the vessel and the capital cost of the transported goods, as expressed by

$$C = \frac{1}{DM} \left((F_s C_{HFO} + F_{p\&s} C_{MDO}) + TCT + \left(MC_M \frac{1}{2} T \left(1 + \frac{C_{IR}}{365} \right) \right) \right) \quad (4)$$

The first factor, i.e., $1/DM$, transforms the cost from a total cost per roundtrip to a cost per ton nautical mile to enable comparisons of freight cost per unit for vessels of different sizes and types employed in various trades. The fuel cost is then calculated as the amount used during sailing F_s , multiplied by the cost for heavy fuel oil C_{HFO} plus the fuel used in port and slow zones $F_{p\&s}$ multiplied by the price of marine diesel oil C_{MDO} . Until quite recently, deep-sea vessels could operate without using marine diesel oil at all. However, with stricter environmental legislations in Europe and in North America, it can be assumed that marine diesel oil will soon be required when navigating in all ports and slow zones. The cost of the vessel is calculated as the time charter cost per day, TC, multiplied by the voyage length, T , measured in days. The capital cost of the transported goods is obtained by the average amount of transported cargo M , the export value per ton of transported goods, C_M , the time used for the one way voyage which is half the roundtrip time $\frac{1}{2}T$ and the linearly distributed capital cost of transported goods $(1+(C_{IR}/365))$. Here, C_{IR} is the annual interest rate as calculated by industry or financial institutions. When the speed is reduced below the service speed (90–95% of maximum speed), two of these three cost terms will increase, and one will decrease, while the total freight work per roundtrip remains constant. The cost terms that are raised when the speed is reduced are the time charter and the capital cost while the fuel cost decreases due to a reduced power requirement (according to Eq. (1)) and fuel consumption (according to Eq. (2)).

Summing up, combining Eqs. (1)–(3) renders it possible to describe the greenhouse gas emissions associated with a specific operational mode expressed, while Eq. (4) provides the costs.

In order to obtain consistent fleet level results, it is important to also address the issue of environmental impacts of shipbuilding. To this end, Life Cycle Assessment (LCA) is the leading methodology for evaluation of environmental impact. In our case we have applied the Environmental Extended Input Output Life Cycle Assessment on-line tool (www.eiolca.net) provided by Carnegie Mellon University and the obtained results includes the relative impacts of various types of products, materials, services, or industries with respect to resource use and emissions throughout the supply chain. Thus, the effect of producing a seagoing vessel would involve emissions at the shipyard, from mining

metal ores, from the steel mill or the aluminum plant, and from the manufacture of engines and electronic parts.

2. Application and analysis

The aim of the analysis is to first identify the emissions and costs for individual ship classes as a function of speed, discuss and assess these, and then combine them to evaluate the emission reduction potential and costs for the global fleet.

2.1. Selection of ship classes for the study

The selection of ship classes for this study was made to facilitate an aggregated representation of the world fleet based on ton-nautical miles produced by the various classes and coverage of ship classes operating within different speed areas. The outcome of this selection was to include bulk, RoRo and container vessels above 15 000 dead-weight (the measure in ton for how much weight a ship can carry at most). Combined, these classes represent 80% of global sea transport.

The chosen vessel types operate within three speed regimes and were expected to exhibit varying responses in terms of costs and emissions resulting from reductions in operating speed. In terms of their utility, RoRo vessels are used for the transport of cars, trucks, heavy machines, forest products and project cargo, and typically have dead-weights between 15 000 and 40 000 tons with service speeds around 20 knots.

Their cargo capacity is also expressed in standard car units and number of lane meters.

Container vessels are employed for the transport of containers filled with a wide range of products and commodities, from high-value items like electronics, to low-value products as well as scrap steel and paper for recycling. Even if the containers look quite standardized, there are different sizes and types and as a result all containers are calculated as multiples of the standardized twenty feet unit (TEU) which has a length of 6.1 m, a width of 2.4 m and a height of 2.6 m, to enable load planning and capacity calculations. Typical dead-weights range from 40 000 to 160 000 tons equivalent to 3500 to 14 000 TEU, and service speeds are around 25 knots.

Bulk vessels are built for carrying either dry or wet cargoes, and the ore-bulk-oil carriers are capable of carrying both. The main dry bulk commodities include iron ore, coal, grain, alumina and aggregates while crude oil is the dominant wet bulk commodity. Measured in freight work, these 6 commodities add up to 60% of the global sea transport work measured in ton nm. Typical dead-weights range from 40 000 to 300 000 tons and service speeds are 13–16 knots.

2.2. The data set used in the analysis

In the performed calculations, both container and RoRo vessels were employed in trade between Asia and Europe, where the distance was 11 000–12 000 nautical miles. The bulk vessels were utilized in typical raw material trades from Australia to China, implying a distance of 4500 nautical miles. The modeling approach assumed that the total transport volumes were constant so as, when the speed is reduced, additional vessels will be required in order to maintain the annual transport capacity. Although speed limitations lead to reductions in operational emissions down to a minimum level, the emissions from shipbuilding increase due to the need for additional vessels.

At the present time, moderate speed reductions can be implied without additional vessels being built since there is an oversupply of vessels (Sea at Risk and CE Delft, 2010). However, in the long run,

emissions from shipbuilding have to be included in the assessment to identify the speeds that minimize total emissions. Since the applied Environmental Extended Input Output Life Cycle Assessment on-line tool is based on US cost levels, which are high compared with new building prices in Asia, it was assumed that the price for US-built vessels of all categories would be twice the actual new building prices (CAPEX). Such an assumption led to a result of 42 900 tons of CO₂ emitted for building a Panamax Bulk vessel, where the weight of the vessel itself, without any cargo, fuel or supplies was 10 000 tons (more than 95% of this weight was steel). It can be argued that 4.3 kg CO₂ per kg ship is rather high, but at least such a value would ensure that the CO₂ effect for building additional vessels would not be underestimated. For the building of a RoRo vessel and a container vessel, the Environmental Extended Input Output Life Cycle Assessment with the same assumption gave 70 000 and 75 000 tons of CO₂, respectively.

All figures pertaining to cost were taken in US dollars (USD) and the price per ton for the two fuels used was $C_{HFO}=400$ and $C_{MDO}=600$. The time charter (TC) rate was based on new building prices (CAPEX), and the annual TC was set to 12% of the new building price and the daily TC was obtained by dividing the annual TC by 350 days. The capital cost of the goods transported, was calculated as a function of their ex-works value per ton and the interest rate for the capital required. Different accounting principles can be used to set the ex-works value, however we have set it based on the accounting principles that it shall reflect the manufacturing cost including the raw materials plus the profit of the manufacturer, while we have used average world market prices for commodities like crude oil, iron ore, coal and grain. The average ex-works value of the cargo onboard the RoRo and the container vessels was set to 5000 USD/ton, while 250 USD/ton was used for the bulk cargo. The interest was taken as 5% per annum.

The main characteristics of the vessels were the following: RoRo vessel—8000 standard car units, 28 000 dwt, CAPEX 82 million USD, TC/day 28 000 USD, CO₂ from shipbuilding 70 000 ton, main engine 18 500 kWh and service speed 20.5 knots; container vessel—6000 TEU, 80 000 dwt, CAPEX 88 million USD, TC/day 30 000 USD, CO₂ from shipbuilding 75 000 ton, main engine 60 000 kWh and service speed 25 knots; and bulk vessel—72 000 dwt, CAPEX 50 million USD, TC/day 17 000 USD, CO₂ from shipbuilding 42 900 ton, main engine 9800 kWh and service speed 14.5 knots.

For all the trades, the vessel dead-weight utilization was set to 50% on a roundtrip basis, as determined based on a bulk vessel loaded 100% one way and returning empty. For RoRo and container vessels, the following figures were utilized: 25–50% one way and 50–75% on the return trip. All these ship types may achieve higher yearly dead-weight utilizations, but the fact of employing identical utilization percentages rendered the comparisons and conclusions transparent.

For the resistance due to waves, the significant wave height used was 2.5 m. This is quite close to the average value that would be obtained for all ocean areas if a full calculation were to be carried out. This increases the average power requirement compared with still water conditions for all the vessels, and while the impact is only 2–3% for container vessel moving at the service speed of 25 knots, it increases to 5% at 19 knots and 15% at 12.5 knots. Since speed reductions also gives reductions of propulsion efficiency, while the auxiliary consumption is speed independent, the net effect is a calculated power reduction to 20% compared with what is required to achieve service speed (the power equation) and to 12% if only still water resistance (based on constant propulsion efficiency) and auxiliary are included. Reducing speed by 50% also gives the same reduction of freight work per hour and the emission per ton nautical mile becomes 40% of the emissions at the service speed (the power equation),

compared with 24% if only still water and auxiliary power is included. For bulk vessels, which moves slower, the impact of including the average wave resistance increases the power requirement by 15% when traveling at a service speed of 14.5 knots. When the speed is reduced with 50% to 7.25 knots, the emissions per ton nautical mile become 54% of emissions at the service speed (with the power equation) compared with 30% if only still water and auxiliary power are included. For RoRo vessels, which travel at a service speed of 20.5 knots, the emission reductions are smaller than for container vessels and larger than for bulk vessels.

2.3. Results regarding speed and cost

The results for the individual ship classes are presented in Fig. 1. The figure contains two separate parts for each of the three vessel types with a common vertical axis. The vertical axis represents the cost in USD for the transport work measured per million ton nm as a function of vessel speed on the right-hand side of the figure, and the same cost as a function of emissions on the left-hand side. By plotting the results this way, it is possible to obtain the emission reduction as a function of the speed reduction.

All the graphs present a dotted and a dashed line; the former includes the cost elements time charter, TC, and fuel oil cost, FC, while the dashed line also takes into account the capital cost of the transported goods, CC. Moreover, the graphs to the left contain a solid line, which includes the life cycle emissions associated with the increased number of vessels required to serve a constant flow of goods as speeds are reduced (in addition to the direct emissions from operation). The graphs to the right demonstrate a minimum cost for a speed lower than the design speed. Furthermore, the section of the curve on the left-hand side of this point is inefficient in terms of cost versus speed, assuming a positive utility assigned to increased speed. This was found for cost curves both including and excluding the value of goods.

When the value of the cargo was added, it caused the entire curve to shift upwards and to the right. Following this, the cost optimum speed increased when the value of the cargo was included. The magnitude of this shift was given by the ratio of capital cost of the goods relative to the time charter and fuel costs. As can be observed, the ship classes demonstrated different behaviors in this respect. The cost optimal speed for bulk ships changed very little with the inclusion of the cargo value, from 12.5 to 13 knots, while the cost curves shifted only marginally upward with the minimum cost changing from 3400 to 3550 USD per million ton nm. For reference, the design speed was 14.5 knots.

For the two other ship classes, the changes were much more significant. For RoRo vessels, the design speed was 20.5 knots, while the cost optimum speed was 16.8 and 19 knots, respectively, excluding and including goods capital costs. The changes were even more significant for container ships for which the design speed was 25 knots, while the cost optimum speed was 15.6 and 18 knots excluding and including goods capital costs. For the latter case, the costs at optimum were 10% lower than at the design speed.

2.4. Results regarding minimizing emissions and Pareto optimality

The graphs on the left side show the trade-off curves between costs and emissions as a function of vessel speed on the right-hand side. All graphs have three distinct lines. The dotted line represents time charter plus fuel cost and direct emissions from operation. The dashed line includes the costs for time charter, fuel, goods capital cost and direct emissions. The solid line corresponds to the same cost elements as the dashed line but

also includes the emissions associated with shipbuilding. This is required for consistency, since the number of ships must be increased as the sailing speed is reduced in order to maintain the same flow of goods. The curves demonstrate that a reduction of the speed below the design speed reduces emissions. The emission reduction is the largest for the first percentage of speed reduction, whereas when the speed is further reduced, the marginal emission reduction gradually becomes smaller until it reached zero for the speed that gives the lowest emissions per ton nautical mile. Further reductions in speed lead to increase of emissions per ton nautical mile.

When plotting emission against cost, a Pareto distribution was obtained, where both emissions and cost increased when the speed was reduced below the minimum emission speed. The dotted line shows this relationship when fuel and the time charter cost is included. When the capital cost of goods was taken into account, the curve moved upwards as shown by the dashed line, and when emissions from shipbuilding were taken into account, the solid lines were caused to shift upwards (cost increase) and to the right (emission increase).

According to these results, the emission optimum speed increased when shipbuilding was included. The magnitude of these shifts in emissions was given by the specific shipbuilding emissions and the additional vessels required, whereas the shift in cost was based on cargo values. As can be observed, the ship classes demonstrated different behaviors in this respect. When minimizing emissions for bulk ships, the speed increased from 6 to 7.2 knots, adding up to 8 ton CO₂ per ton nm when shipbuilding was included in the assessment. At this speed, emissions from shipbuilding constituted 20% of the total, while at the design speed of 14.5 knots, emissions added up to 12.4 ton CO₂ per ton nm of which shipbuilding was 6% of the total. For container vessels, the speed when minimizing the emissions increased from 7.2 to 8.4 knots adding up to 13.9 ton CO₂ per ton nm when shipbuilding was included in the assessment. At this speed, emissions from shipbuilding corresponded to 11% of the total, while at the design speed of 25 knots, emissions added up to 36.4 ton CO₂ per ton nm of which shipbuilding represented 2%. For RoRo vessels, the speed when minimizing the emissions increased from 7.2 to 8.4 knots when shipbuilding was included in the assessment, adding up to 20.9 ton of CO₂ of which 20% came from shipbuilding. On the other hand, at the design speed of 20.5 knots, the emissions were 38.7 ton CO₂ per ton nm of which shipbuilding constituted 5%.

To summarize, when the focus was to minimize emissions, a speed reductions (compared to the design speed) down to 50% for bulk, 59% for RoRo and 67% for container vessels gave emission reductions of 35%, 46% and 62% for the three vessel types. Minimizing emissions led to cost increases and represents the left border of the Pareto optimal curve, while a minimization of cost, also causing emission reductions, corresponds to the right border. Although emission and cost minimization represents the left and right border values on the Pareto curve, the third point of specific interest was the emission when the cost equaled the design speed level. Here, there occurred an emission reduction with a zero abatement cost. This point was found for the following speeds (with the reductions as compared with the design speed in brackets): 17.7 knots (13%) for RoRo, 12.5 knots (13%) for bulk and 12 knots (52%) for container vessels. The emission reductions were 17% for RoRo, 14% for bulk and 53% for container vessels.

2.5. Results for the global fleet

Table 1 summarizes the bottom-up results for each of the vessel groups to a macro level in order to calculate emissions for the whole world fleet as a function of varying priorities.

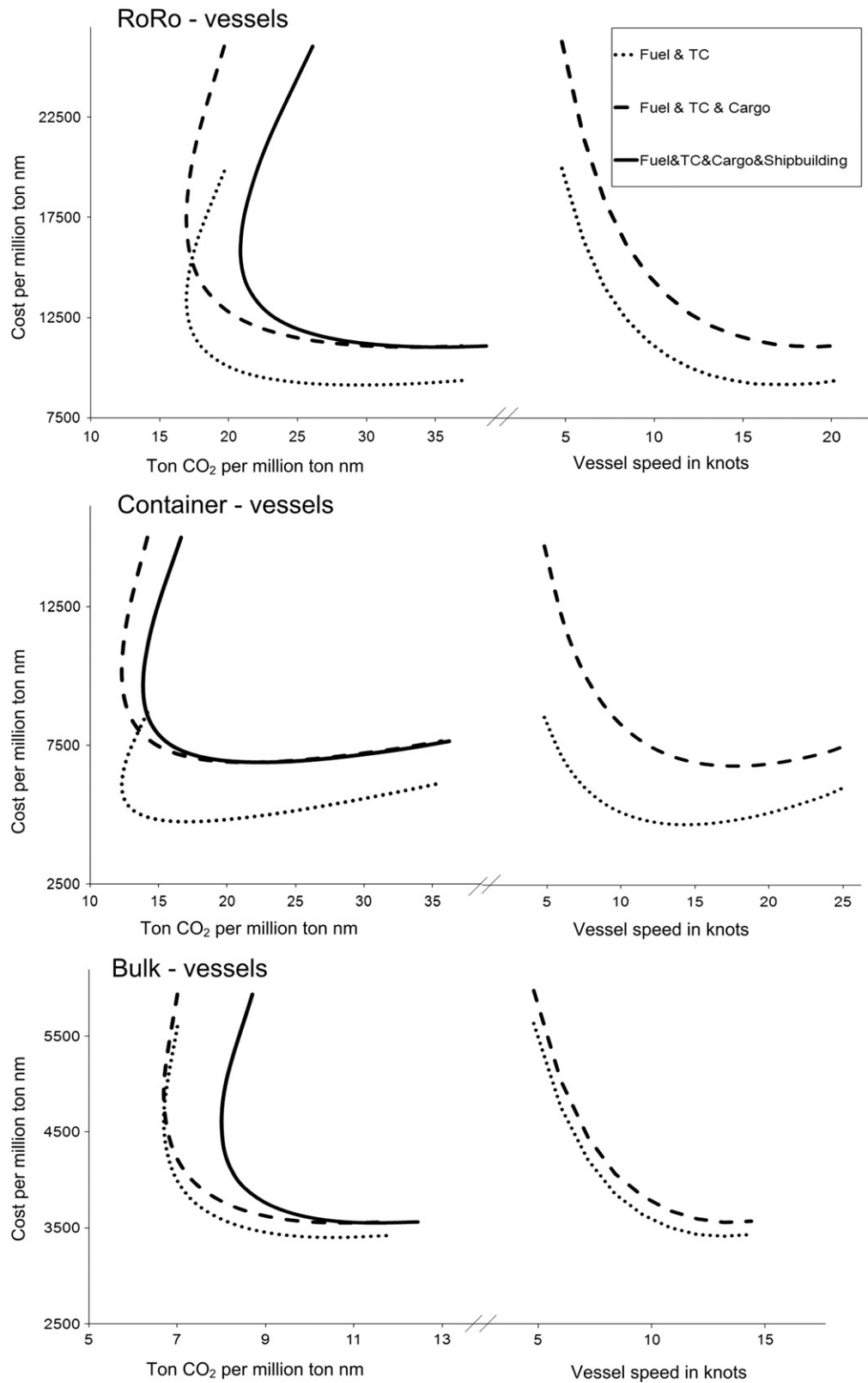


Fig. 1. Emission and cost as a function of vessel speed.

The employed fleet database was the 2007 world fleet as published in the Sea-web database by Lloyds Register Fairplay (now IHS-Fairplay) and the fuel consumption and operational patterns per vessel group were those published by Lindstad and Mørkve (2009).

As can be seen from the table, the world fleet was divided into five groups; RoRo, bulk, container, other cargo vessels and other vessels. The vessel group 'other cargo vessels' includes product and chemical tankers, gas carriers, reefers, general cargo vessels and Ro-Pax vessels which transport both cargo and passengers.

Table 1
Annual emissions as a function of varying priorities.

Vessel type and CO ₂ emission in million tons	Design speed	Minimizing cost	Abatement cost = 0 USD/ton	Abatement cost = 20 USD/ton	Abatement cost = 50 USD/ton	Minimizing CO ₂
RoRo	39	36	33	30	26	21
Container	269	169	118	109	105	103
Bulk	289	259	250	231	215	187
Other cargo vessels	368	286	247	228	213	191
All other vessels	157	157	157	157	157	157
Total	1122	907	804	755	716	659
% of AS IS		81	72	67	64	59

This is a mixed group with vessel speeds ranging from less than the bulkers, to faster than the container vessels, and it was assumed that the emission reduction percentages for the various priorities would correspond to the average of those of RoRo, container and bulk vessels. For other vessels comprising service boats, fishing boats, offshore service vessels, cruise vessels and leisure yachts built for other purposes than cargo transport, constant emissions were assumed.

The table displays that emissions including shipbuilding, when operated at the design speed, are 1120 million ton CO₂ per year of which 76 million tons come from shipbuilding. When the cost is minimized, the emissions are reduced by 19% to 850 million ton with an 8% increase of the fleet. When the focus is changed from cost to emission minimization, four points of interest emerge; emissions minimized under the condition of the cost not exceeding that at the design speed (zero abatement cost), potential emission reductions with an abatement cost of 20 USD/ton, potential emission reduction with an abatement cost of 50 USD/ton and maximizing emission reductions regardless of the abatement cost.

When emissions are minimized for a cost equal to design speed (zero abatement cost), emissions are reduced by 28% to 804 million ton CO₂ with a 19% increase of the fleet. With an abatement cost of 20 USD/ton, the CO₂ emissions can be reduced by 357 million ton, which gives a 33% reduction. If the abatement cost is increased to 50 USD/ton, the emissions can be reduced with 406 million ton of CO₂, corresponding to a 36% reduction. If emission reductions are maximized, the emissions are reduced by 41% to 659 million ton CO₂ with an abatement cost of more than 100 USD/ton CO₂ and a fleet increase of 54%.

3. Discussion and conclusions

The results from the model demonstrated that there is a substantial potential for reducing CO₂ emissions in shipping, since a decrease of 19% can be obtained with a negative abatement cost and since a diminution of 28% would be possible at a zero abatement cost. Achieving minimum emissions of 59% of the current level would lead to cost increases and hence a positive abatement cost based on current prices for fuel and the cost of building new vessels. Since these emission reductions are purely based on lower speeds, as opposed to on new technology, some of them can be achieved straight away. However, in order for the full potential to be realized, more vessels need to be built to maintain the total transport capacity.

3.1. Sensitivity analysis

When comparing the obtained results to data from other studies, they were found to be within a similar range as those presented by Corbet et al. (2009) and Sea at Risk and CE Delft

(2010). If fuel prices increase, the profitable (19%) and free-of-charge (28%) abatement cost options will also increase, whereas they will be lowered with a price reduction on fuel. This statement regarding the fuel price agrees with the results obtained by Corbet et al. (2009), however none of the other studies has focused on this aspect. Based on strict requirements whereby the maximum sulphur content of standard marine fuel oil (HFO) undergoes a step-wise reduction from 3.5% to 0.5% within the next 10 years, marine fuel oil will become more expensive even if oil prices should remain at the current level.

The other main exogenous variable where sensitivity is an issue is the capital cost of the transported goods. In the present analysis, the value of 250 USD/ton was used for bulk commodities to reflect the mix of coal and iron ore at export prices below 100 USD/ton, alumina, fertilizer, grain and other commodities from 150 USD/ton and upwards, and crude oil at 400 USD/ton. It can be argued that the value of 250 USD/ton is both too high and too low, but 13 knots gives the lowest cost for all cargo values between 100 and 400 USD/ton. For the RoRo segment, 5000 USD/ton was used to reflect the combination of new cars in all price ranges, new trucks and heavy machinery with the transport of used cars as well as industrial project cargoes and forest products. One can point out that this value is rather high and if it is reduced by 50% to 2500 USD/ton, 18 knots becomes the speed that gives the lowest cost compared to 19 knots with 5000 USD/ton. Container lines also transport a mix of cargo with a wide range of value per ton, but their operations are frequently analyzed solely on the basis of the high-value goods that are transported. Such an analysis was performed by Psaraftis and Kontovas (2010) who used 30 000 USD/ton. Although the container segment transports products within this price range, it could be argued that a majority of container cargoes presents costs outside it. At the lower end of the container segment can be mentioned cargoes such as paper for recycling and scrap steel, while in the 100–1000 USD/ton range, one finds grain, rice, canned fruits, forest products, steel for manufacturing, ceramic tiles and various other building materials.

It can also be claimed, as was done in this study, that this cargo mix gives an average of 5000 USD or less per ton on a container vessel, and even then, the inventory cost is 20% for a container vessel sailing at the design speed. This value increases to 25% when the speed is reduced from 25 to 18 knots. With a cargo value of 30 000 USD/ton, the capital cost of the goods would be 70% of the total transport cost at the service speed, thereby rendering any speed reductions unprofitable.

We have also considered if port and logistics inefficiencies in general will influence on our conclusions. However, since the assumption is that the total transport volumes are constant, the implication when speed is reduced is that each vessel will do fewer roundtrips and less port calls, but total number of roundtrips and port calls per year will remain unchanged, and speed reductions will then not influence port inefficiencies.

3.2. How to achieve speed reductions

A key issue is how to achieve the speed reductions that will lower emissions. Discussions have already taken place both within UNFCCC and through the Marine Environmental Protection Committee of IMO. The main measures that have been discussed involve an Energy Efficiency Design Index (EEDI) and Market Based Instruments (MBIs) in the form of emissions trading, a fuel levy, or a combination of the two (Lindstad et al., 2010). While the Energy Efficiency Design Index will only reduce emissions from new vessels, which suggests that even after 12–15 years, only half of the fleet will be covered, the Market Based Instruments will have an immediate full effect. The Market Based Instruments are based on the assumption that higher fuel prices will incite operators to reduce speeds, and studies such as that of Corbet et al. (2009) have investigated how the fuel price influences speed decisions taken by the shipping lines, with the conclusion that higher fuel prices result in speed reductions.

The data from the present investigation indicates that things may be more complex and that the impact of fuel prices on speed decisions has been overestimated. Such a statement is based on Pareto solutions – where cost and emissions are optimized – being found for speeds below current service speeds (reference level). From the shipping markets, it is also well known that in a good market, ship-owners will tend to operate at full speed in order to maximize income at both high and low fuel prices. Reduced speeds, on the other hand, are used to save costs and reduce available capacities in a depressed market. The above could indicate that it may be important to understand ship-owners' preferences, as well as those of their customers, in order to enable speed reductions.

It could be an option to introduce utility theory to handle such complex relationships. In economics, utility is a measure of relative satisfaction and in logistics place utility is used for the relative satisfaction of having the right products at the right places at the right time. One objective of introducing utility theory would be to model the relative value of shorter transport times, in order to obtain a better understanding of the price premium that customers would be willing to pay for maintaining short lead times based on fast transport. An alternative approach to using utility theory could be to model the relative value of transport time based on a survey. Even if the focus in this study has been on the cost, the additional cost given by speeds that exceed the speed which gives the lowest cost can be seen as the price premium currently paid by customers to maintain short lead times. In a study carried out for IMO Anger et al. (2010) argued that the willingness to pay for short lead times was high, and their conclusion was that the increase in fuel price due to Market Based Instruments would have to be 800% in order to stabilize emissions at the current level, given the expected growth in world trade until 2050.

We believe that Market Based Instruments at this level would probably be unacceptable, since they – even if they contribute to the required reduction in shipping – might well result in undesired increases in emissions due to a reduction of trade transactions based on comparative advantages, including access to raw materials, a skilled work-force, capital and a competitive cost level, but also the ability to exploit renewable energy sources (Duchin, 2005; Strømman and Duchin, 2006; Strømman et al., 2008). On this basis, the conclusion would be that while high Market Based Instruments would undoubtedly reduce fuel oil consumption in shipping, a major shortcoming is that this is a mechanism that does not distinguish between trade transactions contributing to lower emissions and those that do not.

Another option could be speed reductions enforced through speed limits. This is a measure used worldwide for road transport

to reduce accidents and energy consumption, but a maritime application has not been among the main measures considered by IMO for greenhouse gas reductions. Speeds limits can be implemented as absolute limits not to be exceeded at any point during the sailing, or as an average speed limit measured between waypoints in ports of departure and arrival through existing identification and tracking system (AIS) technologies.

Introducing speed limits would reduce the transport work performed by the sailing fleet of vessels. To uphold the given transport work capacity in the market, the absolute fleet of vessels would have to be increased accordingly, as shown in Table 1. This signifies that the speed limits will have to be gradually lowered to enable the shipyards to add the extra capacity needed. However, parts of this extra capacity needed to enable speed reductions are already in place due the current oversupply of vessels (Sea at Risk and CE Delft, 2010).

Further, speed limits may affect supply chains, competition in the shipping market, and safety. For the supply chains, it has been claimed that lower speeds will require changes in the supply chains which would be deemed unacceptable by cargo owners and their customers. However, such changes appear to have been successfully implemented to accommodate slow steaming (lower speeds) during the current recession. An explanation could be that while supply chain management in general focuses on reducing total lead times and maximizing utility, it also renders it possible to make the required adjustment to any changes, such as longer transport times. From the point of view of competitiveness in the sea transport markets, speed limits could introduce changes to the market playing field as known today. This is a point where a broad and deep discussion is required, and we are not able to fully cover this in the present paper.

An initial question is whether a speed limit should be set as one fixed limit for all vessels, or differentiated. A 'one speed for all vessels' scheme might be an 'easy way out', but it will also have challenges. In order for a one-limit scheme to lead to reductions for all vessel types the speed will have to be reduced down to 8–12 knots which might double the transport times of general cargo. On the other hand, one challenge with differentiated speed limits is that the current classification of vessels is made based on cargo handling systems and not on the cargo they transport. This means that the RoRo, container and open hatch vessels, which cover the speed range from 16 to 25 knots, and transport what may be termed 'general cargo', are classified differently. Feasible ways to handle differentiated speed limits such as 18 knots for passengers, 14 knots for general cargo and 10 knots for bulk products could be to decide that the speed limit is given for each voyage by the main cargo types on the vessel. An alternative solution could be to make 10 knots the general limit and enforce a significant fuel levy per knot above 10 knots to allow faster sailings up to the maximum speed allowed. Introducing speed limits should also give a positive contribution to safety, since the measure will contribute to speed reductions in congested fairways. Any scheme for speed limits should however not disable vessels from being built with a power and propulsion system which gives speed reserves needed for escaping pirates and maintaining complete control in harsh weather.

As a conclusion, this study has demonstrated that emissions from shipping can be reduced from 1122 million ton CO₂ per year to 804 million ton CO₂, which corresponds to a 28% reduction at zero abatement cost, by lowering speeds. If the abatement cost is increased, the emission reduction potential is raised to 33% with 20 USD/ton CO₂ and to 36% with 50 USD/ton CO₂. Since these reductions are purely based on lower speeds, they can in part be performed straight away and it is our judgment that limits are the best means of bringing down speeds to the desired levels for all ship types.

Acknowledgments

We are grateful to Egil Jullumstrø, naval architect and hydrodynamic expert in MARINTEK, for his contribution with valuable comments regarding power requirements when vessels operate at speeds below service speeds. Many thanks also to Christopher Paalson, senior consultant and manager of IHS Fairplay, for contributing with new building costs for vessels and their daily time charter equivalents.

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