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Overview Paper

Speed models for energy-efficient maritime transportation: A taxonomy and survey

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ABSTRACT

International shipping accounts for 2.7% of worldwide CO_2 emissions, and measures to curb future emissions growth are sought with a high sense of urgency. With the increased quest for greener shipping, reducing the speed of ships has obtained an increased role as one of the measures to be applied toward that end. Already speed has been important for economic reasons, as it is a key determinant of fuel cost, a significant component of the operating cost of ships. Moreover, speed is an important parameter of the overall logistical operation of a shipping company and of the overall supply chain and may directly or indirectly impact fleet size, ship size, cargo inventory costs and shippers' balance sheets. Changes in ship speed may also induce modal shifts, if cargo can choose other modes because they are faster. However, as emissions are directly proportional to fuel consumed, speed is also very much connected with the environmental dimension of shipping. So when shipping markets are in a depressed state and "slow-steaming" is the prevalent practice for economic reasons, an important side benefit is reduced emissions. In fact there are many indications that this practice, very much applied these days, will be the norm in the future. This paper presents a survey of speed models in maritime transportation, that is, models in which speed is one of the decision variables. A taxonomy of such models is also presented, according to a set of parameters.

1. Introduction

1.1. Background

Speed is a key variable in maritime transportation. Ships travel slower than the other modes, but a basic premise is that there is value in ship speed. As long-distance trips may typically last 1–2 months, the benefits of a higher speed may be significant: they mainly entail the economic added value of faster delivery of goods, lower inventory costs and increased trade throughput per unit time. The need for higher speeds in shipping was mainly spurred by strong growth in world trade and development, and in turn was made possible by significant technological advances in maritime transportation in a broad spectrum of areas, including hull design, hydrodynamic performance of vessels, engine and propulsion efficiency, to name just a few. By extension, developments in cargo handling systems and supply chain management and operation have also contributed significantly to fast door-to-door transportation.

However, increasing fuel prices, depressed market conditions and environmental issues as regards air emissions from ships have brought a new perspective to ship speed. If this perspective had not received much emphasis in the past, this is not so today, and it will receive even more attention in the future. Simply stated, for a variety of reasons, economic

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and environmental, sailing fast may not necessarily be the best choice, and optimizing ship speed is receiving increased emphasis these days and is likely to do so in the years ahead.

Perhaps the most significant factor that is making a difference in recent years is the environmental one: a ship has to be environmentally friendly as regards air emissions. This general goal is true for all ships. But it is even more so for high-speed ships, because of the non-linear relationship between speed and fuel consumption. It is obvious that a ship that goes slower will emit much less than the same ship going faster.

Gases emitted from ships can be classified into several categories. Green House Gases (GHGs) include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), among others. Non-Green House Gases include mainly sulphur oxides (SO_x) and nitrogen oxides (NO_x). Various other pollutants, such as particulate matter (PM), volatile organic compounds (VOC), black carbon, and others, are also emitted. The effects of all of the above gases on global climate are diverse and most are considered negative if not kept under control. Among other effects, GHGs contribute to global warming, SO_x cause acid rain and deforestation, and NO_x cause undesirable health effects.

As early as in 1997 in Kyoto, the United Nations Framework Conference on Climate Change (UNFCCC) has designated the International Maritime Organization (IMO), the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine pollution by ships, as the body responsible for regulating maritime air emissions. However, progress on that front has generally been slow. In 2008, the Marine Environment Protection Committee (MEPC) of the IMO adopted amendments to the MARPOL Annex VI regulations that deal with SO_x and NO_x emissions. But on the GHG front, and in spite of much discussion, shipping is still not being included in the UNFCCC global emissions reduction target for CO_2 and other GHGs, and in fact until very recently, shipping was the only mode of transport for which GHG emissions were not regulated. The era of non-regulation for shipping GHGs officially came to an end in July 2011, when, after considerable debate and fierce opposition from developing countries, the MEPC adopted the Energy Efficiency Design Index (EEDI) for new ships. Even so, further measures to curb future GHG growth in shipping are being sought with a high sense of urgency.

Already in 2008 the IMO had designated the Baltic Sea, the North Sea and the English Channel as ‘Sulphur Emissions Control Areas’ (SECAs), with the purpose of limiting SO_x emissions, and in 2010 the IMO designated the entire US–Canadian coastal zone as an ‘Emissions Control Area’ (ECA), with 2012 as kick off year and (at least at this stage) ambitious goals to reduce SO_x, NO_x, and PM emissions. Last but not least, in Europe the 2011 White Paper on Transport (EU, 2011) has set, among other things, very ambitious ‘decarbonization’ goals, with a stipulated 60% reduction in transport GHG emissions by year 2050.

1.2. The importance of speed

According to the 2009 GHG study by the IMO (IMO, 2009), international shipping contributes 2.7% of the CO_2 emitted globally. Fig. 1 shows the distribution of global CO_2 emissions, from which it can also be seen that the top CO_2 producer is electricity and heat production (35%) and the top CO_2 transport mode is road (21.3%).

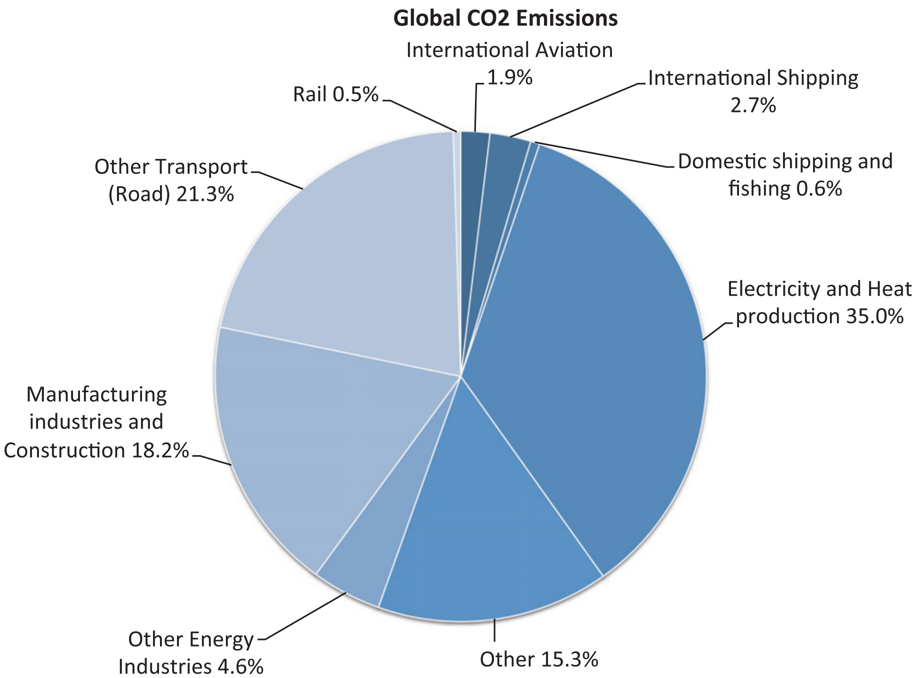


Fig. 1. Emissions of CO_2 from shipping compared with global total emissions for 2007. Adapted from IMO (2009).

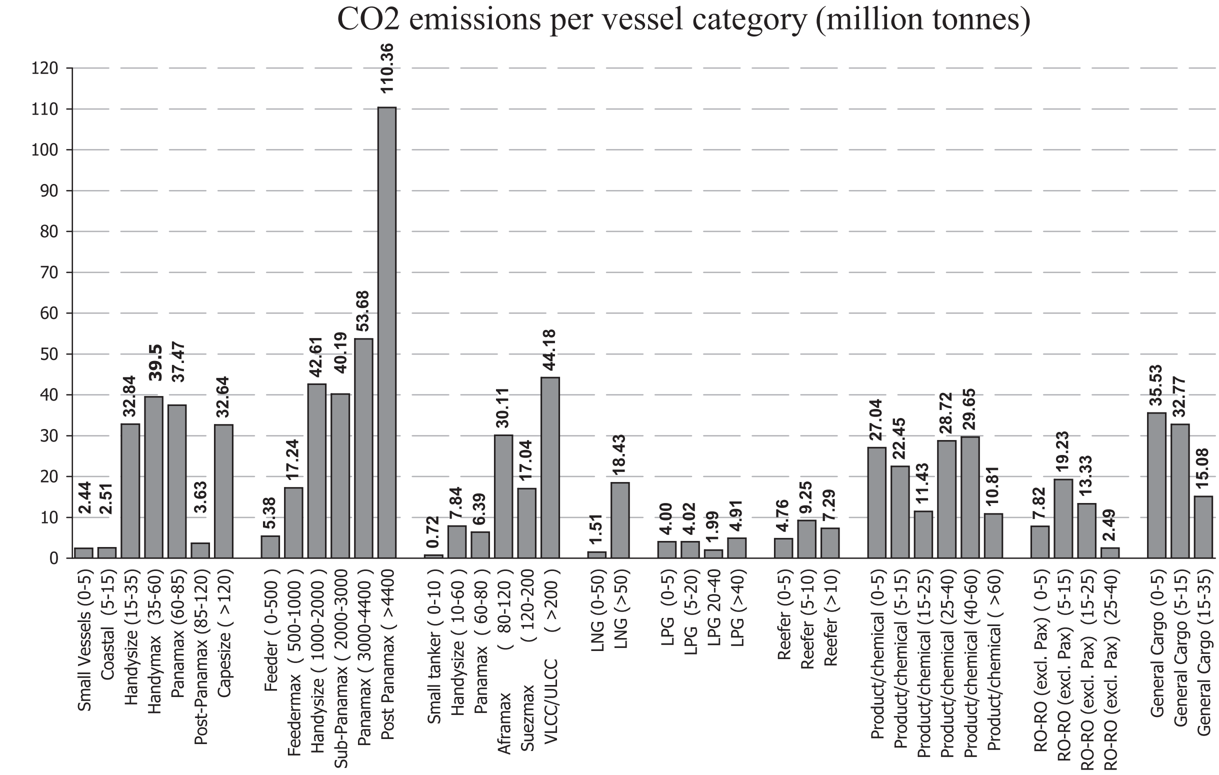


Fig. 2. CO_2 emissions, world fleet, 2007. *Source*: Psaraftis and Kontovas (2009a)

According to the same study, the total quantity of CO_2 emitted is 870 million tonnes for international shipping and 1050 million tonnes for all shipping (2007 fleet data).

The importance of ship speed on GHG emissions can be seen in Fig. 2, which breaks down CO_2 emissions from the world commercial fleet by ship type-size combination (Psaraftis and Kontovas, 2009a). The data is from the IHS Fairplay database and the base year is 2007 (45,620 commercial ships accounted for).

According to this analysis, containerships are the top CO_2 emitters in the world fleet. This is perhaps something to be expected, given the relatively high speeds of these vessels (20–26 knots) as opposed to those carrying bulk cargoes (13–15 knots) and given the nonlinear relationship between speed and fuel consumption and hence emissions. What is perhaps not so obvious to expect is that just the top tier category of container vessels (712 vessels of 4400 TEU[1] and above) are seen to produce 110.36 million tonnes of CO_2 emissions, which is higher than the 106 million tonnes produced by the entire crude oil tanker fleet (2028 vessels). This means that if ship speed were to be reduced, perhaps uniformly across the board, or even selectively for some categories of vessels, emissions would be reduced too, perhaps drastically. Reducing speed could also have important side benefits: cost reduction is one, and helping a depressed market in which shipping overcapacity is the norm these days is another. In that sense, reducing ship speed may conceivably be a 'win–win' proposition.

At the same time, reducing speed may have other ramifications which may not be beneficial. For instance, in the long run more ships will be needed to produce the same transport throughput, and this will entail some costs, some of them financial and some environmental (emissions due to shipbuilding, recycling, etc.). Also, cargo in-transit inventory costs will generally increase, due to the increased transit time of the cargo. These inventory costs are proportional to the value of the cargo, so if a ship hauls high-value goods, sailing at a lower speed may entail significant costs to the shipper.

Another side effect of speed reduction is that in the short run, freight rates will go up once the overall transport supply shrinks because of slower speeds. Reducing speed may help a depressed market, but it is the shippers who will suffer and in fact they will do so in two ways: they will pay more, and receive their cargo later.

Yet another possible side effect concerns effects that speed reduction may have on other modes of transport, to the extent these are alternatives to sea transport. This is the situation as regards many short sea trades, in Europe but also in North America. If ships are made to go slower, shippers may be induced to prefer land-based transport alternatives, mostly road, and that may increase overall GHG emissions, as road is certainly worse than maritime in terms of GHG emissions per tonne-km.

[1] Twenty Foot Equivalent, the dimension of a $8 \times 8 \times 20$ ft container.

All of the above issues, which have become more important in recent years, necessitate taking stock at models, studies or other research in which ship speed is a decision variable, irrespective or not if there is an 'emissions' dimension considered. Even though the number of such references is relatively small, it has recently grown and there are a number of relevant papers that are worthy of note. To our knowledge, there has not yet been a focused survey of such papers. This paper makes an attempt to conduct such a survey, and takes also the opportunity to report relevant recent developments, present some basics, clarify possible misconceptions, and develop a taxonomy of relevant models.

1.3. Ship speed at two levels

If the objective is to reduce emissions by reducing speed, this can be done at two levels. The first level is technological (strategic), that is, build future ships with reduced installed horsepower so that they cannot sail faster than a prescribed speed.

Even though this is not the main thrust of this paper, a few words on this level are in order: designing ships of significantly lower operating speeds seems to be a projected trend that may be the norm for the future, especially for containerships. The first cellular containerships that went up to 33 knots in the late 1960s, when fuel was cheap, are gone forever. The current trend is that the current regime of 24–26 knots maximum speed would be reduced to something like 21–22 knots, and some trades may even go as low as 15–18 knots, according to a 2006 study by Lloyds Register (Lloyds List, 2008). The new 18,000 TEU 'triple E' boxships that Maersk has ordered will have design speeds that are lower than the current (19 knots versus 25.5 for the 'Emma Maersk') and are claimed that they will operate at fuel consumption of 50% less than the industry average and 20% better than the existing best. EU-funded research project "Ulysses," whose logo is, conveniently enough, a snail, aims at designing tankers and bulk carriers that can sail as slow as 5 knots (Ulysses, 2012).

The second level is logistics-based (tactical/operational), that is, have an existing ship go slower than its design speed. In shipping parlance this is known as "slow steaming" and may involve just slowing down or even 'derating' a ship's engine, that is, reconfiguring the engine so that a lower power output is achieved, so that even slower speeds can be attained.[2] Depending on engine technology, 'slow steaming kits' are provided by engine manufacturers so that ships can smoothly reduce speed at any desired level. In case speed is drastically reduced, the practice is known as "super slow steaming".

In practice, super slow steaming has been pioneered by Maersk Line after it initiated trials involving 110 vessels beginning in 2007. Maersk Line North Asia Region CEO Tim Smith said that the trials showed it was safe to reduce the engine load to as low as 10%, compared with the traditional policy of reducing the load to no less than 40–60% (TradeWinds, 2009). Given the non-linear relationship between speed and power, for a containership a 10% engine load means sailing at about half of the design speed. Furthermore, China Ocean Shipping (Group) and its partners in the CKYH alliance (K Line, Yang Ming Marine and Hanjin Shipping) were also reported to introduce super-slow steaming on certain routes (Lloyd's List, 2009).

Slow steaming is not only practiced in the container market, although it may seem to make more sense there due to the higher speeds of containerships. Slow steaming is reported in every market. In December 2010, Maersk Tankers was reported to have their Very Large Crude Carriers (VLCCs) sailing at half their speed. The design speed of 16 knots was reduced to speeds less than 10 knots on almost one third of its ballast legs and between 11 and 13 knots on over one third of its operating days. For example, a typical voyage from the Persian Gulf to Asia normally takes 42 days (at 15 knots laden and 16 knots in ballast). Maersk Tankers decreased speed to 8.5 knots on the ballast leg, thus increasing roundtrip time to 55 days and saving nearly $400,000 off the voyage's bunker bill (TradeWinds, 2010).

As said earlier, this paper mainly surveys models in which ship speed is a decision variable at the tactical/operational level. These models come mainly from the Operations Research and Maritime Economics literatures, and, as such, are not necessarily homogeneous in scope and approach. One thing they have in common is the incorporation of speed and the study of the impact of changes of speed on various attributes of the operation, including emissions.

The rest of this paper is structured as follows. Section 2 presents some basics. Section 3 goes over relevant literature and presents a taxonomy of models. Section 4 presents the conclusions and discusses prospects for the future.

2. Basics

2.1. Ship speed as an input or as a decision variable

Most of the models found in the maritime transportation literature (see Christiansen et al. (2007) for a comprehensive survey) assume fixed and known speeds for the ships. See for instance Rana and Vickson (1991), Agarwal and Ergun (2008), Hwang et al. (2008), Grønhaug et al. (2010) and Song and Xu (2012a,b), among others. In these models, ship speed is typically considered as an *implicit input* to the problem, implicit in the sense that it is used to compute various other *explicit inputs* that depend on speed. Inter-port sailing times, due dates for cargo pickup and delivery, and ship operating costs, of which fuel costs are an important component, are the most important of these explicit inputs. Regarding fuel costs, it is well known from basic naval architecture that there is a non-linear relationship between ship speed and fuel consumption, so the impact of a change in ship speed on ship operating costs can be quite dramatic (more on this later).

[2] Such a reconfiguration may involve dropping a cylinder from the main engine or other measures.

By virtue of the fact that speed is not an explicit input in such models, its potential impact on the outputs of these models can only be considered indirectly, to the extent that various solutions can be contemplated if the speed input (and, as a result, all model inputs that depend on speed) take on different values. The same is true as regards sensitivity or other parametric analyses. A fortiori, if speed is not a decision variable, selecting optimal speed via such models can only be done in a similar oblique way, which can be quite cumbersome as there may be more than one speed to be optimized (per ship, per leg of route, etc.).

Not including speed as a decision variable may in some cases remove flexibility in the overall decision making process and render fixed-speed solutions subobtimal. For instance, a ship sailing at a prescribed speed to a certain port, only to have to wait there because the port is congested, may be a higher cost solution than one in which the ship is allowed to sail at a lower speed so as to arrive when the port is not congested any more. Overall emissions would be higher in that case as well. There are several models in the literature that include port capacity constraints, berth occupancy constraints, time window constraints or other constraints that preclude the simultaneous service of more than a given number of vessels (see, for instance, Cordeau et al. (2005) and Halvorsen-Weare and Fagerholt (2010), among others). Such constraints would conceivably be easier to meet were it not for the assumed constancy in ship speed, the latter typically being considered an exogenous parameter implicitly or explicitly affecting some of the problem's variables such as ships' arrival times.

Assuming fixed ship speeds is typically also the case for models that compute shipping emissions worldwide. See for instance Psaraftis and Kontovas (2009a) and IMO (2009), among others. In their calculations, these models typically take as input *design speeds* extracted from commercially available ship databases, such as those maintained by IHS Fairplay, among others. Ship speed information in such databases is for speeds corresponding to 100% Maximum Continuous Rating (MCR), a ship's maximum power, although the quality of such information is questionable as this data is typically provided by ship owners, with no serious certification mechanism behind the process. There is no optimization involved in most of these models, but as their impact for policy-making purposes is important, any misrepresentation of speed, and, as a result, of implied total fuel consumption and hence emissions, may very well have ramifications as regards the policies that should be pursued for the reduction of emissions from ships.

2.2. Fuel consumption functions

As stated earlier, fuel consumption (and hence fuel costs and emissions) depend non-linearly on ship sailing speed. The simplest model is to assume one type of fuel consumed on the ship, available at a known price of p (in \$/tonne). Then the daily *at sea* fuel cost of a ship sailing from port i to port j is equal to $pf(v_{ij},w_{ij})t_{ij,}$ where $f(v_{ij}, w_{ij})$ is the ship's daily fuel consumption at sea (in tonnes/day), a known function of the ship's speed v_{ij} and payload w_{ij} from i to j, and t_{ij} is the ship's sailing time from i to j, given by the ratio (d_{ij}/v_{ij}), sailing distance divided by speed. Function f depends on many ship parameters, such as type and size of power plant, including main and auxiliary engines, geometry of ship hull, propeller design, and other parameters (weather conditions for instance). It can even be defined for $w_{ij} = 0$ (ship going on ballast). *In port* fuel costs are proportional to overall total port residence time, and these depend on per day fuel consumption of the ship's auxiliary engines while in port. In case the ship uses different fuels for its main engine and auxiliary engines (for instance Heavy Fuel Oil – HFO and Marine Diesel Oil – MDO, respectively), total fuel cost is the summation of all relevant fuel types.

The fact that function f can be a complex function which may not even be defined in closed form does not prevent us from considering some modeling approximations. A usual approximation is that function f is equal to $A + Bv_{ij}^n$ with A, B and n input parameters such as $A \geqslant 0$, $B > 0$ and $n \geqslant 3$. Another approximation is that for a given speed, f is proportional to $(w_{ij} + L)^{2/3}$, where L is the weight of the ship if empty plus fuel on board and consumables (modified admiralty formula, see also Barrass (2005)).[3] A combination of these two approximations can also be considered. Most papers in the literature assume a cubic function, that is, $A = 0$ and $n = 3$ and no dependency on payload. $n = 3$ is usually a good approximation for tankers and bulk carriers and for the range of typical operational speeds of these vessels. A basic drawback of a cubic function is that it is invalid for very low speeds. In fact this function gives zero fuel consumption at zero speed, which is not the case in practice, as a ship, even stationary, consumes some fuel. Another drawback of a cubic function is that it may not be a good approximation for some ship types, containerships being the most notable example. For these ships, exponent n can be 4 or 5 or conceivably even higher.

Fig. 3 shows two typical fuel consumption curves for a VLCC, one for the laden condition and one for the ballast condition. Consumption of auxiliary engines is included. The functions in the figure are general and based on real data. Notice also that the curves are not defined below some minimum speed levels (on which more later).

2.3. Emissions coefficients

CO_2 produced is proportional to fuel burned, with the proportionality constant being known as the 'carbon coefficient'. The old IMO GHG study of 2000 used a coefficient of 3.17 (tonnes of CO_2 per tonne of fuel) independent of fuel type, but its 2009 update (IMO, 2009) used slightly lower coefficients, which ranged from 3.021 for HFO to 3.082 for MDO. For alternative fuels such as Liquefied Natural Gas (LNG), the carbon coefficient can range from 2.6 to 2.8. This feature makes LNG

[3] A first order approximation is that f does not take into account the reduction in the ship's total displacement due to fuel, lubricating oil or other consumables (such as fresh water) being consumed along the ship's route, since displacement would not change much as a result of that consumption.

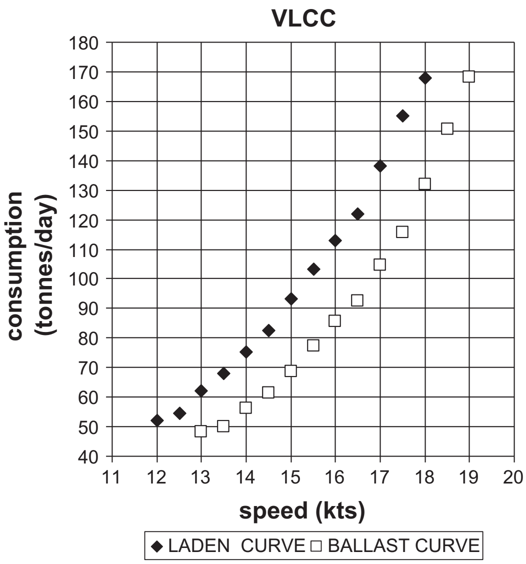


Fig. 3. Fuel consumption versus speed (in knots) for a VLCC. *Source*: Gkonis and Psaraftis (2012).

more attractive than fossil fuels for propulsion, among other advantages, such as lack of sulphur and other substances and producing more energy per unit weight than fossil fuels.

Equally linear is the relationship between SO_2 emissions and fuel burned, with the coefficient depending on the type of fuel. One simply has to multiply total bunker consumption (in tonnes per day) by the percentage of sulphur present in the fuel (for instance, 4%, 1.5%, 0.5%, or other) and subsequently by a factor of 0.02 to compute SO_2 emissions (in tonnes per day).[4]

NO_x emissions depend on engine type. The ratio of NO_x emissions to fuel consumed ranges from 0.087 for slow speed engines to 0.057 for medium speed engines.

2.4. Who is the speed optimizer and what is being optimized

There are other reasons for which fixed-speed models may not map reality in a satisfactory way. Ships simply do not trade at predetermined speeds. Those who pay for the fuel, that is, a ship owner whose ship trades on the spot market, or a charterer if the ship is on time charter, may want to choose the ship speed as a function of (a) fuel price and (b) market spot rate. In periods of depressed market conditions, as is the typical situation these days, ships tend to slow steam. The same is the case if bunker prices are high. Conversely, in boom periods or in case fuel prices are low, ships tend to sail faster.

An exception to the case that the ship owner or the charterer can freely choose an optimal speed for the ship is in case the ship is *on spot charter* and speed is prescribed in the charter party contract, either explicitly (speed is, say, 15 knots) or implicitly (pickup and delivery dates are prescribed). In spot charters (rental of the ship for a single voyage) the fuel is paid for by the ship owner. Agreeing on a prescribed speed in the charter party involves in most cases only the laden part of the trip, with the owner free to choose his speed on the ballast return leg. The speed that is agreed upon for the laden leg may or may not be the speed that the ship owner would have freely chosen if no explicit agreement were in place. If it is higher, the ship owner may ask for a higher rate than the prevailing spot rate, understanding of course that in this case he may lose the customer to a competitor ship, with which the charterer can obtain more favorable terms. For a discussion of possible distortions and additional emissions that can be caused by charter party speed agreements see Devanney (2011).

What is perhaps not immediately obvious is that even though the owner's and time charterer's speed optimization problems appear at first glance different, the optimal ship speed for both problems turns out to be the same. A proof is in Devanney (2010) for a rudimentary scenario of a ship hauling cargo from port 1 to port 2 and returning to port 1 on ballast (empty), and goes roughly as follows.

For a given ship, a ship owner in the spot market should operate at a speed that maximizes profit per day. Then his speed optimization problem is the following:

$$max_v\{sC/(d/v) - pf(v) - E\} \tag{1}$$

where s is the spot rate received by the owner (in \$/tonne), C is the ship's cargo capacity (in tonnes), d is the roundtrip distance (in nautical miles), v is the sailing speed in nautical miles per day,[5] p is the bunker price (in \$/tonne), $f(v)$ is the daily fuel

[4] The 0.02 SO_2 factor is exact and comes from the chemical reaction of sulphur and oxygen to produce SO_2.

[5] This is 24 times the speed in knots. We use this unit to avoid carrying the number 24 through the calculations.

consumption function at speed v (tonnes/day) and E are the operating expenses borne by the ship owner other than fuel costs, including crew wages, insurance, etc. (in $/day).

In the above scenario, time in port has been ignored, although including it is a straightforward extension. Also the function $f(v)$ is assumed to be the same in both directions (laden and ballast), although having different functions and different speeds on each leg is also a straightforward extension.

For a time charterer who has chartered the same ship, and who is the effective owner of the vessel during the period of the contract (also known in shipping parlance as the "disponent owner"), he faces the following problem:

$$min_v\{s[R - Cv/d] + pf(v) + T\} \tag{2}$$

where R is how much cargo needs to be moved (tonnes/day) and T is the time charter rate paid to the owner ($/day)

Eq. (2) above assumes that any difference between the cargo capacity required by the time charterer (R) and what the chartered ship can provide if sailing at speed v (Cv/d) can be chartered in the spot market at a spot rate of s. If the difference $[R - Cv/d]$ is positive (meaning that the chartered ship sailing at speed v cannot fully satisfy the charterer's needs), then additional capacity is chartered in at a rate of s, assuming the spot chartered ship sailing at the same speed v. If this difference is negative (meaning that there is spare capacity in the time chartered ship), then that spare capacity can be chartered out at the same spot rate s.

What is the difference between problems (1) and (2)?

In fact, in (1) the term E does not depend on speed and can be discarded from the objective function, leading to

$$max_v\{sC/(d/v) - pf(v)\} \tag{3}$$

In (2), one can separate the term ($sR + T$) which does not depend on speed and thus can be discarded as well. What is then left is

$$min_v\{pf(v) - sCv/d\} \tag{4}$$

It is easy to see that problems (3) and (4) are essentially the same, thus leading to the same optimal speed.

Factoring out the spot rate s, both problems can be rewritten as follows:

$$min_v\{(p/s)f(v) - Cv/d\} \tag{5}$$

Eq. (5) shows that for both problems, a key determinant parameter of the speed optimization problem is the *nondimensional ratio* $\rho = p/s$ of the bunker price divided by the spot rate, since for a given ship and route the optimal speed will be the same as long as ρ remains constant. Higher ρ ratios will generally induce lower speeds than lower ρ ratios. This corresponds to the typical behavior of shipping lines, which tend to slow steam in periods of depressed market conditions and/or high fuel prices and go faster if the opposite is the case.

Fig. 4 shows a typical evolution of p, s and ρ for the tanker market. The period is 2010–2010, the route is Persian Gulf to Japan. HFO is the fuel and the fuel supplier is in the Persian Gulf.

It can be seen that strong fluctuations can be expected in these parameters, particularly in the spot rate. For instance, for the above period the ratio ρ fluctuates from a low of about 20 (January 2009) to a high almost three times as much, only 8 months later. Ship owners and charterers have not been observed to be as responsive in their speed adjustments as the month-to-month fluctuations of this ratio would suggest, but certainly one can see that this ratio is anything but constant.

Taking this one step further, if we assume a fuel consumption function of the form $f(v) = A + Bv^n$ and set the derivative of the expression in brackets of (5) with respect to v equal to zero, we get

$$v_0 = \{C/n\rho dB\}^{1/(n-1)} \tag{6}$$

Assuming v_0 is within the range of allowable speeds (of which more below), for two distinct ratios ρ_1 and ρ_2 corresponding to optimal speeds v_{01} and v_{02}, it is

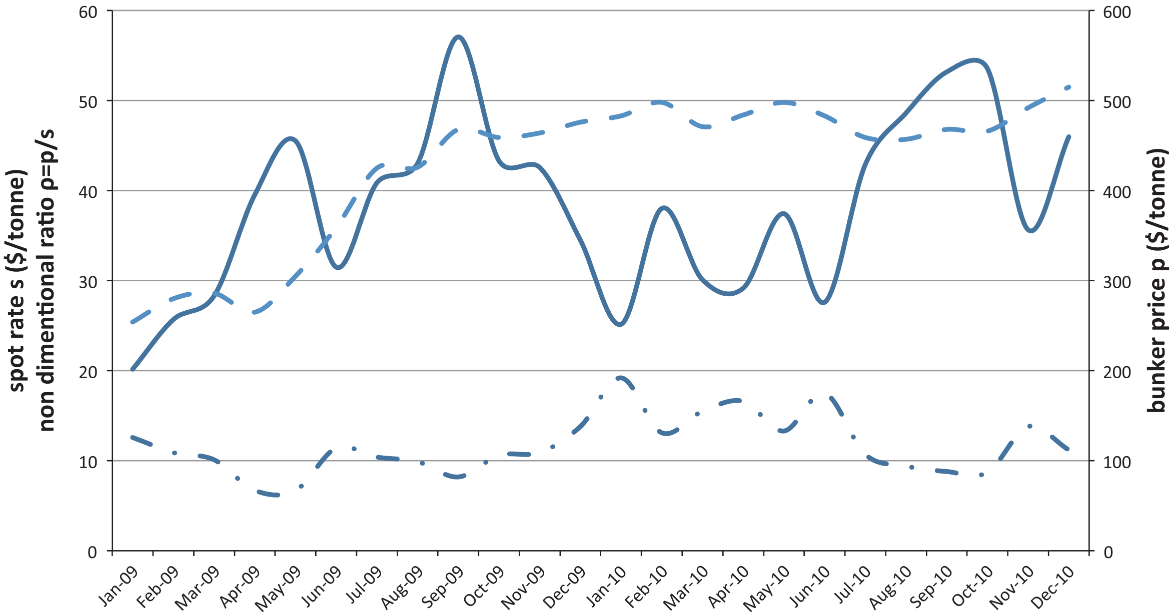
$$(v_{02}/v_{01}) = (\rho_1/\rho_2)^{1/(n-1)} \tag{7}$$

Table 1 calculates the ratio (v_{02}/v_{01}) for several values of the ratio (ρ_1/ρ_2) and n. It can be interpreted as the degree of slow steaming as a function of variations of the ρ ratio and the exponent n of the fuel consumption curve.

According to this model, it can be seen that ships that have a higher exponent n (these are likely to be containerships) would have a tendency to slow steam proportionally less than bulkers and tankers for the same variations in ρ.

2.5. Impact of inventory costs

More elaborate speed models can be developed. For instance, problem (2) does not include inventory costs of cargo, to be borne by the charterer and due to the fact that the cargo is in transit for $d/2v$ days (again, d is the roundtrip distance and cargo travels only one way). These costs depend on transit time and hence on speed, a lower speed entailing higher such costs. If these costs are not already factored in the negotiated market spot rate s, they are equal to $\beta C/2$ ($/day) if β is the per day and per tonne inventory cost of the cargo. The latter is equal to Pr/365 if P is the CIF value of the cargo in $/tonne and r is the charterer's cost of capital.



	Jan-09	Feb-09	Mar-09	Apr-09	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10	May-10	Jun-10	Jul-10	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10
s ($/tonne)	12.6	10.9	10.1	6.7	6.7	11.4	10.4	9.9	8.2	10.6	10.9	13.8	19.2	13.1	15.5	16.6	13.3	17.5	10.7	9.4	8.8	8.7	13.8	11.2
ρ=p/s	20.16	25.69	28.32	39.55	45.52	31.49	40.87	43.03	57.07	43.3	42.57	34.49	25.16	38.02	30.09	29.16	37.44	27.6	42.9	48.62	53.18	53.56	35.65	45.98
p ($/tonne)	254	280	286	265	305	359	425	426	468	459	464	476	483	498	471	484	498	483	459	457	468	466	492	515

Fig. 4. Evolution of bunker price p, spot rate s and their ratio $\rho = p/s$. Data Source: Drewry's Shipping Economist (2009–2010).

Table 1
Ratio (v_{02}/v_{01}) versus (ρ_1/ρ_2) and exponent n.

ρ_1/ρ_2	$n = 3$	$n = 4$	$n = 5$
1/1	1.00	1.00	1.00
1/2	0.71	0.79	0.84
1/3	0.58	0.69	0.76
1/4	0.50	0.63	0.71

Cargo inventory costs can be important, mainly in the liner business which involves trades of higher valued goods than bulk trades. The unit value of the top 20 containerized imports at the Los Angeles and Long Beach Ports in 2004 varied from about $14,000/tonne for furniture and bedding to $95,000/tonne for optic, photographic and medical instruments (CBO, 2006). Delaying one tonne of the latter category of cargo by one week because of reduced speed would cost some $91 if the cost of capital is 5%. For a $75,000/tonne payload this would amount to some $6.8 million. This may or may not be greater than the reduction of cost due to reduced speed (see Kontovas and Psaraftis (2011) for some examples).

It is straightforward to check that if inventory costs are included, Eq. (4) can be modified by replacing the spot rate s by $(s - \beta d/2v)$. This problem is tantamount to the owner's problem (3) if the spot rate s is replaced by $(s - \beta d/2v)$, if in fact cargo inventory costs are not factored in when the ship owner negotiates the spot charter with the charterer.

We mention these rudimentary problems because many models that we have reviewed assume (explicitly or implicitly) a fixed revenue for the ship owner and hence ignore the first term in (3). This is typically the case for routing and scheduling models in which the set of cargoes is fixed. If the amount of cargo to be transported in a year or within a given time period is fixed, then the ship owner's revenue is also fixed and then obviously the speed optimization problem of the ship owner is a cost minimization problem, subject to the constraint that this fixed quantity of cargo should be hauled. However, a ship owner may like to take advantage of high spot rates by hauling as much cargo as possible within a given period of time. In that case, the set of cargoes is not fixed. Conversely, if the market is low, ships tend to slow steam, as the additional revenue from hauling more cargo is less than the additional cost of the fuel. Even a charterer or an industrial shipping company may conceivably want to take advantage of such opportunities. Not factoring in the state of the market in a speed model means that the model may not capture one of the fundamental facets of shipping industry behavior, according to which the state of the market, along with the price of fuel, are the two main determinants of the speed of vessels.

The above simple model can be extended to the case in which speeds are optimized separately for the laden and ballast legs of a route, assuming different fuel consumption functions for each leg, and port times and costs are included. Fig. 5

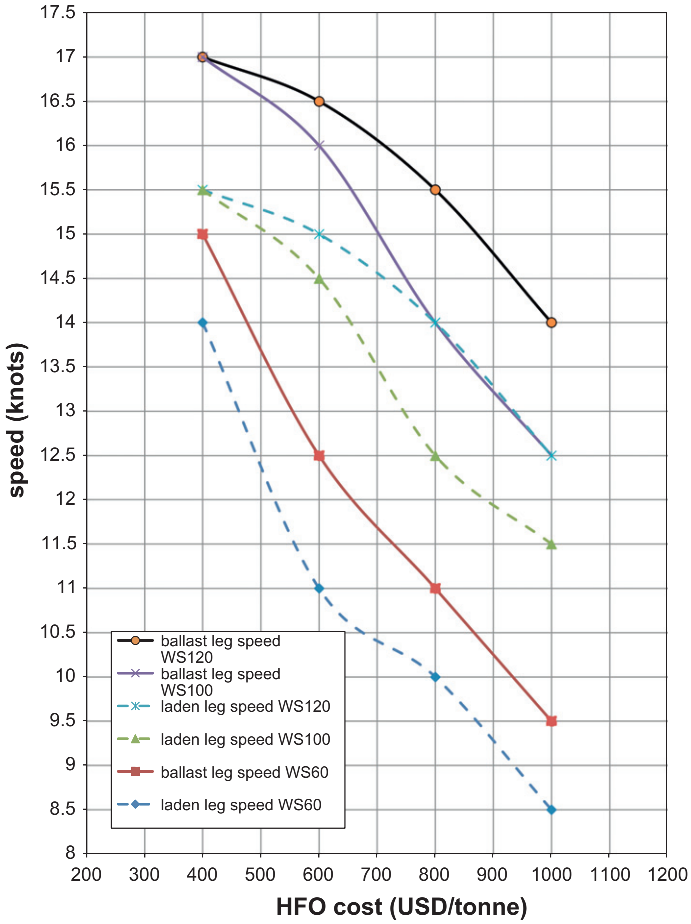


Fig. 5. Optimal VLCC laden and ballast speeds as functions of fuel price and spot rate. Spot rates are in WS. *Source*: Gkonis and Psaraftis (2012)

shows how optimal speeds in the laden and ballast leg conditions may vary as a function of fuel price and market rate for a modern VLCC operating from the Persian Gulf to Japan. Spot rates are expressed in terms of World Scale (WS) equivalents.[6] Cargo inventory costs are being included as an option in Fig. 6.

One can observe that optimal ballast speeds are typically higher (by 1–1.5 knots) than optimal laden speeds, except if cargo inventory costs are accounted for, in which case laden speeds can be higher than ballast speeds (depending on fuel price). In practice however, many tankers sail faster on the laden leg than on the ballast leg, which is sub-optimal. The reason for this is more likely to be attributed to charter party speeds than inventory costs (Devanney, 2011).

In an even more general case, in which the ship is intermediately full at each route leg (a typical situation with containerships), different speeds can be chosen for different legs of the route, so long as they are within a ‘‘speed window'' $[v_{LB}(w_{ij}), v_{UB}(w_{ij})]$, where $v_{LB}(w_{ij})$ and $v_{UB}(w_{ij})$ are lower and upper bounds (respectively) on ship speed if the ship's payload from i to j is w_{ij}. Typically both bounds are dictated by the maximum power and technology of the engine and by the ship's payload when sailing from i to j. Practically both speed bounds are decreasing functions of w_{ij} (a more heavily loaded ship is not able to run as fast as an emptier ship). The upper bound exists because of limits in the ship's power. The lower bound exists because it is simply impossible for a ship engine to run lower than a certain power, below which the engine simply stalls. For a given payload, modern, electronically controlled engines, possibly equipped with ‘slow steaming kits', generally have a lower v_{LB} than older, mechanical camshaft engines. Weather also plays a role in both bounds, with a usual approximation involving a ‘speed margin' for anything else than calm weather.

Other model formulations do not optimize on a per day basis, but in terms of total costs or profits for a prescribed set of cargoes, for instance on a fixed route scenario or even in a routing and scheduling problem for which the ship route needs to be optimized.

[6] For a certain tanker route, WS is defined as 100 times the ratio of the prevailing spot rate on that route divided by the ‘base rate' on that route (see Stopford (2004)).

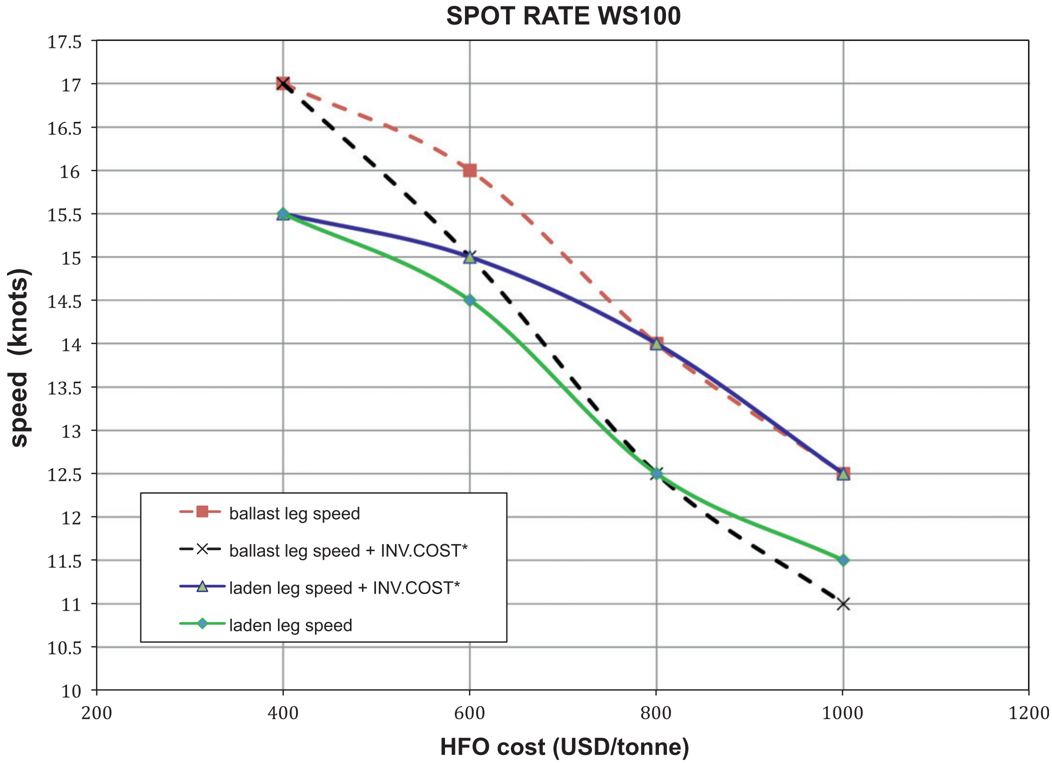


Fig. 6. Optimal VLCC laden and ballast speeds with and without inventory costs. *Source*: Gkonis and Psaraftis (2012)

Take for instance the case in which a ship on a fixed route wants to minimize costs over a specific route leg of length d. If v is the ship speed (miles per day), w is the ship payload during the leg (tonnes), p is the fuel price (\$/tonne), $f(v,w)$ is the fuel consumption function (tonnes/day), T is the time charter rate the charterer is paying (\$/day), β is the inventory cost of the cargo (\$/tonne/day), and $V = \{v\colon v_{LB}(w) \leqslant v \leqslant v_{UB}(w)\}$ is the set of allowable speeds, then the speed optimization problem for the charterer (who is the party paying for the fuel) for the specific leg is

$$min_{v\in V}\{[pf(v,w)+\beta w+T](d/v)\}$$

As d is constant, this problem reduces to

$$min_{v\in V}\{[pf(v,w)+\beta w+T]/v\}$$

If function f is general (for instance given as a pointwise function), this problem can be solved by complete enumeration over all feasible values of v. If function f is given by a mathematical expression (cubic or other), more can be said.

Assuming for instance that $f(v,w) = (A + Bv^n)(w + L)^{2/3}$, the problem's objective function becomes

$$\{[pf(v,w)+\beta w+T]/v\} = \{[p(A+Bv^n)(w+L)^{2/3}+\beta w+T]/v\} = K/v + Mv^{n-1} \tag{8}$$

with $K = pA(w + L)^{2/3} + \beta w + T$ and $M = pB(w + L)^{2/3}$.

Define v^* the speed that makes the 1st derivative of expression (8) with respect to v equal to zero.

Then $v^* = \{K/[M(n-1)]\}^{1/n}$

If U is the optimal speed, then

If $v^* \leqslant v_{LB}(w)$, $U = v_{LB}(w)$
If $v_{LB}(w) \leqslant v^* \leqslant v_{UB}(w)\}$, $U = v^*$
If $v_{UB}(w) \leqslant v^*$, $U = v_{UB}(w)$

Even though this is a different model than the previous one, here too it can be seen that the higher the freight rate T, the lower the fuel price p, and the higher the value of the cargo (and hence β), the higher is the optimal speed U. This would seem to fit the pattern observed in many container trades. For instance, in the Far East to Europe trunk route, the busiest in the world, freight rates and average value of cargo are about double in the westbound direction than in the eastbound direction. This is reflected in the operational speeds, as most of slow steaming can be observed eastbound (Journal of Commerce, 2010).

Using this model one can also determine the minimum emissions speed. In the general case this is the speed that solves the following problem

$$min_{v \in V}\{f(v, w)(d/v)\}$$

The most likely solution of this problem given the forms that are likely to be encountered for function f is $v_{LB}(w)$.

For the case $f(v,w) = (A + Bv^n)(w + L)^{2/3}$, estimating the minimum emissions speed is meaningful only if $A > 0$, because clearly if $A = 0$ the minimum emissions speed is $v_{LB}(w)$ (which is likely to be the case anyway).

$$\text{To do so, let } v^{**} = \{A/(B(n-1))\}^{1/n}$$

This is the speed that makes the derivative of f with respect to speed equal to zero.

If u is the minimum emissions speed, then

If $v^{**} \leqslant v_{LB}(w)$, $u = v_{LB}(w)$
If $v_{LB}(w) \leqslant v^{**} \leqslant v_{UB}(w)\}$, $u = v^{**}$
If $v_{UB}(w) \leqslant v^{**}$, $u = v_{UB}(w)$

It is straighforward to show that $v^{**} < v^{*}$ and $u \leqslant U$.

With the above basics clarified, what can one say about speed models that have appeared in the literature? The next section attempts to answer this question.

3. Taxonomy of speed models

3.1. General

Determining the optimal speed of ships is not new in the literature, irrespective of whether or not emissions are considered. A first observation is that most of the models (at least implicitly) assume that fuel costs are being borne by the ship owner. In the tramp shipping market (served by tankers, dry bulk carriers, product carriers, and gas carriers) this is the case if the ship is on spot charter. It is known that the predominance of charter party contracts are time charters, in which fuel costs are borne by the charterer. Even though most models assume the ship owner as the party that bears the costs, including fuel, the related optimization problem is typically cost minimization rather than profit maximization. This is tantamount to assuming that revenue for the service is fixed. This is not the case however in most instances and thus some of the models that optimize speed do not capture the trade-off between a higher speed to make more profit-earning trips per unit time and the impact of such higher speed on costs (mainly on fuel).

For problems in the liner market (served by containerships and ro/ro ships), a similar situation pertains. Ship owners who run liner services using their own ships want to maximize profits and the same trade-offs are at play. But also using chartered ships to provide liner services is not uncommon, as a liner company typically employs a mix of owned and chartered vessels.

For the so-called 'industrial' types of problems, in which a company (for instance, an oil company) uses its own ships to move its own cargoes, again the usual objective is cost minimization. What is not often mentioned however is that these companies always have the option to enter the market, by either offering excess capacity at the prevailing spot rate, or hiring extra capacity at such rate. Thus, in a boom period it may make sense for an oil company to run its ships at a higher speed, so as to offer the excess capacity obtained to the spot market. Of course, that this opportunity exists does not necessarily mean it will be used.

The other general observation is the scarcity of 'dynamic' speed models in the literature, even though a model that assumes no fixed cargo throughput within a certain time interval, but a rolling horizon in which costs or profits are optimized per unit time might want to consider ship speed as a key variable. However this is not necessarily the case: a recent paper that develops heuristics on dynamic ship routing and scheduling probems (Tirado et al., forthcoming) does not incorporate speed aspects. An exception concerns weather routing models, in which typically ship speed is dynamically updated (see also Section 3.2).

With these general observations, let us examine the literature. There are many ways of classifying related papers and models. A first-order classification involves grouping references into two major categories:

(a) Those that present models in which emissions are not considered.
(b) Those that present models in which emissions are considered (together with other considerations).

3.2. Non-emissions speed models

As expected, these are papers or other publications that chronologically constitute the oldest set of reviewed papers, in terms of average publication date, although some of them are relatively recent.

Alderton (1981) presents a variety of criteria to determine the speed that maximizes profit and discusses how sensitive these speeds are to such inputs as port time, voyage distance, freight rates and bunker costs. The influence of cargo inventory costs is also taken into account. He differentiates between what he terms "Least Cost Speed", the one that maximizes profit per tonne carried, and "Maximum Profit Speed", the one that maximizes profit per day.

Benford (1981) proposes a simple procedure to select the mix of available ships from a fleet and their speeds in order to achieve the best solution for a fleet owner. The approach is confined to non-liner trades (in fact his examples are from the coal trades in the Great Lakes). He assumes that the owner has only one contract, meaning that total revenues are fixed, hence the objective is minimum cost.

Perakis (1985) relaxes some of Benford's fleet deployment model assumptions and arrives at an optimal solution that reduces by 15% the operating costs vis-a-vis those of Benford's.

Ronen (1982) investigates the effect of oil prices on the optimal speed of ships and presents three models, namely for the ballast (or positioning) leg, the income generating (or laden) leg and a variant of the laden case for which a penalty/bonus is given for late/early arrival. He analyzes the tradeoff between fuel savings through slow steaming and loss of revenues due to the increase of voyage time.

Perakis and Papadakis (1987a,b) deal with fleet deployment and the optimal speed for ships operating between a single loading port and a single discharging port. In that problem laden and ballast speeds for each ship are treated as the decision variables. In their second paper a sensitivity analysis of the optimal solution is performed and for the longer term problem, a time-dependent cost function and probabilistic analysis is used.

An expanded model to address a set of loading and unloading ports is presented in Papadakis and Perakis (1989) under the same assumption as in their previous work that each ship returns to the loading port in ballast. The same authors address a weather routing problem in which the objective is to minimize transit time and in which using control theory it is proven that the maximum permissible speed is the optimal speed (Perakis and Papadakis, 1989).

Another weather routing problem is examined in Lo and McCord (1998), who present a fuel consumption minimization approach that addresses the uncertainty that results from the time lags between the time to collect and process raw data on ocean currents and the delivery of the estimation. They formulate the routing problem as an adaptive, probabilistic dynamic program.

Brown et al. (1987) study a crude oil tanker routing and scheduling problem that takes into account cost components and generate feasible ship schedules with different speeds and alternate routes of the ballast legs. For the laden condition, speed is not a decision variable since it is implicitly determined by the given loading and discharging dates.

Perakis and Jaramillo (1991) develop a more complex fleet deployment model for the liner trades. The objective is to minimize costs. A linear programming formulation is developed and the speed problem is decomposed from the deployment problem. The option to charter in additional vessels is also considered and the model includes port, canal and lay up costs.

Bausch et al. (1998) develop a spreadsheet-based interface for scheduling the fleet of tankers and barges. Embedded is a set partitioning model that optimizes cost. The model is used by dispatchers whose native language is not English but who communicate with one another via the model interface.

Fagerholt (2001) considers a flexible situation in determining the optimal speeds on the various legs of the schedule. This is the so-called 'soft- time window' case, in which penalties are imposed if the vessel arrives at a port outside a specified time window. It is motivated by the fact that allowing some customers to have controlled time violations for both loading and unloading of cargo it may be possible to obtain better schedules and high reductions in shipping costs.

An extensive discussion of the various aspects of speed in maritime transportation from various angles is in Stopford (2004), which is the well known seminal book on maritime economics. The basic model assumes a cubic speed function, although it is stated that other exponents may be applicable.

Alvarez (2009) presents a mixed integer programming (MIP) formulation for the joint optimization of routing and fleet deployment of container vessels. Speed is considered as a variable so that the sailing time between any two ports is assumed to be deterministic and the time in port is fixed for each port-ship combination. The model minimizes the operating expenses of a liner company over a tactical planning horizon and the algorithm includes the possibility of rejecting transportation demand on a selective basis, with lost revenue and some monetary penalty.

Notteboom and Vernimmen (2010) deal with the impact of high fuel costs on the design of liner services on the Europe–Far East trade and discuss the way that shipping lines have adapted their schedules in terms of speed and number of vessels deployed for each loop. Furthermore, a cost model is developed to estimate the impact of the additional bunker cost on the operational costs and cost comparisons for different vessel sizes and vessels speeds are presented.

Lang and Veenstra (2010) study the problem of container vessel arrival planning and in that context assume a linearized speed model in which fuel cost is to be minimized. Linearization takes place for computational purposes. Even though fuel price is not an explicit input, results are presented under high and low fuel price regimes, the price difference between these two scenarios being 35%.

None of the surveyed models attempts to estimate the equilibrium spot rate that would be established as a function of the fuel price and the optimal speed that ships would choose as a result. Devanney (2010) presents such an approach for VLCCs, by looking at the interaction of the VLCC fleet supply and demand curves.

A more general model is presented in Devanney (2007), which models the world's petroleum transportation network as a linear program, and simultaneously determines tanker optimal speeds in the laden and ballast legs, FOB and CIF prices of crude oil at origin and destination points, and the market equilibrium spot rates in various routes. The related software (termed Martinet) is only commercially available.

Norstad et al. (2011) present the tramp ship routing and scheduling problem with speed optimization, where speed is introduced as a decision variable. Although the main objective is to maximize profit by allowing the option of picking up spot cargoes, for the speed optimization subproblem the objective is to minimize costs on a certain leg of the route. The paper presents search heuristics to solve this problem and propose alternative algorithms. Various comparisons are also provided.

Ronen (2011) studies the effect of oil price on the trade-off between reducing sailing speed and increasing the fleet size for container ships and develops a procedure to indentify the sailing speed and number of vessels that minimize annual operating costs.

Meng and Wang (2011) propose an optimal operating strategy problem arising in liner shipping industry that aims to determine service frequency, containership fleet deployment plan, and sailing speed for a long-haul liner service route. The problem is formulated as a mixed-integer nonlinear programming model and solved using an efficient and exact branch-and-bound based e-optimal algorithm. A case study based on an existing long-haul liner service route with fixed service frequency and fixed ship type is presented and the results for the optimization in ship number and sailing speed are compared with Ronen (2011) and Gelareh and Meng (2010).

Wang and Meng (2012a) investigate the optimal speed of a fleet of container ships on each leg of each ship route in a liner network using a mixed-integer nonlinear programming model while considering transshipment and container routing. Their model uses a power bunker consumption function which is calibrated using historical operating data from a global liner shipping company.

Wang and Meng (2012b) develop and solve a model for a proposed liner ship route schedule design problem with sea contingency and uncertain port time in order to minimize the ship cost and bunker cost, while fulfilling the port-to-port transit time constraints. For each leg of each ship route they solve the optimal sailing speed problem in order to identify the optimal bunker consumption function as a function of the available sailing time t. Then they solve the schedule design problem by determining the arrival time and the number of vessels for each route by minimizing the sum of ship cost and the expected total bunker cost while satisfying the transit time constraints. However, late arrival at a port is not allowed in their model.

Thus, Wang and Meng (2012c) present a robust schedule design problem which takes into account the penalty for late arrival or late container handling as a result from uncertain port time. The problem is formulated using a mixed-integer nonlinear stochastic programming model and solved using an algorithm that incorporates a sample average approximation method, linearization techniques, and a decomposition scheme. In addition, numerical results based on an Asia–America–Europe ship route are presented to demonstrate that the algorithm obtains near-optimal solutions.

Yao et al. (2012) perform a study on bunker fuel management for container trades in which ship speed and fuel purchase location are the main decision variables. Minimization of total bunker costs is the objective function.

Last but not least, Psaraftis (2012b) addresses a multi-origin multi-destination ship pickup and delivery problem in which ship speed is included as a decision variable. A general function is assumed for the fuel consumption function and it is seen that the speed decision can be decomposed from the pickup or delivery decision. It is also seen that fuel price and market freight rate can influence the routing decision.

Even though the above models do not consider emissions, possible extensions could examine what would happen if the social cost of emissions (and essentially CO_2) is incorporated into the cost functions assumed by these models. Doing so would internalize the external cost of these emissions, a central (although seldomly applied) environmental policy goal.

3.3. Emissions speed models

Speed models that also consider emissions in a logistical context are on the average more recent.

Psaraftis and Kontovas (2009b) investigate the simple scenario where a fleet of identical ships, each of which loads from a port A, travels to port B with a known speed, discharges at B and goes back to port A in ballast, with a known speed. A result of the analysis is that total emissions would be always reduced by slowing down, even though more ships would be used. Another result is that if speed is reduced in a Sulphur Emissions Controlled Area (SECA) in order to reduce SO_x emissions and this is compensated by a speed increase outside the SECA so that total transit time is the same, overall emissions increase.

Corbett et al. (2010) develop equations relating speed, energy consumption, and total cost to evaluate the impact of speed reduction on emissions. They also explore the relationship between fuel price and optimal speed.

Du et al. (2011) use a speed model in the context of a berth allocation problem, in which they assume that the ship operator acts so as to minimize per route leg fuel consumption. A non-linear and not necessarily cubic fuel consumption function is obtained by regression analysis. The regression coefficients are obtained from data provided by a major marine engine manufacturer. Wang et al. (2013) improve this model so that general fuel consumption functions can be handled more tractably.

Eefsen and Cerup-Simonsen (2010) examine the tradeoffs between lower fuel costs and higher inventory costs associated with speed reduction, as well as their impact on emissions. The model was used to investigate the transport costs and carbon emissions on a particular container route from China to Europe on a 6600 TEU containership.

Faber et al. (2010) estimate that emissions of bulkers, tankers and container vessels can be reduced maximally by about 30% in the coming years by using the current oversupply to reduce speed, relative to the situation in 2007.

Fagerholt et al. (2010) consider a single route speed optimization problem with time windows and proposed a solution methodology in which the arrival times are discretized and the solution is based on the shortest path of the directed acyclic graph that is formed. Reduction in ship emissions are also computed. For the same problem, and drawing also from the results of Norstad et al. (2011) and Hvattum et al. (in press) show that if fuel cost is a convex function of vessel speed, optimal speeds can be found in quadratic time.

Qi and Song (2012) investigate the problem of designing an optimal vessel schedule in the liner shipping route to minimize the total expected fuel consumption (hence also emissions) considering uncertain port times and frequency requirements on the liner schedule. The general optimal scheduling problem is formulated and tackled by simulation-based stochastic approximation methods.

Cariou (2011) investigates slow steaming strategies especially in container shipping and measures the reduction of CO_2 achieved in various container trades. In addition, the paper concludes that for the main trades speed reduction is cost beneficial when bunker price is at least \$350–\$400 per tonne.

Kontovas and Psaraftis (2011) examine speed reduction as an operational measure to reduce fuel consumption with a focus on container vessels. Since time at sea increases with slow steaming, there is a parallel and strong interest to investigate possible ways to decrease time in port. To that effect, a related berthing policy was investigated as a measure to reduce waiting time.

Another aspect of the problem is studied in Psaraftis and Kontovas (2010), where the impact of speed reduction on modal split is investigated, in the sense that cargoes that go slower may choose alternative modes of transport, particularly if their inventory costs are high. This may be true not only for short sea trades, but for longer haul ones, for example using the Trans-Siberian railway to move cargoes to or from the Far East. Multinomial logit models are introduced.

Lindstad et al. (2011) present an analysis at the strategic level. They investigate the impact of lower speeds on the cost and emissions of the world fleet and argue that there is a significant potential for the reduction of GHGs if speed is reduced. They explore Pareto-optimal policies and recommend speed limits as a possible way to achieve speed reduction.

An opposing view is presented by Cariou and Cheaitou (2012), who investigate policy options contemplated by the European Commission and compare speed limits versus a bunker levy as two measures to abate GHGs, with a scenario from the container trades. They conclude that the latter measure is counterproductive for two reasons. First, because it may ultimately generate more emissions and incur a cost per tonne of CO_2 which is more than society is willing to pay. Second, because it is sub-optimal compared to results obtained if an international bunker-levy were to be implemented.

Last but not least, Gkonis and Psaraftis (2012) have developed a series of models that optimize speed in both the laden and ballast legs for several tanker categories (VLCC–ULCC, Suezmax, Aframax, product tankers, LNG and LPG carriers) and for a variety of scenarios. The modeling approach consists of two steps. The first step performs a speed optimization for both laden and ballast sailing. This is carried out over certain defined routes and for a certain ship. The second step calculates the annual emissions for the global tanker fleet, broken down into size brackets. The data used is based on actual speed-consumption curves, rather than theoretical or modeling approximations. The impacts of inventory costs, bunker costs, freight rates and other parameters on optimal speeds and emissions are estimated.

3.4. Taxonomy

A finer-grain taxonomy classifies the literature of the previous two sections according to the following parameters:

Optimization criterion: The main variants here are cost (to be minimized) and profit (to be maximized). Other variants include fuel consumption, transit time, or others. To be sure, some models in the literature are not cast as optimization problems. In these papers we set ‘cost’, ‘profit’, or other, depending on what the model described by the paper tries to measure.

What is the shipping market/context of the problem: This may be tankers, bulk carriers, containerships, or other ship types. It may even involve the whole commercial fleet.

Who is the decision maker: By this we mean who decides what the ship speed should be. This can be the ship owner or the charterer. For weather routing problems, it is typically the ship’s master. An attempt to designate who is the decision maker is made even if the model is not an optimization model.

Fuel price an explicit input? Yes if fuel price is explicitly included as one of the explicit inputs of the problem, no otherwise.

Freight rate an input? Yes if freight rate (spot, or other) is explicitly included as one of the explicit inputs of the problem, no otherwise. There are also models that compute that rate as an equilibrium rate depending on supply and demand.

Fuel consumption function: It could be cubic, non-linear, linearized, general or unspecified.

Optimal speeds in various legs: Whether or not the model computes optimal speeds for each leg of the route (versus a single optimal speed).

Optimal speed as function of payload: Whether or not the model can compute the optimal speed as a function of how much full or empty the ship is.

Logistical context: This could be a fixed route scenario, a ship routing and scheduling problem, a fleet deployment problem, or other.

Size of fleet: One ship, or many ships.

Adding more ships an option: This is so if adding (or subtracting) ships is an option so as to maintain constant throughput.

Inventory costs included: Yes if cargo carrying (inventory) costs are included in the model, no otherwise.

Emissions considered: Yes or No.

Modal split considered: Yes if model calculates the split among alternative and competing modes of transport as a function of problem inputs.

Ports included in formulation: Yes if port times, costs, congestion, port emissions or other port-related variables are included in the model.

With the above in mind, in Tables 2a–2e we present the taxonomy of more than 40 speed- related papers or other publications that we have reviewed. It should be clarified that the determination of each of the above parameters in each model involves a certain degree of subjectivity, and it is governed by our own (imperfect at times) understanding of the related papers.

4. Conclusions and way ahead

This paper has provided a taxonomy and survey of speed models in maritime transportation, recognizing that ship speed is a key determinant to both shipping economics and the environmental sustainability of maritime transportation. It has also explained the basics behind speed optimization and placed it within the broader picture of issues facing the shipping industry.

As the 'speed knob' is very much at play these days and will be more so in the future, we anticipate that research in this area will continue. In particular, we anticipate maritime logistics research to increasingly take into account environmental considerations.

Below we highlight some issues that are likely to shape further developments in this area.

4.1. Reduced freight rates and fleet overcapacity

The fact that slow steaming is being practised today can be confirmed by the fact that whatever fleet overcapacity exists has been virtually absorbed. In fact, according to Clarksons (2011) there has been practically zero tanker and bulk carrier lay up: in mid-2011 there were only 0.2 million tonnes of bulkers laid up out of 564.1 million tonnes afloat, and 2.6 million tonnes of tankers laid up out of 440.1 million tonnes afloat.

A similar situation pertains to containerships. Of the approximately 15 million TEU global containership capacity in 2011, less than 0.3 million TEU were idle (Alphaliner, 2011).

To the extent that this trend continues, slow steaming is expected to continue as a widely applied practice, and logistical networks will be impacted as a result of the practice.

4.2. Coping with port congestion

Adjusting ship speed can be an important tool to tackle port congestion. Demand for port or terminal services is subject to random fluctuations, and peaks in that demand may very well exceed available capacity. Whenever this is the case, delays

Table 2a
Taxonomy part I.

Taxonomy parameter/ paper	Alderton (1981)	Alvarez (2009)	Bausch et al. (1998)	Benford (1981)	Brown et al. (1987)	Cariou (2011)	Cariou and Cheaitou (2012)	Corbett et al. (2010)
Optimization criterion	Profit	Cost	Cost	Cost	Cost	Cost	Cost	Profit
Shipping market	General	Liner	Tanker/barge	Coal	Tanker	Container	Container	Container
Decision maker	Owner	Owner	Owner	Owner	Owner	Owner	Owner	Owner
Fuel price an explicit input	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Freight rate an input	Input	No	No	No	No	No	No	Input
Fuel consumption function	Cubic	Cubic	Unspecified	Cubic	Unspecified	Cubic	Cubic	Cubic
Optimal speeds in various legs	Yes	Yes	No	No	Only ballast	No	No	No
Optimal speeds as function of payload	Yes	Yes	No	No	No	No	No	No
Logistical context	Fixed route	Joint routing and fleet deployment	Routing and scheduling	Fleet deployment	Routing and scheduling	Fixed route	Fixed route	Fixed route
Size of fleet	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships
Add more ships an option	Yes	No	No	No	No	Yes	Yes	Yes
Inventory costs included	Yes	No	No	No	No	No	Yes	No
Emissions considered	No	No	No	No	No	Yes	Yes	Yes
Modal split considered	No	No	No	No	No	No	No	No
Ports included	Yes	Yes	Yes	No	No	No	Yes	No

Table 2b
Taxonomy part II.

Taxonomy parameter/paper	Devanney (2007)	Devanney (2010)	Du et al. (2011) Wang et al. (2013)	Eefsen and Cerup-Simonsen (2010)	Faber et al. (2010)	Fagerholt (2001)	Fagerholt et al. (2010)	Gkonis and Psaraftis (2012)
Optimization criterion	Profit	Cost or profit	Fuel consumption	Cost	N/A	Cost	Fuel consumption	Profit
Shipping market	Tanker	Tanker (VLCC)	Container	Container	Various	General	Liner	Tanker, LNG, LPG
Decision maker	Owner	Owner or charterer	Owner	Owner	N/A	Owner	Owner	Owner
Fuel price an explicit input	Yes	Yes	No	Yes	No	No	No	Yes
Freight rate an input	Computed	Computed	No	No	No	No	No	Input
Fuel consumption function	Cubic	General	Non-linear	Cubic	Cubic	Cubic	Cubic	General
Optimal speeds in various legs	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Optimal speeds as function of payload	No	No	No	No	No	No	No	No
Logistical context	World oil network	Fixed route	Berth allocation	Fixed route	Fixed route	Pickup and delivery	Fixed route	Fixed route
Size of fleet	Multiple ships	One ship	Multiple ships	Multiple ships	Multiple ships	Multiple ships	One ship	Multiple ships
Add more ships an option	Yes	Yes	No	Yes	Yes	No	No	Yes
Inventory costs included	Yes	Yes	No	Yes	No	No	No	Yes
Emissions considered	No	No	Yes	Yes	Yes	No	Yes	Yes
Modal split considered	No	No	No	No	No	No	No	No
Ports included	Yes	No	Yes	Yes	No	No	No	Yes

Table 2c
Taxonomy part III.

Taxonomy parameter/paper	**Hvattum et al (2012)**	Kontovas and Psaraftis (2011)	Lang and Veenstra (2010)	Lindstad et al. (2011)	Lo and McCord (1998)	Meng and Wang (2011)	Norstad et al. (2011)	Notteboom and Vernimmen (2010)
Optimization criterion	Fuel consumption	Cost	Fuel costs	Pareto analysis	Fuel consumption	Cost	Cost	Cost
Shipping market	General	Container	Container	All major ship types	General	Liner	Tramp	Container
Decision maker	Owner	Charterer	Owner	Owner	Ship's master	Owner	Owner	Owner
Fuel price an explicit input	No	Yes	No	Yes	No	Yes	No	Yes
Freight rate an input	No	Input	No	No	No	No	No	No
Fuel consumption function	Convex	Cubic	Linearized	Cubic	Cubic	Cubic	Cubic	Unspecified
Optimal speeds in various legs	Yes	Yes	No	No	N/A	No	Yes	No
Optimal speeds as function of payload	No	Yes	No	Yes	No	No	No	No
Logistical context	Fixed route	Fixed route	Vessel arrival planning	Fixed route	Weather routing	Fleet deployment	Pickup and delivery	Fixed route
Size of fleet	One ship	Multiple ships	Multiple ships	Multiple ships	One ship	Multiple ships	Multiple ships	Multiple ships
Add more ships an option	No	Yes	No	Yes	No	No	No	Yes
Inventory costs included	No	Yes	No	Yes	No	No	No	No
Emissions considered	Yes	Yes	No	Yes	No	No	No	No
Modal split considered	No	No	No	No	No	No	No	No
Ports included	No	Yes	Yes	Yes	No	Yes	No	Yes

Table 2d
Taxonomy part IV.

Taxonomy parameter/ paper	Papadakis and Perakis (1989)	Perakis (1985)	Perakis and Jaramillo (1991)	Perakis and Papadakis (1987a) Perakis and Papadakis (1987b)	Perakis and Papadakis (1989)	Psaraftis (2012b)	Psaraftis and Kontovas (2009b)	Psaraftis and Kontovas (2010)
Optimization criterion	Cost	Cost	Cost	Cost	Time	Cost	Cost	Cost
Shipping market	Tramp	Tramp	Liner	Tramp	General	General	Tramp	General
Decision maker	Owner	Owner	Owner	Owner	Ship's master	Charterer	Charterer	Charterer
Fuel price an explicit input	Yes	No	Yes	Yes	No	Yes	Yes	No
Freight rate an input	No	No	Yes	No	No	Input	Input	Input
Fuel consumption function	General	Cubic	Cubic	General	N/A	General	Cubic	General
Optimal speeds in various legs	Yes	No	Yes	Yes	N/A	Yes	Yes	No
Optimal speeds as function of payload	No	No	No	No	No	Yes	Yes	No
Logistical context	Fleet deployment	Fleet deployment	Fleet deployment	Fleet deployment	Weather routing	Pickup and delivery	Fixed route	Fixed route
Size of fleet	Multiple ships	Multiple ships	Multiple ships	Multiple ships	One ship	One ship	Multiple ships	Multiple ships
Add more ships an option	No	Yes	Yes	No	No	No	Yes	Yes
Inventory costs included	Yes	No	No	Yes	No	Yes	Yes	Yes
Emissions considered	No	No	No	No	No	Yes	Yes	No
Modal split considered	No	No	No	No	No	No	No	Yes
Ports included	Yes	No	No	Yes	No	No	Yes	No

Table 2e
Taxonomy part V.

Taxonomy parameter/ paper	Qi and Song (2012)	Ronen (1982)	Ronen (2011)	Stopford (2004)	Wang and Meng (2012a)	Wang and Meng (2012b)	Wang and Meng (2012c)	Yao et al. (2012)
Optimization criterion	Fuel consumption	Profit	Cost	Profit	Cost	Total cost and fuel cost	Cost	Fuel cost
Shipping market	Liner	Tramp	Container	General	Container	Liner	Liner	Container
Decision maker	Owner	Owner	Owner	Owner	Owner	Owner	Owner	Owner
Fuel price an explicit input	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Freight rate an input	No	Input	No	Input/ computed	No	No	No	No
Fuel consumption function	Cubic	Cubic	Cubic	Cubic	Linearized	Cubic	Linearized	Cubic
Optimal speeds in various legs	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Optimal speeds as function of payload	No	No	No	No	No	No	No	No
Logistical context	Scheduling	Fixed route	Fixed route	Fixed route	Scheduling	Scheduling	Scheduling	Bunker fuel management
Size of fleet	Multiple ships	One ship	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships
Add more ships an option	No	No	Yes	No	No	No	No	No
Inventory costs included	No	No	No	Yes	No	No	No	No
Emissions considered	Yes	No	No	No	No	No	No	No
Modal split considered	No	No	No	No	No	No	No	No
Ports included	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 3
Parameters for determination of EEDI reference values for different ship types.

Ship type	*a*	*c*
Bulk carrier	961.79	0.477
Gas carrier	1120.00	0.456
Tanker	1218.80	0.488
Container ship (65% DWT)	186.52	0.200
General cargo ship	107.48	0.216
Reefer	227.01	0.244
Combination carrier	1219.0	0.488

and congestion occur, with considerable costs to shipping lines and shippers and negative ramifications downstream the supply chain. Costs and emissions may actually be even higher if a ship sails to a port at maximum speed only to wait in line to enter once there. One of the possible ways to streamline peaks in demand is to institute a system where ship speed is adjusted so that port capacity is respected time-wise. The related speed optimization problem may be formulated at the operational level and would entail cooperative decision making between the port and the ships destined to it (or at least a subset of these ships). Systems such as "booking by rendez vous", in which a ship and a port book a mutually agreeable time slot for service and the port guarantees berthing on arrival so long as the ship is punctual to the rendez vous would go hand-in-hand with such a speed adjustment setting (see Kontovas and Psaraftis (2011) for a description of such a system).

Methodologically, this would entail extending berth allocation, quay crane scheduling and other related models to incorporate ship speed optimization considerations. See, among others, Cordeau et al. (2005) for the berth allocation problem, Moccia et al. (2006) for the quay crane scheduling problem, and Stahlblock and Voss (2007) and Bierwirth and Meisel (2010) for comprehensive surveys of such problems.

4.3. The adoption of EEDI

Perhaps the most sweeping piece of regulation that will have an impact on ship speeds (and in fact at the strategic level) is the recent adoption of Energy Efficiency Design Index (EEDI) by the IMO. Indeed, after years of discussion and intensive and highly political debate between developed and developing countries, the finalization of the regulatory text on the EEDI for new ships was agreed upon at the 62nd session of IMO's Marine Environment Protection Committee – MEPC 62 in July 2011.

For a given ship, the EEDI is provided by a complex formula, of which the numerator is a function of all power generated by the ship (main engine and auxiliaries), and the denominator is a product of the ship's deadweight (or payload) and the ship's 'reference speed', defined as the speed corresponding to 75% of MCR, the maximum power of the ship's main engine. The units of EEDI are grams of CO_2 per tonne mile. The EEDI of a new ship is to be compared with the so-called "EEDI (reference line)," which is defined as EEDI (reference line) = $aDWT^{-c}$, where DWT is the deadweight of the ship and a and c are positive coefficients determined by regression from the world fleet database, per major ship category.

For a given ship, the attained EEDI value should be equal or less than the required EEDI value which is provided by the following formula.

$$\text{Attained EEDI} \leqq \text{Required EEDI} = (1 - X/100)\text{aDWT}^{-c} \tag{9}$$

where X is a "reduction factor" specified for the required EEDI compared to the EEDI Reference line.[7]

The reference line parameters a and c in (9), which have been finalized by regression analysis after a long debate within the IMO are presented in Table 3, although they are subject to revision.

It is interesting to note that Ro/ro vessels are thus far excluded from EEDI, because no adequate regression coefficients have been obtained for this class of vessels. This is an open subject that the IMO hopes to close in the foreseeable future.

A basic problem with EEDI is that compliance effectively imposes a limit on a ship's *design speed*, as the left-hand side of inequality (9) is a polynomial function of the design speed whereas the right-hand side is independent of speed. Thus, whereas the real goal of EEDI is to design ships with better hulls, engines and propellers so as to be more energy efficient, an easy solution might be to reduce design speed, and, as a consequence, installed power. This may have negative ramifications on ship safety. It may also have negative effects on total CO_2 emitted, as an undepowered ship would burn more fuel and hence emit more CO_2 at the same speed, particularly if it tries to maintain speed in bad weather.

4.4. Market based measures

A parallel effort at the IMO concerns the so-called Market Based Measures, or MBMs. MBMs are economic instruments that entice the ship owner to adopt measures to make the ship emit less CO_2. MBMs are also used to raise money to invest in carbon-reducing technologies outside the shipping sector.

[7] The values of X specified by the IMO are 0% for ships built from 2013–2015, 10% for ships built from 2016 to 2020, 20% for ships built from 2020 to 2025 and 30% for ships built from 2025 to 2030. This means that it will be more stringent to be EEDI compliant in the years ahead.

At this point there are 10 distinct MBM proposals before the IMO. An Expert Group has been formed and some initial discussions have been held, but no final decision has been reached as of yet. These MBMs include a levy on fuel, an emissions trading scheme, various hybrid proposals based on EEDI, and others.

In terms of what has been described in this paper, it is interesting to note that among the various MBM proposals, the levy proposal is perhaps the only one that can handle slow steaming automatically. In the short run, a levy on fuel would effectively raise the price of fuel and as a result would make the ship go slower. If the levy is equal to the social cost of CO_2, this would fully internalize its external cost. In the long run, the same measure would encourage a ship owner to invest in technologies that would make the ship burn less fuel. For an analysis of the MBMs of the table at the IMO, see IMO (2010) and Psaraftis (2012a).

4.5. Instituting speed limits?

Realizing that reducing speed also reduces emissions, some researchers and some lobbying groups have recommended instituting speed limits on shipping. Among the researchers, see Lindstad et al. (2011) for an argument and Cariou and Cheaitou (2012) for a counter argument. Among the lobbying groups, the Clean Shipping Coalition (CSC), a Non-Governmental Organization, advocated at IMO/MEPC 61 that *"speed reduction should be pursued as a regulatory option in its own right and not only as possible consequences of market-based instruments or the EEDI."* However, that proposal was rejected by the IMO. In spite of this decision, lobbying for speed limits has continued by CSC and other groups.

It is clear that slow steaming and speed limits are two different things, as the first is a voluntary response and the second is an imposed measure. If the speed limit is above the optimal speed that is voluntarily chosen, then it is superfluous. If it is below, it may cause distortions in the market and costs that exceed the benefits of speed reduction. Possible side-effects include:

- Building more ships to match demand throughput, with more CO_2 associated with shipbuilding and recycling.
- Increasing cargo inventory costs due to delayed delivery.
- Increasing freight rates due to a reduction in tonne-mile capacity.
- Inducing reverse modal shifts to land-based modes (mainly road) that would increase the overall CO_2 level.
- Implications on ship safety.

It is clear that imposing speed limits, either on a global or on a regional level, is an emissions abatement measure that should be studied very carefully in terms of its possible side effects, as it is quite conceivable that its overall costs might exceed its benefits.

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