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Balancing the economic and environmental performance of maritime transportation

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ABSTRACT

This paper looks at the implications of various maritime emissions reductions policies for maritime logistics. There can be important trade-offs that have to be made between the environmental benefits associated with such measures as reduction in steaming speed and change in the number of vessels in the fleet, and more conventional logistics attributes such as in-transit inventory holdings.

1. Introduction

There are three main ways to reduce maritime greenhouse gas (GHG) emissions. Technical measures include more efficient ship hulls, energy-saving engines, more efficient propulsion, use of alternative fuels such as fuel cells, biofuels or others, "cold ironing" in ports (providing electrical supply to ships from shore sources), devices to trap exhaust emissions (such as scrubbers), and others, even including the use of sails to reduce power requirements. Market-based instruments measures are classified into two main categories, emissions trading and carbon levy schemes. Finally, there are operational options mainly involve speed optimization, optimized routing, improved fleet planning, and other, logistics-based measures.

Some of these measures, although effective in meeting environmental objectives, may have non-trivial side effects on the economics of the logistical supply chain; for instance, reductions of speed and changes in the number of ships in the fleet and possibly on things such as in-transit inventory and other costs. There are also larger issues in that measures that increase maritime costs, and particularly, short-sea shipping, will shift some traffic to more environmental damaging land transport modes. This paper examines some of the models that have been developed to embrace the trade-offs between maritime logistics effects and policies to reduce the environmental effects of shipping.

2. Background

It is generally agreed that containerships are the largest maritime CO_2 emitters (Psaraftis and Kontovas, 2009) because of their quest for speed that is compounded by the fact that fuel consumption is a non-linear function of speed. As containerships typically have much higher speeds than tankers or bulk carriers (as high as 25–26 knots as opposed to 14–15), their share of emissions is proportionally higher. For commercial reasons, therefore, speed reduction has been a popular measure at times of high fuel prices as in 2008 when speeds often fell to the 21–22 knots range.

Whatever are the merits of speed reduction, slow steaming can be realized at two levels: First a ship that is designed to go 26 knots may sail at say 14. This entails reconfiguring the engine so that it performs well under a reduced load. The second level is strategic, and may be considered as a technical measure and involves building ships with smaller engines to sail 14

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Table 1
Comparison of emission factors kg CO2/kg fuel. Source: International Maritime Organisation (2008b).

Fuel type	GHG-WG 1/3/1	IPCC 2006 guidelines			Revised 1996 guidelines
		Default	Lower	Upper	
Marine diesel and marine gas oils (MDO/MGO)	3.082	3.19	3.01	3.24	3.212
Low sulphur fuel oils (LSFO)	3.075	3.13	3.00	3.29	
High sulphur fuel oils (HSFO)	3.021				

knots instead of 26. The main difference between the approaches is that the first is reversible whereas the second is not. Additionally, if the smaller-engined ship attempts to sail at higher speeds or just maintain speed in bad weather, its fuel consumption and emissions would likely be higher than if its engine were more powerful.

Implementing a long-term strategic speed reduction would involve modifying the design of ships, including hull shapes, installing smaller engines in future vessels, and modifying propeller designs. For completeness, one would also investigate not only emissions with low speed designs, but also due to other factors, including emissions at shipyards and ultimately, scrapping. This strategic approach to the emissions problem is also known as the 'life-cycle', or 'cradle-to-grave' approach. It is an important component in the quest to formulate possible strategic decisions and policies to curb emissions from shipping in the long run. We do not deal with the life-cycle dimension of the emissions problem.

Most previous work on emissions has centered on generic matters such as ship design, technology, propulsion, fuels, combustion, and the impact of emissions on weather and climate, with work linking emissions and maritime logistics being relatively scant.[1] The International Maritime Organisation (IMO) (2008a), however, has moved forward, albeit it in a rather uneven manner with its Marine Environment Protection Committee (MEPC) adopting amendments to the MARPOL Annex VI regulations on sulphur oxide (SO_x) requiring a maximum 3.50% content by 1 January 2012 and 0.50%, by 1 January 2020. At recent meetings of the MEPC, though, there continued a clear split between industrialized member states, such as Japan and Northern European countries, and a group of developing countries including China, India and Brazil, on how to proceed. The latter typically speak in favor of the principle of "common but differentiated responsibility" (CBDR) under the United Nations Framework Conference on Climate Change.

European legislation mainly concerns the SO_x content of emissions. The maximum sulphur content for marine fuels under EU directive 2005/33/EC is in line with MARPOL Annex VI, albeit with different implementation dates. What is different is that the EU Directive has set a sulphur limit for all fuel used by passenger vessels operating regular service to or from EU ports from August 11th 2006 to 1.5%. Furthermore, according to Article 4b of the same Directive, from January 1st, 2010 a 0.1% limit comes into effect for most inland waterway vessels and ships at berth in EU ports.

The US Environmental Protection Agency has established a tier-based timeline for implementing NO_x emission standards for marine diesel engines as of 2007. These standards are similar to those in MARPOL Annex VI that was ratified by the US in October 2008 but had come into force in May 2005. Canada has not yet ratified Annex VI, however Canada and the US have jointly proposed to the IMO the designation of an Emissions Control Area for their coastal waters.

3. Some scenarios

To calculate CO_2 emissions, bunker consumption is multiplied by an appropriate emissions factor, F_{CO2}; 3.17 is the factor most widely used (Endresen et al., 2007) and this used here in most calculations. Table 1 summarizes emissions factors.

SO_2, which is not a GHG, depends on the type of fuel used. For computation, bunker consumption is multiplied by the percentage of sulphur present in the fuel and by 0.02; 0.02 being exact in the sense that it is derived from the chemical reaction of sulphur with oxygen. NO_x emissions depend on type of engine in use. The ratio of NO_x emissions to fuel consumed (tonnes per day to tonnes per day) ranges from 0.087 for slow speed engines to 0.057 for medium speed engines. Also directly proportional to the amount of fuel used is its cost. Fuel costs can be estimated by multiplying the amount of bunkers used by the price of fuel. While it is typically assumed that the price of fuel is constant, it is very much market-related, and, as such, can fluctuate widely. Ships also often consume different kinds of fuels during a voyage and in port.

Speed reduction reduces fuel bills and emissions, and, in a depressed market, may help support freight rates by artificially shrinking the fleet. But the outcome is in practice an empirical matter. Assuming a given ship, and for speeds that are close to the original speed, the effect of speed on fuel consumption is assumed cubic; the daily fuel consumption F at sea at speed V is a cubic function of that speed. This is only an approximation valid for small changes in speed. If speed changes drastically, a different relationship may emerge between V and F. The cube law however is still a useful approximation.

We can initially explore trade-offs between CO_2 emissions and other attributes of a ship's operation. The scenario assumes a fleet of N identical vessels, each with a payload of W. Each loads from port A, travels to port B at speed V_1 (in km per day), discharges at B and goes back to A in ballast, at speed V_2. The distance between A and B is L km and the time

[1] Some exceptions include, Perakis and Papadakis (1987) that looks at speed optimization in the context of fleet deployment. More directly related is Corbett et al. (2009) that applies fundamental equations relating speed, energy consumption, and the cost to evaluate the impact of speed reduction, while Notteboom and Vernimmen (2009) examined bunker fuel costs. Psaraftis et al. (2009) looks at ways of decreasing port costs.

in port is T_{AB} days. Further, the ships are on a term charter and the charterer – the effective owner of the fleet for the duration of the charter – incurs a cost of $\$O_C$ per ship per year; a cost that depends on market conditions at the time the charter and includes the charter cost and other non-fuel related expenses, such as canal tolls, port dues, and handling expense. Not included are fuel expenses that are paid separately by the charterer.

Assume that each ship's operational days per year are D ($0 < D < 365$) and that daily fuel consumption by both main and auxiliaries engines is f tonnes per day in port, and F_1, F_2 tonnes per day at sea, for the laden and ballast legs. The effect of speed change on fuel consumption is cubic, i.e., $F_1 = k_1V_1^3$ and $F_2 = k_2V_2^3$, where are constants.

Cargo inventory costs are $\$I_C$/tonne and per day of delay. In computing these costs, it is assumed that cargo reaches the port 'just-in-time' for each ship arrival. In that sense, inventory costs accrue only when loading, transiting, and discharging. These costs are the in-transit inventory costs, but they can be fairly easily generalizing to include storage costs at a port.

If the market price of the cargo at the destination (cif price) is $\$P$/tonne, then one day of delay in the delivery of a tonne of cargo will inflict a loss of $\$PR/365$ to the cargo owner, where R is his cost of capital expressed as an annual interest rate. For N ships, annual fleet costs are

$$D \cdot N \frac{p\left[T_{AB}f + L\left(k_1V_1^2 + k_2V_2^2\right)\right] + I_CW\left(T_{AB} + \frac{L}{V_1}\right)}{\frac{L}{V_1} + \frac{L}{V_2} + T_{AB}} + N \cdot O_C$$

Further, if we assume the speeds of ships are reduced by a $\Delta V \geqslant 0$.[2] To keep annual throughput constant, we have to add ΔN additional ships, assumed identical in design to the original N ones.

$$\Delta N = N\left(\frac{\frac{L}{V_1-\Delta V} + \frac{L}{V_2-\Delta V} + T_{AB}}{\frac{L}{V_1} + \frac{L}{V_2} + T_{AB}} - 1\right)$$

An implicit assumption is that these ΔN ships are readily available and can immediately be incorporated into the fleet at a cost of $\$O_C$ per ship per year, the same as that paid to charter the original N ships. However, there may be a lack of supply of available ships leading to an increase in charter rates above $\$O_C$. This possibility is assumed away.

If $V_1 = V_2 = V$ (this may not mean that $k_1 = k_2$), the difference in fleet costs is[3]:

$$\Delta(\text{total fleet costs}) = NL\Delta V \frac{-pD(2V - \Delta V)(k_1 + k_2) + \frac{I_CWD + 2O_C}{V(V-\Delta V)}}{2\frac{L}{V} + T_{AB}} \tag{1}$$

The difference in fuel costs alone (costs after minus costs before) is

$$\Delta(\text{total fuel costs}) = -NL\Delta V \frac{pD(2V - \Delta V)(k_1 + k_2)}{2\frac{L}{V} + T_{AB}} \tag{2}$$

Fuel and fleet cost differentials are independent of port fuel consumption because the new fleet string, even though more numerous than the previous one, will make an equal number of port calls in a year, therefore fuel burned while in port will not change. For $\Delta V \geqslant 0$, and for all practical purposes, the differential in fuel costs is always negative or zero, as difference $2V - \Delta V$ in Eq. (2) is positive for all realistic values of speeds and speed reductions. This means that reducing speed cannot result in higher fuel bills, even though more ships will be required. The same is true as regards emissions, as these are directly proportional to the amount of fuel consumed.

3.1. Beneficial speed reductions

Even though Δ(fuel cost) in expression 2 is always negative or zero, Δ(fleet cost) in expression 1 may be positive or negative, or may reach a minimum value other than zero, depending on the values of parameters. Both in-transit inventory and non-operational ship costs would increase by reducing speed, and this may offset or counteract the corresponding decrease in fuel costs. High values of either I_C or O_C, or both, would increase the chances of this happening.

To illustrate the situation we look at the effect of a speed reduction from 21 to 18 knots for a fleet of 25 identical Panamax containerships assuming; W is 50,000 tonnes, L is 3000 nautical miles, p is $600/tonne, D is 360 days, F at 21 knots is 115 tonnes/day, and f is 4 tonnes/day. The arithmetic shows we would need 4.17 extra ships to achieve the same cargo throughput per year. Further, if the sum of additional cargo inventory costs and other operational costs of the extra ships is less than $108,332 per vessel per day, then speed reduction is cheaper overall.

To compute in-transit inventory costs, we assume the cargo consists of high value, industrial products with an average cif price of $30,000/tonne. Assuming the cost of capital at 7%, one day of delay for a tonne of cargo would entail an inventory cost of $5.75/tonne/day. The in-transit inventory costs in this case means an annual difference of $215,753,000 in favor of moving the cargo faster; an amount greater than the fuel cost differential of $164,755,000 per year. The slower case speed scenario would reduce CO_2 emissions by 870,456 tonnes per annum, but with a time charter rate of $25,000/day, the typical

[2] We assume there is no speed increase, even though this may be financial justified. Any increase would always result in higher fuel consumption and emissions, but may lower inventory and some other costs.

[3] If the two speeds are not equal, the expression is adjusted.

charter rate for a Panamax containership in 2007, non-fuel operational costs are approximately $266,146000/year compared with $228,125,000 for the fleet going full speed. There is therefore, a net cost differential of $89,019,000/year in favor of not reducing speed; in-transit inventory and other operational costs offset the positive difference in fuel costs.

These results may change if the charter rate and/or average cif price of cargo are different. For instance, even a lower charter rate, of say $6,000/day, as in 2010, would still favor the high speed scenario. But if the average cif price of cargo is lower, the slow speed case becomes more attractive. For the original example, if the average cif price drops below $17,620/tonne, the slow speed scenario is preferable.

3.2. Effect on modal split

Another side-effect of a speed reduction in short, but sometimes deep, sea shipping may be a shifting to more environmentally intrusive land-based modes. For example, one could see cargoes moving between the Far East and Europe shift to the trans-Siberian railway, or to trucks. The trans-Siberian railway is some 10,000 km, which compared to the Far-East to Western Europe ocean route that can be 43,000 km, plus 2000 km from a port to Moscow. The rail route is capable of carrying some 100 million tonnes of cargo per year and uses electric traction, but hauling additional cargo via this route would entail consuming of extra energy, that will emit CO_2 unless produced from nuclear or hydroelectric sources.

Electric railways may emit as much as 18 grams of CO_2 per tonne-km as opposed to 7.8 for a large containership sailing at maximum speed. If the ship's speed is reduced, emissions will decline in a quadratic fashion implying that 150,000 tonnes of cargo (roughly a fully laden large containership) traveling 12,000 km by rail would produce 32,000 tonnes of CO_2, as opposed to some 18,000 tonnes of CO_2 for the ocean option if the ship is going at 60% of the maximum speed.

Given that the trans-Siberian railway already saves 14 days or so on the Far-East to Western Europe route (Loginovs, 2009), a potential modal shift in response to slower sailings could have a major economic impact. For extremely high-valued products where the cif is $85,000/tonne and the annual interest rate is 8%, an additional 26-day delay due to containership speed reductions of 40% would raise the difference of in-transit inventory costs to $743/tonne in favor of rail. Other scenarios for shorter distances may be devised, for instance within Europe or North America, which may favor cargo shifts to road transport, the result there being worse in terms of GHG emissions.

To formally quantify effects of speed reduction on modal split, assume that there are two mode options to move cargo from A to B; mode 1 is by ship and mode 2 is by rail or road. Let x_i be the fraction of the cargo that will choose mode i ($i = 1, 2$), assuming there is available capacity to do so ($0 \leqslant x_i \leqslant 1$) and assume the modes split follows a multinomial logit distribution;

$$x_i = \frac{e^{-\lambda C_i}}{e^{-\lambda C_1} + e^{-\lambda C_2}}$$

where λ is a positive constant; C_i is the generalized cost of mode i, equal to $C_i = p_i + kt_i$, with p_i as the freight rate from A to B via mode i ($/tonne), t_i as the transit time from A to B via mode i (days) and k as a positive constant ($/tonne/day). Variable k reflects the value of time for the cargo in question, and is commodity-dependent, being higher for more expensive cargoes; it is the per day and per tonne of cargo inventory cost of the cargo.

Assume now that speed is reduced in mode 1. The effect of this will be a net increase of transit time t_1, and possibly a change of the freight rate p_1, the latter being decided either by the carrier or being the result of a new market equilibrium. Assume that the parameters for mode 2 do not change. Transit time for mode 1 will increase as the average transit speed from V to $V - \Delta V$ falls; V being defined as the average speed so that it incorporates any effects of intermediate stops at ports en route. x_1^*, C_1^*, etc. denote the new parameters for mode 1; it can be shown that

$$x_1^* = x_1 e^{-\lambda(p_1^* - p_1) + k(t_1^* - t_1)}$$

If L_1 km is the distance traveled by mode 1, (which may not be the same as L_2, the distance traveled by mode two), then $t_1 = L_1/V$, $t_1^* = L_1/(V - \Delta V)$, and,

$$x_1^* = x_1 e^{-\lambda(p_1^* - p_1) + k\frac{L_1 \Delta V}{V(V-\Delta V)}} \tag{3}$$

Then if the exponent is close to zero, a reasonable approximation is:

$$x_1^* = x_1 \left(1 - \lambda(p_1^* - p_1) + k\frac{L_1 \Delta V}{V(V - \Delta V)}\right)$$

Table 2
x_1^*/x_1 as a function of k and the price difference.

$k/(p_1^* - p_1)$	0	-$100/tonne	-$200/tonne
$2/day/tonne	0.958	1.059	1.170
$5/day/tonne	0.898	0.993	1.097
$10/day/tonne	0.807	0.892	0.986

If we assume V is 800 km/day (an average speed of about 18 knots), ΔV is 0.3 V or 240 km/day (a reduction to about 12.6 knots in average speed), L_1 is 40,000 km, and λ is \$0.001/tonne, then the values x_1^*/x_1 can be calculated parametrically, as a function of k and the price difference $(p_1^* - p_1)$ as in Table 2.

One sees that if the freight rate stays the same, then the maritime share of cargo will always fall, and more so for more expensive items. The only chance that the mode's share may increase is if the speed reduction is accompanied by a simultaneous freight rate decrease, and this only for relatively cheaper cargoes.

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Corrigendum

Corrigendum: Balancing the economic and environmental performance of maritime transportation [Transportation Research Part D 15 (2010) 458–462]

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We have spotted an algebraic error in Psaraftis and Kontovas (2010), for which we are solely responsible. Fortunately, this error does not alter the conclusions of the paper.

On page 461, the following formula is postulated for the new fraction of traffic x_1^* that will choose mode 1 as a function of several other parameters:

$$x_1^* = x_1 e^{-\lambda(p_1^* - p_1) + k(t_1^* - t_1)}$$

The correct formula is

$$\frac{x_1^*}{x_2^*} = \frac{x_1}{x_2} e^{-\lambda(p_1^* - p_1 + k(t_1^* - t_1))}$$

This correction carries over to Eq. (3), which now is

$$\frac{x_1^*}{x_2^*} = \frac{x_1}{x_2} e^{-\lambda\left(p_1^* - p_1 + k\frac{L_1 \Delta V}{V(V - \Delta V)}\right)} \tag{3}$$

and to its approximation if the exponent is close to zero, which now is

$$\frac{x_1^*}{x_2^*} = \frac{x_1}{x_2}\left(1 - \lambda\left(p_1^* - p_1 + k\frac{L_1 \Delta V}{V(V - \Delta V)}\right)\right)$$

The only substantive difference with the previous formulation is that now x_1 (or $x_2 = 1 - x_1$) is an additional parameter that has to be specified, in addition to k and the price difference $(p_1^* - p_1)$. Below we realistically assume a value of $x_1 = 0.95$, but similar results pertain for different values. Table 2 will look as follows:

Table 2
x_1^*/x_1 as a function of k and the price difference.

$k/(p_1^* - p_1)$	0	−$100/tonne	−$200/tonne
$2/day/tonne	0.999	1.003	1.007
$5/day/tonne	0.994	1.000	1.004
$10/day/tonne	0.988	0.994	1.000

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As one can see, our main conclusion does not change: if the freight rate stays the same, then the maritime share of cargo will always fall, and more so for more expensive items. The only chance that the mode's share may increase is if the speed reduction is accompanied by a simultaneous freight rate decrease, and this only for relatively cheaper cargoes.

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Psaraftis, H.N., Kontovas, C.A., 2010. Balancing the economic and environmental performance of maritime transportation. Transportation Research D 15, 458–462.