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Low carbon maritime transport: How speed, size and slenderness amounts to substantial capital energy substitution

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ABSTRACT

Three responses that reduce energy consumption and CO_2 emissions in maritime transport are slower speeds, larger vessels and slender hull designs. We use crude oil carriers as our illustrative example; these represent nearly a quarter of international sea cargo movements. We estimate the potential and costs in these which can all be described as capital substituting for energy and emissions. At different degrees of flexibility and time scales: speed reductions are feasible immediately when there are vessels available, though more capital will be tied up in cargo. Deployment of larger and more slender vessels to a greater extent requires fleet renovation, and also investments in ports and infrastructure. A novel finding in our analysis is that if bunker costs rise as a result of emission costs (fees, quotas), then this may depress speeds and emissions more than if they result from higher oil prices. The reason is that for higher oil prices, more capital tied up in cargo may give cargo owners an interest in speeding up, partly counteracting the impulse from fuel costs that tends to slow vessels down. Emission costs, in contrast, do not raise cargo values.

Introduction

In this study, we analyze maritime transport – using crude carriers as an example only to discover that we revert to an old theme of capital energy substitutability, now of re-emerging importance. Limiting ourselves to a subset of emission reduction opportunities that exists with present technology, we demonstrate a big potential and responsiveness for reducing energy per unit of output, i.e. fuel use (and emissions) per ton mile transported. We demonstrate that much of the responsiveness is, in fact, capital substituting for energy, and in three ways:

Speed optimization

Traditionally, ships have typically been built to operate at their boundary speeds based on hydrodynamic considerations (Faltinsen et al., 1980). The boundary speed can be defined as the speed at which, for a given hull, the resistance coefficient starts to rise with increasing speeds (Silverleaf and Dawson, 1966). For an average bulk or tank vessel which typically has a

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block coefficient[1] in the 0.80–0.87 range (1.0 for a shoe box), the boundary speed area starts at 12–13 knots, with a gradual increase of resistance coefficient and power requirements rising toward infinity for speed above 16–17 knots (Lindstad et al., 2014). For vessel types designed for higher speeds such as large container carriers the block coefficient are much lower, i.e. in the 0.6–0.65 range. This gives boundary speed areas starting at 17–20 knots, and power requirements which go toward infinity for speeds above 26–27 knots. Today's high bunker prices have challenged the practice of running vessels at design speeds, i.e. typically 90–95% of boundary speeds, allowing an operational interest in the relationship between speed and emission (Corbett et al., 2009; Seas at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010; Lindstad et al., 2011; Jonkeren et al., 2012). A key insight builds on the observation that the power output required for propulsion is a function of the speed to the power of three. This implies that when a ship reduces its speed, the fuel consumption per freight work unit is reduced. This first emission reduction, through speed reduction only, is a very 'pure' substitution, capital for energy or emissions. Lower speeds basically require more capital tied up in vessels and cargo. If vessel capacity is available, as in a situation of an economic downturn and excess supply, capital tied in more cargo at sea will be a main consequence: in long term equilibrium slower cargo movements also require a larger fleet. In the current paper, we include the possibility that optimal speed is set jointly for cargo-owner and ship-owner, as would be economically efficient from society's perspective. This possibility can be envisaged concretely, for instance as they agree on a speed in the contract called the charter party. Such an optimal speed includes, in addition to the freight rate and the bunker prices traditional in the ship-owner's calculation, also the speed inducement given by the cost of capital tied up in cargo (Psaraftis and Kontovas, 2014) for instance as when the cargo owner gests paid at delivery and can free up capital from that point onwards. We apply costs of capital at various rates for this purpose, and note that for crude oil carriers – our study – the effect on speeds from an increase in oil prices combines the co-varying impulses of bunker price increases that slow vessels down and cargo price increases that speed them up.

Larger vessels

Second, larger ships – and shipments – tend to be more energy efficient per freight unit (per ton mile of goods transported) than smaller (Cullinane and Khanna, 2000; Sys et al., 2008; Notteboom and Vernimmen, 2009; Stott and Wright, 2011; Lindstad et al., 2012; Lindstad, 2013). The key observation is that when the ship's cargo-carrying capacity is doubled, the required power and fuel use typically increases by about two thirds, so fuel consumption per freight unit is reduced. The vessel's building cost increases with about half of the increase in cargo capacity, and also costs of crew, maintenance and management rise less than proportionally with cargo capacity.

Slenderness

Third, while speed reductions and economies of scale in vessel and shipment sizes often require changes in the supply chain due to longer transport times, port requirements and storage facilities, it is possible to introduce more energy efficient designs (we call these slender designs) without changes to the logistics. Lindstad et al. (2013b) have analyzed potential cost and emission reductions for Panamax bulkers by increasing the vessel beam (width) to enable more slender hull forms and longer bow sections, while maintaining the cargo carrying capacity. These changes reduce the block coefficient and increase the boundary speed, allowing a reduction in fuel consumption per freight unit. These alternative designs are too large for the existing Panama Canal, but they could give significant cost and emission reductions when the new canal locks open in 2016. Despite its importance, the Panama Canal is not the only infrastructure that limits the external measurements of the vessel. When external hull dimensions cannot be increased, the only option for making vessels more slender will be to reduce their cargo carrying capacity compared to more full bodied designs. Lindstad et al. (2014) have assessed profit, costs and emissions for such slender bulk vessel designs and shown that designs with up to 30% lower cargo carrying capacity, can give lower costs and emissions per ton transported. Regarding sensitivity, these slender designs outperform the traditional full bodied designs with fuel price at 2012–2014 levels, i.e. 600 USD per ton, but they comes out competitive even at bunker fuel prices as low as 300 USD per ton.

While we shall go through these estimates in detail, below, we can notice that – quite roughly – the three responses that we study; speed, size and slenderness, all represent a higher input of capital per ton-mile produced. This is most markedly for speed (which requiring more cargo and ships at sea) and for slenderness (which requires a somewhat costlier build for a given carrying capacity). For larger vessels, the vessel and non-energy costs will be lower per freight unit and for a given amount of cargo at sea, but capital requirements will be greater at port sides, both because of larger storage requirements and the infrastructure required for handling larger vessels and shipments.

Methods

The employed model enables assessment of cost, fuel consumption and emissions as a function of vessel speed, sea conditions and vessel characteristics, i.e. vessel size, hydrodynamic design and cargo load (Lindstad et al., 2014). The system boundaries focus on the vessels and their use, so the land side of the port terminals is excluded. The model consists of three

[1] Block coefficient is defined as $C_B = \frac{\nabla}{L \cdot B \cdot T}$ where ∇ is the displaced volume, L is length, B is beam and T is draught.

main equations, of which the power element describing fuel consumption is the most important. The power function takes into account: the power needed for still water conditions P_s, the power.

Required for waves P_w, the power needed for wind P_a, the required auxiliary power $P_{aux,}$ and propulsion efficiency η as expressed by Eq. (1).

$$P_i = \frac{P_s + P_w + P_a}{\eta} + P_{aux} \tag{1}$$

$$P_s = \frac{\rho \cdot C_s \cdot S \cdot v^3}{2}$$

$$P_w = \frac{C_{w} \cdot \rho \cdot g \cdot \left(\frac{H_{1/3}}{2}\right)^2 \cdot B^2 \cdot \omega}{L} \cdot (v + u)$$

$$P_a = \frac{C_a \cdot \rho_a \cdot A \cdot (v + u_a)^2}{2} \cdot v$$

$$\eta = \min\left(\eta_0\left(j + k \cdot \sqrt{\frac{v}{V_d}}\right), \eta_0\left(1 - r \cdot H_{\frac{1}{3}}\right)\right)$$

The still water power is given by P_s, where, ρ is the density of water, C_s is the total still water resistance coefficient, S is the wetted surface and v is the ship speed (Lewis, 1988). This implies: First that when a ship reduces its speed, the fuel consumption per freight work unit is reduced; Second that a more slender design with equal cargo carrying capacity as a full bodied design can sail at a reduce fuel consumption per freight unit due to its lower resistance coefficient.

The power requirement due to wave resistance (Lloyd, 1988) is given by P_w where C_w is the drag coefficient for the added wave resistance, ρ is the density of water, g is the vertical force, $H_{1/3}$ is the significant wave height (the amplitude is half the height), B (beam) is the width of the ship at the waterline, L is the length of the ship at the waterline, v is the vessel speed, ω is the wave circular frequency and u corresponds to the speed of the waves relative to that of the vessel, u defined as $u = v + \frac{\omega}{k}\cos\beta$ where k is the wave number and β is the wave direction, defined so that $\beta = 0$ is head waves. The drag coefficient for the added wave resistance is a function of the relationship between width (beam) of the vessel and bow section length. This implies that if two vessels have the same beam measurements, the one with the longest bow section will experience less added resistance in waves compared to the one with a shorter bow section (Van der Boom, 2010). In rough sea, which reduces the achievable speed for all vessels, a slender design can therefor maintain a higher speed compared to the more full bodied designs (Faltinsen, 1990; Lindstad et al., 2013b, 2014).

The additional power for wind resistance (Lewis, 1988) is given by P_a where C_a is the drag coefficient for the aerodynamic, ρ is the density of air, A is the surface area projected for the wind, v is the vessel speed, and u_a corresponds to the component of the speed of the wind against the direction of travel of the vessel.

The auxiliary power, P_{aux}, needed for running pumps and for producing electricity for lighting as well as all the supporting systems of the ship, is a function of the vessel type and size, and the cargo it carries.

The propeller efficiency η is a function of the vessel speed and sea condition, and η_0 corresponds to the propulsion efficiency at the design speed V_d and calm sea. The model implies that the propulsion efficiency drops when speed is reduced or when the significant wave height increases $H_{1/3}$ (Lindstad et al., 2013a, 2014).

The cost per ton transported comprises the fuel cost and the time charter equivalent cost (TCE) which covers the financial items, depreciation and operating cost of the vessel, as expressed by Eq. (2):

$$C = \frac{1}{M}\sum_{i=0}^{n}\left(\frac{D_i}{v_i}\cdot\left((K_f \cdot P_i \cdot C_{Fuel}) + \frac{Capex\, v_{k_1k_2}}{24}\right)\right) + \left(D_{lwd}\cdot\left((K_f \cdot P_{aux} \cdot C_{Fuel}) + \frac{Capex\, v_{k_1k_2}}{24}\right)\right) \tag{2}$$

The equation consists of two terms, the first calculates cost at sea and the second calculates cost in ports. Here M is the weight of the cargo carried. During a roundtrip voyage, the sea conditions will vary and this is handled by dividing each voyage into sailing sections, with a distance D_i for each sea condition, and the total for the voyage is given by the summation of the sailing sections from 0 to n. The second factor (D_i/v_i) gives the hours in each section of the voyage. The hourly fuel cost per section is given by $(K_f \cdot P_i \cdot C_{Fuel})$; where K_f is the fuel required per produced kW h, P_i is power required and C_{Fuel} is the cost per fuel unit. In addition to fuel, the cost of operating a vessel comprises financial items, depreciation and operating cost expressed as $Capexv_{k1k2}$. Here, $Capexv$ is the new-building price of the vessel, k_1 of $Capexv$ gives the daily fixed and variable cost as a percentage of capex, and k_2 gives the daily basic fixed amount, which is independent of vessel size and its new-building cost. The second term calculates cost in ports when loading, discharging and waiting based on total days used D_{lwd}.

The fuel consumption per ton transported is given by Eq. (3).

$$F = \frac{1}{M}\sum_{i=0}^{n}\left(\frac{D_i}{v_i}\cdot(K_f \cdot P_i)\right) + (D_{lwd}\cdot(K_f \cdot P_{aux})) \tag{3}$$

The equation consists of two terms: the first calculates fuel at sea and the second fuel in ports.

Data

The vessel types in focus for this study are ocean going tankers which transport crude oil from oil-producing areas to the oil-refineries. In total, these vessels perform 20–25% of the global seaborne freight work, measured in ton nautical miles (UNCTAD, 2014). More than 90% of the crude is transported by Aframax, Suezmax or Very large crude carriers (VLCC). Typical size of an Aframax is 90–120 000 dwt, where deadweight (dwt) expresses how much a vessel can carry at most. For Suezmax, which are the largest tankers which can pass the Suez Canal, typical sizes are 140–200 000 dwt. While VLCC tankers are around 300 000 dwt. Table 1 shows the main characteristics of typical Aframax, Suezmax and VLCC tankers and the same values for the alternative designs. The first alternative design is a slender Aframax with reduced cargo carrying capacity compared to a standard Aframax. The second is a wide and long Aframax with a very slender hull form and hence lower block coefficient. The third is a Suezmax built according to maximum beam for Suez and with extended length. The new-building prices are based on average 2014 broker's reports and the daily time charter equivalent (TCE) is calculated based on these prices with $Capex\,v_{k_1}$. = 9% p.a. and $Capex\,v_{k_2}$ = 3000 USD per day. It should be noted that the new-building cost for the alternative designs is higher than for the standard designs per dwt, since the cost of making the hulls will be higher. Three fuel prices are used: C_{Fuel}, 300 USD/ton which was the level early 2015; 600 USD/ton which was close to the average for the period from 2012 to 2014; and 900 USD/ton to simulate what would happen if fuel prices increased 50% above the average 2012 to 2014 level. When fuel prices increase, the cargo inventory costs (given by the value of the cargo multiplied with the required daily return) increase proportionally, and this gives a financial encouragement to increase speeds on the laden leg. The explanation is that higher laden speed reduces laden voyage days and hence the cargo inventory costs (see, for instance, Psaraftis and Kontovas, 2014). While a large oil company can consider crude oil on board a vessel as part of its supply chain and hence be indifferent with some days at sea relative to in other storage (thus perhaps use zero or a low interest, and perhaps the production cost of oil rather than its market price), oil traders will generally have higher financial cost and hence a higher daily cargo inventory cost. However in periods with higher volatility in oil prices, the potential profit or loss by delaying cargo or even use crude oil tankers as storage might far exceed any increase or decrease of the cargo inventory cost: To investigate the impact of the cargo inventory cost we use two interest levels, zero to show the impact if the cargo inventory cost is not taken into consideration, and 15% per annum to represents a high contrast but not atypical for risk-prone businesses like petroleum, commodity trading, and shipping. Lower or zero interest rate allows lower speeds: letting inexpensive capital substitute more forcefully for energy. This effect is very similar to our comparison of a higher bunker price with a lower, illustrating that the relative price between capital and energy is at work in capital/energy substitution.

Regarding wind and weather patterns, these vessels operate globally. Instead of using only calm sea conditions or data from the Pacific or North Atlantic, we use a simplified model containing 30% with 4 m head waves and 70% calm water conditions (Lindstad et al., 2013b, 2014). The wind speed u_a is taken as zero in calm water and 14 m/s in the 4 m head waves condition, rewarding performance in rougher sea without neglecting calm sea performance.

The operational profile for these vessels will generally be a function of their size; the largest vessels will do the longest voyage and that the smallest will do the shortest and hence more voyages per year. This reflects that tonmile work of transport is most efficiently done by larger vessels while the docking and loading and unloading at each end are actually better done by smaller ones. Jansson and Shneerson (1982) develop this point: 'handling cost per ton becomes higher as ship size increases, whereas hauling costs per ton becomes lower'. In their work 'factor substitution takes place exclusively via changes in ship size' leaving greater room for responsiveness in our work which includes variation in speed and hull design. In some trades, two Suezmax vessels or three Aframax vessels can substitute for a VLLC vessel, in other trades, port or canal restrictions will limit the substitution opportunities. To give one example, a VLCC from Arabic Gulf to Europe will have to sail around Africa, while the Suezmax or Aframax tankers take the much shorter route through the Suez Canal. Of course, though at higher bunker costs the value of canal and port expansions are higher, such expansions are in some contexts prohibitive, in others costly and of a long term nature, still representing capital substituting for energy, emissions and other inputs.

Our calculations are based on one way voyages of 4500 nm, carrying their design load (typically 85% of their maximum), and returning empty in ballast. We include waiting, loading and discharging, and the fuel required to heat and pump the crude.

Results

We examine the question of how much it can cost to reduce carbon emissions, which is equivalent to reducing fuel consumption.

Vessel speeds

First we estimate how carbon emissions per tonmile transported are reduced through slower speeds. Fig. 1 shows round-trip costs and fuel use per ton of crude transported for a standard Aframax 110′ dwt. The common vertical axis represents the cost in USD per ton of crude transported, as a function of vessel speed on the right-hand side of the figure, and as a function of fuel usage on the left-hand side. We can thus read fuel use reduction as a function of speed reduction. The right panel shows costs, and the speed which minimizes ship owner's cost, i.e. not including the cargo inventory cost for three

Table 1
Main vessel characteristics.

	Dwt ton	Main dimensions meter	Block coefficient	New-building price MUSD	Time charter equivalent – TCE USD/day
Aframax 110′ dwt	110000	234 × 42 × 15.5	0.83	54	16400
Aframax 100′ dwt – Slender	100000	234 × 42 × 15.5	0.75	50	15400
Aframax 110′ dwt – with Suezmax Length & width	110000	264 × 48 × 15.5	0.66	60	17800
Suezmax 158′ dwt	158000	264 × 48 × 17.2	0.82	65	19100
Suezmax 158′ dwt – Long & wide	158000	303 × 50 × 17.2	0.7	70	20300
VLCC 300′ dwt	300000	320 × 60 × 21.5	0.81	95	27500

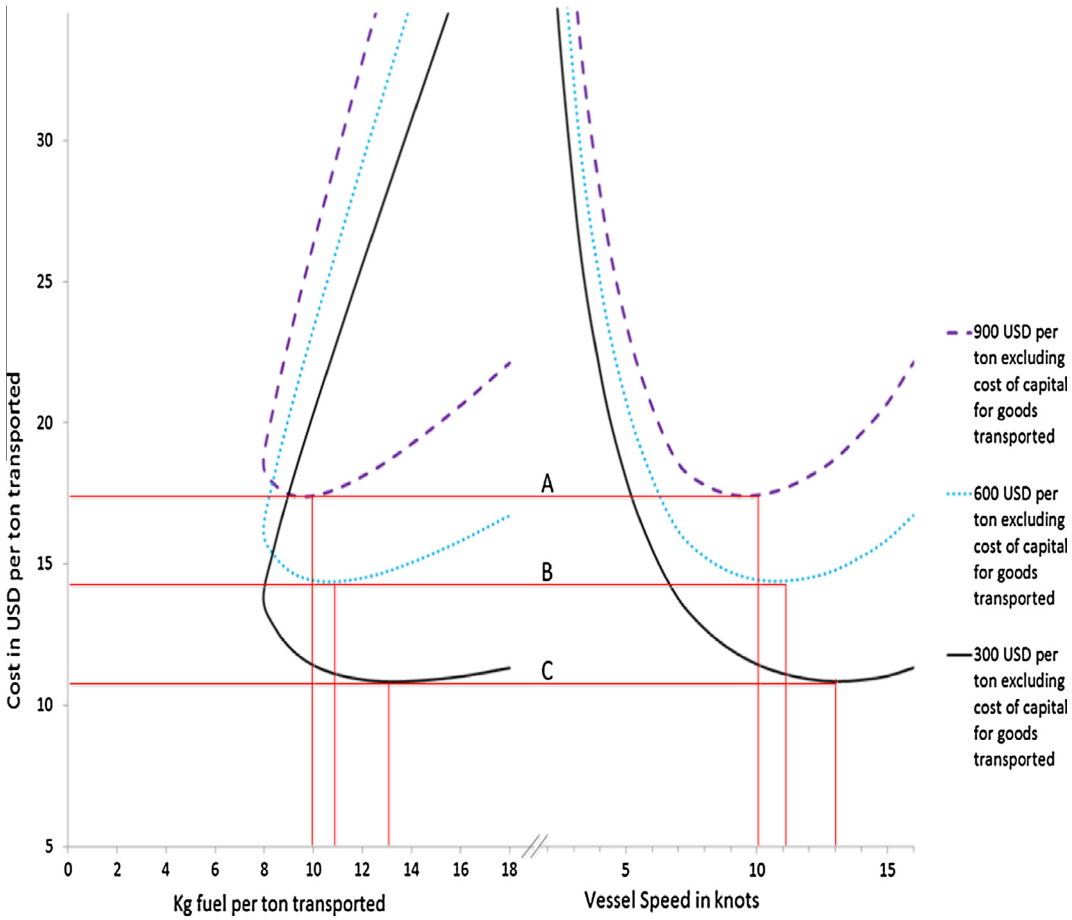

Fig. 1. Fuel and cost per ton transported as a function of speed and fuel cost for a standard Aframax.

alternative fuel prices. The letter A is used to mark the cost minimizing speed for the highest fuel cost, i.e. 900 USD per ton, the letter B for a fuel cost of 600 USD per ton and the letter C for the lowest fuel cost, i.e. 300 USD per ton.

The figure shows that when fuel prices increase, the cost minimizing speed for the roundtrip voyage decreases from 13 knots with a fuel price of 300 USD per ton to 11 knots with a fuel price of 600 USD per ton and to 10 knots with a fuel price of 900 USD per ton. Independently of oil price the cost minimizing laden speeds will be around 1.5–2 knots lower than the ballast speeds, since lower resistance makes it cheaper to sail faster in ballast than laden. Another observation is that at higher fuel prices the cost difference between operating at highest achievable speed (15–16 knots) is about 30%, compared to 10% at the lowest fuel price. Thus, in a low fuel cost environment, not only do vessels run fast and close to design speed, but the industry also pays less attention to speed optimization.

The curves demonstrate that a reduction of the speed below the design speed reduces fuel consumption and hence emissions. The fuel reduction is largest for the first percentages of speed reduction. At very low speeds, further reductions in speed lead to longer voyage times and raises fuel consumption per ton of crude transported.

Cargo inventory cost

To investigate the impact of the cargo inventory cost we use two interest rate levels, zero to show the impact if the cargo inventory cost is not taken into consideration and 15%. These are meant as illustrations; a zero rate may apply in conditions where cargo owner's capital interests are not conveyed to shipment operations (or cargo owner is indifferent between oil at sea and actually delivered), and 15% may be a very high loan interest rate but a reasonable return requirement in a risk prone business. Implications of lower and higher rates as well as of alternative assumptions are straightforward extensions and not shown.

When cargo inventory cost is included, it shifts the entire curve upward and to the right, as illustrated in Fig. 2 for a standard Aframax. Following this, the cost minimizing speed for the roundtrip increases when the value of the cargo are included. The magnitude of this shift is given by capital cost of the goods relative to the time charter and fuel costs. Fig. 2 shows that the impact of including the financial cost of the crude onboard raises the cost minimizing speed from 11 to 12.5 knots for a fuel price of 600 USD per ton. It can also be observed that the cost terms that increase when the speed is reduced are the time charter and the capital costs, while fuel costs reach their minimum around seven knots. Similar cost curves could be shown for both the Suezmax and the VLCC, where the difference will be that the larger vessels will have lower total cost due to economies of scale both in fuel use and the time charter equivalent (TCE) vessel costs. Fig. 3 shows the ballast and laden cost minimizing speeds with and without the cargo inventory cost for a standard Aframax with the same fuel price as in Fig. 2, i.e. 600 USD per ton. For the ballast leg there is no cargo inventory cost and hence only one cost minimizing speed.

The main observations are: First, the cost minimizing laden speed increases from 10 to 13 knots when the cargo inventory cost is included which raises the roundtrip average from 11 to 12.5 knots; Second, when the cargo inventory cost is included in the speed optimizing decision, the laden speed will be higher than the ballast speed, while the opposite will be the case if speed is set by engineering criteria (a certain speed costs more on loaded leg than in ballast), and with low or no concern for capital tied in cargo.

A view reflecting our conversations with industry practitioners is as follows: In freight contracts, agreements are made on speed, in principle allowing cargo owner's concerns for delivery time and capital tied in cargo to influence speed. But practitioners and industry observers might argue that this speed agreement may be dominated by routine, and thus being sluggish and leaving room for discretion to ship-owner. With crude carriers' dominance of spot freight (single voyage delivery agreements), ship-owners will typically have the full decision making alone in ballast leg, while cargo owners' concern leads to higher speeds on loaded legs than in ballast when low freight rates coincide with high oil prices (and capital costs). A recent study published by the GENSCAPE (2015) vessel tracker company for large crude oil carriers (VLCC) on the TD3 route transporting oil from Middle East to Japan shows that the laden speed in 2013 and 2014 was nearly constant at 12.5–13 knots while the ballast speed varied between 11 and 13.5 knots in the same period. And that the highest ballast speeds, occurred when the freight rates where high and the lowest when the freight rates where low. Another observation is that both laden and ballast speeds has increased in 2015 after the crude oil and bunker prices dropped by around 50% compared to 2012–2014 levels. The larger variance in ballast speeds compared to laden speeds seen since 2008 has also been described by Gkonis and Psaraftis (2012) and ultra-slow steaming in ballast with speeds down to the 5–7 knots when freight rates are low.

The importance of the daily cost of financing the cargo in transit, i.e. the cargo inventory cost on the speed decisions for shipping in general has been analyzed previously by (Psaraftis and Kontovas, 2010, 2013; Lindstad et al., 2011). What is special in the case of crude oil transport is that when the fuel price increases, the value of the cargo increases proportionally. In contrast, with the exception of the interest rate, there are no corresponding directs links between bunker prices on the one hand and value of goods transported by for instance container lines on the other hand. This is one of the explanation why the average operational speed of crude oil tankers above 80000 dwt has been reduced only from 14 to 12 knots from 2007 to 2012, while the average operational speed of container vessels in the same period has been reduced from 21 to 16 knots (Smith et al., 2014). Other explanations are a much larger overcapacity in the container segment and higher fuel intensity.

It is therefore worth investigating if a Market Based Measure such as a fuel tax or a CO_2 scheme will be a more efficient measure to reduce fuel consumption and hence emissions for crude oil carriers. The main difference will be that an emission tax (or quota system) will raise the cost of burning oil, just like an oil price increase – both for the vessel and end user of the cargo – but an emission tax does not raise the value of the oil in transit. Fig. 4 compares the effect of fuel price of 900 USD per ton where the cost minimizing speed is marked by the line with letter A, with a CO_2 cost per ton of 100 USD introduced on top of the fuel price, also raising fuel costs from 600 USD to approximately 900 USD per ton and the related cost minimizing speed as marked by the line with letter B.

The main observation when comparing the curves in Figs. 1 and 4 is that the inclusion of cargo inventory costs raises the cost minimizing speed: by 1.5 knots to 14.5 knots for the lowest fuel price (D), and by 1.5 knots to 12.5 for a fuel price of 600 USD/ton (C) and 11.5 knots for a fuel prices of 900 USD per ton (D). Comparing the effect of fuel price increases versus the effect of similar increases through a fuel tax or a CO_2 fee, the following observations can be made. Fig. 3 shows that a 50% increase of the fuel price from 600 to 900 USD reduces the cost minimizing speed from 12.5 to 11.5 knots and fuel consumption from 13.1 to 11.6 kg per ton of crude transported. In comparison if fuel cost is increased similarly through a CO_2 fee the cost minimizing speed is reduced from 12.5 to 11 knots and fuel consumption from 13.1 to 10.9 kg per ton of crude trans-

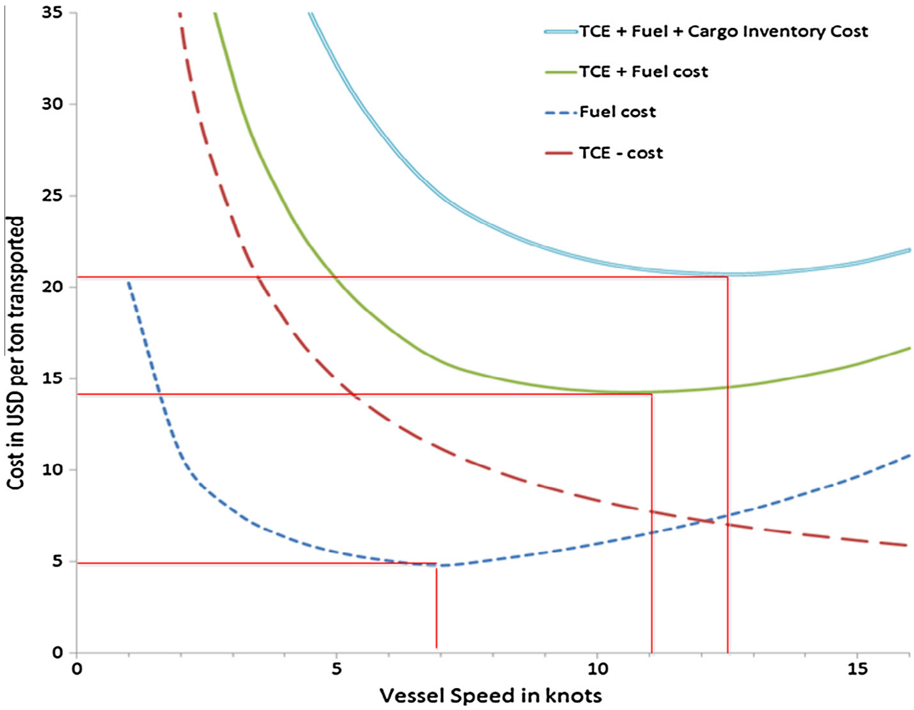

Fig. 2. Cost per ton transported as a function of speed and cost terms for a standard Aframax.

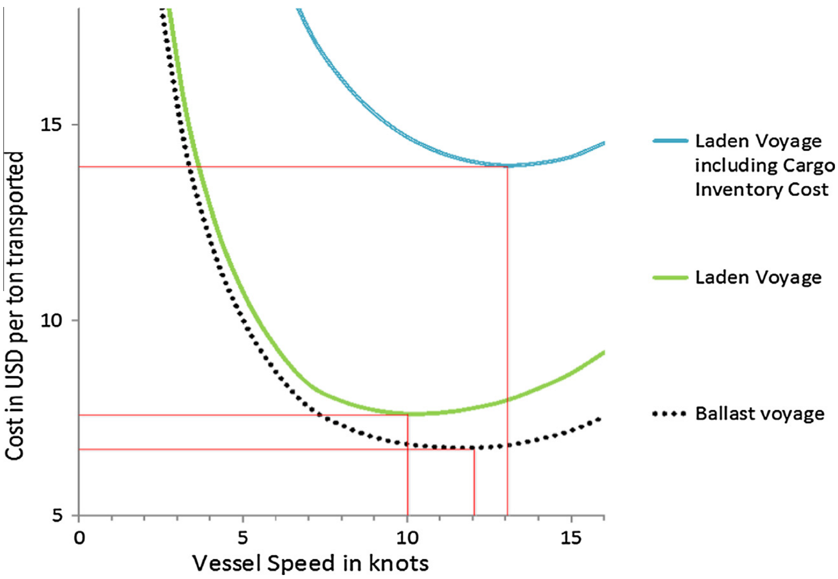

Fig. 3. Laden and ballast voyage cost per ton as a function of vessel speed.

ported. Thus, for crude oil tankers, CO_2 fees reduce speeds and emissions more than the oil price increases that would give the same rise in cost per ton of fuel.

Slender hulls and larger vessels

Going one step further, we investigate the question of how much it can cost to reduce carbon emissions through more slender vessels, through larger vessels and the combined effect of all the investigated measures. Fig. 5 illustrates the potential cost saving through more slender vessels, through larger vessels and the relationship between these measures and the speed, all at bunker price assumed at 900 USD per ton.

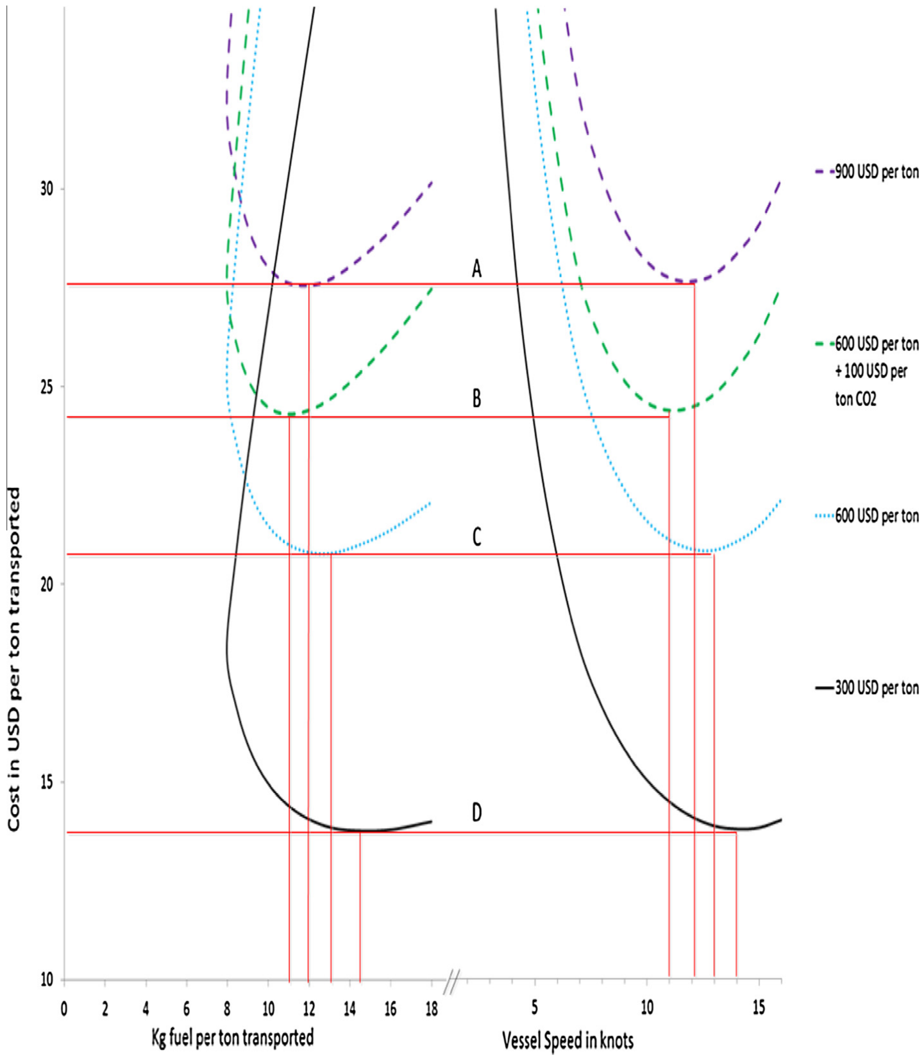

Fig. 4. Fuel and cost per ton transported for a standard Aframax as a function of speed and fuel and carbon price.

The main observations are: First, replacing a standard Aframax 110′ dwt with one which is slightly more slender, i.e. the 100′ dwt Aframax reduces cost and emissions per ton transported (and thus, for a given voyage, per tonmile); Second, larger reductions can be achieved by replacing it with an Aframax with Suezmax length and width. This reduces cost and emissions from line A to line B; Third, replacing the Standard Aframax with a Suezmax increases these savings further as illustrated by the difference between the lines A and C; Fourth, for Suezmax vessels the difference between the standard design and the slender design are smaller compared to the difference between the alternative Aframax designs. The explanation is that the Suez canal limits the opportunities for significant increases of external measurements; Fifth the largest savings are achieved by employing the largest vessels, i.e. VLCC as shown by the difference between line A and D, however it comes at the cost of more capital tied up in port infrastructure and in raw material (for some trades, obviously, a benefit of smaller vessels is a shorter distance, through a canal). In addition these larger vessels cannot be used in all trades due to port or fairway restrictions. While some such restrictions will be relieved if the economic environment favors energy- and emission efficiency more strongly than today, the costs of such infrastructure changes are beyond this analysis.

In Table 2 the key figures are shown and compared as a function of vessel design and fuel and carbon price. The first column gives the design, its measurements and capacities. For each design there is one line for speed, one for cost and one for fuel. The first main column shows the key figures for each of the designs if they were operated at 16 knots and a fuel cost of 600 USD per ton. It should be noted that we quote 16 knots as design speed for all designs, for simplicity of exposition. In reality, typical designs speed for Aframax is around 15–15.5 knots with max speeds of 16 knots while the VLCC's have design speeds around 16 knots and max speeds up to 17 knots.

Then follows the key figures at cost minimizing speeds for the investigated fuel prices: 300 USD per ton; 600 USD per ton; 600 USD per ton plus a CO_2 fee of 100 USD per ton CO_2, which gives a fuel equivalent cost of approximately 900 USD per ton;

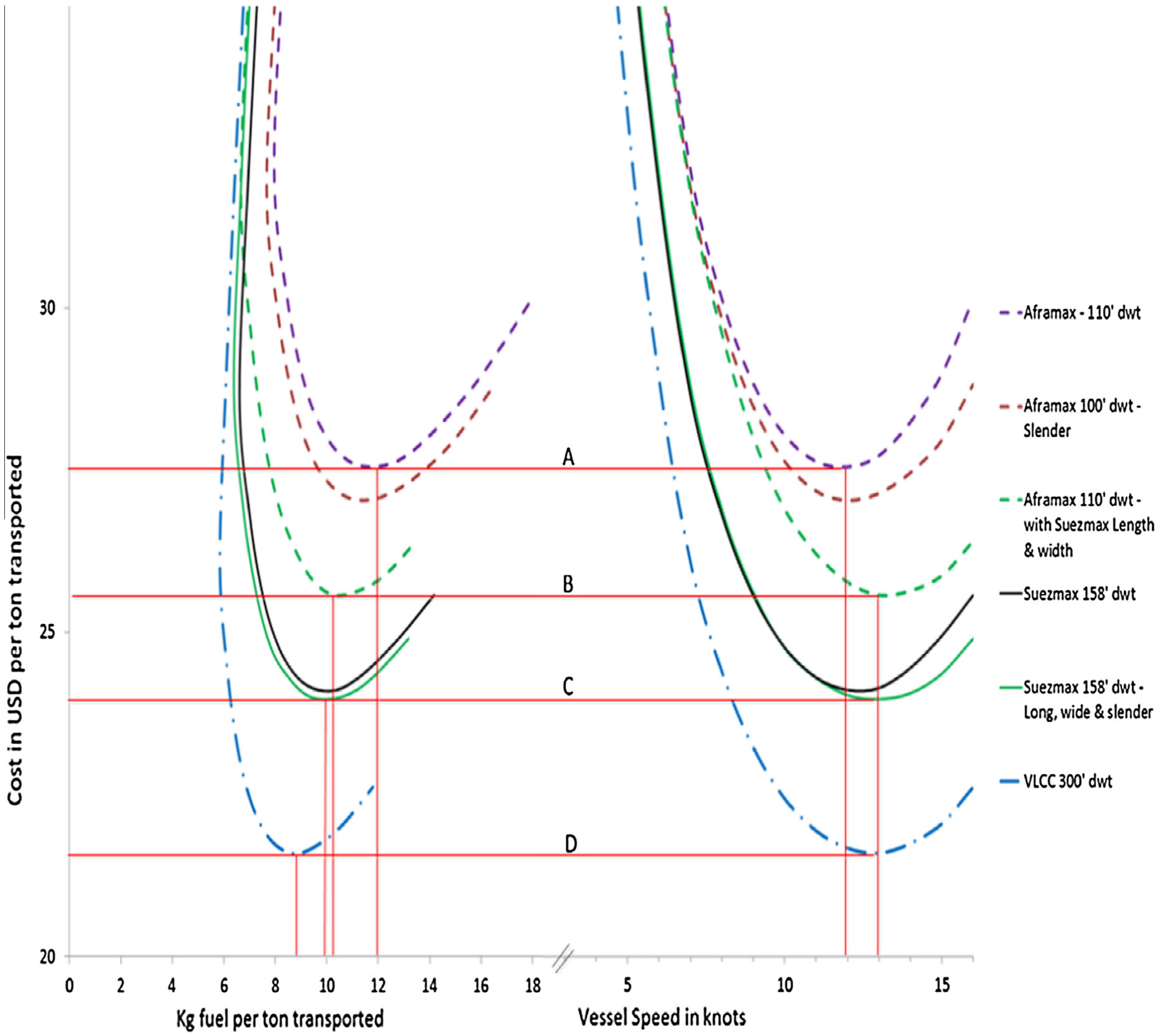

Fig. 5. Fuel and cost per ton transported as a function of speed and vessel size and design (fuel price = 900 USD per ton).

and then simply a bunker price of 900 USD per ton. First we compare operation at design speed with cost minimizing operation for a fuel price of 600 USD per ton; Second the additional effect of a CO_2 tax which increases the effective price of burning fuel to 900 USD is investigated; Third, the effect of a pure fuel price increase to 900 USD per ton is investigated. The two last columns shows for a given vessel the elasticity's of speed and fuel consumption with respect to a fuel price increase through a CO_2 fee and through a pure fuel price (both give a fuel equivalent price of approximately 900 USD per ton). It should be noted that the carbon content in the fuel is a fuel specific value, i.e. 3.2 per kg of fuel for Heavy Fuel Oil, 3.1 kg for Marine Diesel Oil and 2.7 for Liquid Natural Gas and not 3 kg CO_2 per kg fuel, however these details do not influence the main results of the comparison.

The first observation is that when vessel reduces their speed bellow design speed, the cost reduction is much smaller than the reduction in fuel consumption and hence emissions.

The second observation is that the performance advantage of slender vessels compared to standard designs are a significantly lower fuel consumption at high speeds, i.e. 25% lower per nautical mile at 15–16 knots versus 10–15% at cost minimizing speeds with fuel cost of 600 USD per ton or above.

The third observation is that the largest vessels, i.e. the VLCC can operate at 16 knots with 34% lower fuel consumption and a cost which is 25–27% lower than the standard Aframax. If the comparison is made at the cost minimizing speed, the reduction in fuel consumption and emissions are about the same, percentage wise. In comparison with the slender designs, economies of scale reduce costs more but reduce fuel and emissions less. This is logical since the larger vessels can add savings in personnel and building costs to the savings in fuel economy.

Fourth; when the fuel price increases, the cargo value of the crude increases proportionally (at constant interest rates) and this gives a financial encouragement to increase speed which partly counterbalances the bunker price inducements

Table 2
Comparing key figures as a function of vessel design and fuel and carbon price.

		Design speed	Cost minimizing operation				Cost minimizing compared to design speed	Change with Fuel cost increase from 600 USD per ton		Elasticities with respect to fuel cost, ton nm kept constant	
		600 USD/ton	300 USD/ton	600 USD/ton	600 USD/ton + CO_2 100 USD/ton	900 USD/ton	600 USD/ton (%)	600 USD/ton + CO_2 100 USD/ton (%)	900 USD/ton (%)	600 USD/ton + CO_2 100 USD/ton	900 USD/ton
Aframax 110′ dwt											
Speed	knots	16.0	14.5	12.5	11.0	11.5	−22	−31	−28	−0.24	−0.16
Cost per ton	USD/ton	22.1	13.8	20.8	24.3	27.6	−6	17	33		
kg fuel per ton	kg/ton	18.0	14.5	13.1	10.9	11.6	−27	−17	−11	−0.34	−0.23
Aframax 100′ dwt – slender											
Speed	knots	16.0	15.0	13.0	11.0	11.5	−19	−31	−28	−0.31	−0.23
Cost per ton	USD/ton	21.2	13.5	20.4	23.9	27.0	−4	17	33		
kg fuel per ton	kg/ton	16.6	15.0	12.5	10.4	11.2	−25	−17	−10	−0.33	−0.21
Aframax 110′ dwt – with Suezmax length & width											
Speed	knots	16.0	16.0	14.0	12.5	13.0	−13	−22	−19	−0.21	−0.14
Cost per ton	USD/ton	19.7	13.0	19.4	22.6	25.6	−2	16	32		
kg fuel per ton	kg/ton	13.5	13.5	11.2	10.0	10.5	−17	−11	−7	−0.22	−0.13
Suezmax 158′ dwt											
Speed	knots	16.0	14.5	12.5	11.0	11.5	−22	−31	−28	−0.24	−0.16
Cost per ton	USD/ton	18.8	11.7	17.9	20.8	23.9	−5	16	33		
kg fuel per ton	kg/ton	14.2	12.9	10.9	9.1	9.6	−23	−17	−12	−0.34	−0.24
Suezmax 158′ dwt – long & wide											
Speed	knots	16.0	15.0	13.0	12.0	12.5	−19	−25	−22	−0.15	−0.08
Cost per ton	USD/ton	18.4	11.7	17.7	20.9	24.0	−4	18	35		
kg fuel per ton	kg/ton	13.2	11.9	10.6	9.2	10.0	−20	−13	−6	−0.26	−0.11
VLCC 300′ dwt											
Speed	knots	16.0	14.5	12.5	11.5	12.0	−22	−28	−25	−0.16	−0.08
Cost per ton	USD/ton	16.4	10.1	15.8	18.4	21.3	−4	16	35		
kg fuel per ton	kg/ton	11.8	10.2	8.8	8.1	8.6	−25	−8	−3	−0.17	−0.05

to reduce speeds. In comparison, if a bunker price increase instead is induced by a CO_2 fee, there are no financial encouragements from cargo inventory value to speed up. Due to this, the elasticity of speed with respect to fuel costs is higher in absolute value when it results from an emission fee:

−0.24 compared to when it results from higher oil prices: −0.16. A similar responsiveness is found for the Slender Aframax and the Suezmax. The elasticities of fuel consumption or emissions per ton mile show a similar pattern, due to the responsiveness in speed and the corresponding responsiveness in fuel consumption per ton mile: the Aframax 110′ dwt reduces emissions for a given amount of transportation work with an elasticity of: −0.34 if the fuel price increase is through an emission fee, compared to: −0.23 if the fuel price increase is through a general oil price increase.

Discussion

We have examined the quantitative scope and costs of reducing carbon emissions with today's vessels and today's technology. Our results indicate:

Speed

First, the current operational speed of the crude oil tankers (Smith et al., 2014) is in the same range as the cost minimizing speeds with today's fuel prices; When comparing the obtained results to data from other studies regarding cost and emissions through speed reductions, they were found to be within a similar range as those presented by Corbett et al. (2009), Sea at Risk and CE-Delft (2010) and Lindstad et al. (2011). The observation that maritime shipping output is highly elastic as long as capacity is only partially employed was made early by pioneering economists working with oil tankers as examples (Koopmans, 1939; Johansen, 1972).

Slender hull designs

Second, more slender vessel designs reduce costs for all the investigated fuel prices, thus providing emission reductions at no cost when new-buildings are forthcoming (i.e. with a greater time lag than speed changes). Comparing these results with the traditional rules of thumb in ship design and operation, the contrast is quite stark. Traditionally tank and bulk vessels have been built with high block coefficients to maximize the cargo-carrying capacity for given external dimensions, while our conclusion is that even with the lowest investigated fuel price i.e. 300 USD per ton of fuel, more slender designs with lower block coefficient reduce costs. These results are found to be within similar range as those presented for dry bulker by Stott and Wright (2011), Lindstad et al. (2013b) and Lindstad et al. (2014).

Larger vessels and shipments

Third, larger vessels reduce costs per ton mile. Comparing the results with data from other studies of reductions in emission and cost, they were found to be within a similar range as those for container vessels presented by Notteboom and Vernimmen (2009) and for all cargo vessel types by Lindstad et al. (2012). In general there are few studies within this area, although figures are available that demonstrate the importance of economies of scale for emission reductions per freight unit since the Second World War (Buhaug et al., 2009; Jansson and Shneerson, 1982). The importance of economies of scale through larger vessels is also – together with reduced operational speed – the main reason for the reduction in total GHG emissions from 2007 to 2012 as documented by Smith et al. (2014), i.e. the average cargo vessel has increased from 22 500 dwt in 2007 to 30 500 dwt in 2012.

Fourth, when fuel prices increase, the capital cost of crude oil cargo increases proportionally (assuming constant interest rates) and this gives a financial encouragement to increase speed, partly counterbalancing the bunker price inducements to slowing down. The results of including the cargo inventory cost on the speed decisions has been analyzed previously by Lindstad et al. (2011), Psaraftis and Kontovas (2010, 2013). While in the case of transport of crude oil and oil products fuel prices and cargo values move together, there are no corresponding directs links for other trades.

Fifth an increase in bunker prices, especially when resulting from an emission charge, raises the competitiveness of vessels that are more slender within each class and raises the competitiveness in terms of costs for larger versus smaller shipments and vessels. These responses will to some extent be increasing over a slightly longer time scale, since they may require new-buildings and certain changes in ports, handling equipment, tanks, dredging etc., but they will be certain to result to a small extent in the short term, too, if the industry is exposed to a pressure to reduce emissions. Such inducements should include inducements to such sensible and economically efficient measures as slowing down shipments and making shipments in more energy efficient hulls, be they larger or more slender or both. For this reason, CO_2 taxes or fees are more effective than fuel price increases when the cargo to be transported is crude oil or other products where their value is a direct function of the oil price.

Conclusions and policy implications

Transport is an energy intensive activity, and thus generally emission intensive. But maritime transport is also fairly energy efficient and emission efficient. An illustration of this fact is that a very large crude oil carrier (VLCC), roughly transporting the same commodity as it burns – will only burn about a percent of what it can deliver on a voyage as long as Arabian Gulf to the US. Crude oil transport, thus, can be seen fairly literally as a Samuelson iceberg model of transport: what part of 'cargo value' is sacrificed when shipping from A to B (Krugman, 1991). As we show here, the part of the crude oil cargo that is consumed – and emitted – is sensitive to hull shape, shipment size and speed, and to factors determining these, such as oil and bunker prices, emission costs and freight rates. While one might argue there is not much potential in making such an activity more emission effective, we come out of the analysis showing that merely the effects of low-cost options such as speed adjustments, more slender vessels and larger vessels will reduce emissions for a given output quite significantly, and at moderate costs.

Our analysis shows that larger vessels and slender vessels are cost reducing, but our analysis excludes portside considerations: the cases in which smaller vessels are chosen will often be for reasons of accessibility or convenience to ports, handling, importers and exporters. However, since using larger vessels is more effective (cheaper and less polluting), one should expect the portside investments allowing larger shipments and vessels to be made in part as a city or a port grows in economic activity and throughput. The higher share of larger vessels in world trade seen in recent decades (Lindstad et al., 2015) can perhaps be seen as an indication that the world will be able to continue to benefit from the efficiency gains in larger vessels as long as there is growth in output to support the necessary portside infrastructure investments.

Much of the responsiveness we analyze – including speed reductions – is cost saving at today's prices, but parts of the measures in direction of slenderness and larger shipment sizes may depend on fleet replacement and certain port side adjustments. Since our analysis focuses on the shipment costs, though including capital tied up on ships and cargo, one should not be blinded by our conclusion of cost savings (thus negative abatement costs), but rather by the observation that a subset of measures within known technologies can provide very significant emission reductions at moderate costs. Vessel capacities allowing, speed reductions alone will reduce emissions quite substantially in the short term, so combinations that include a time-bound expansion in the average vessel size and slenderness will bring these inexpensive reductions even further, even if land-side adjustments are required.

In 2000, the first IMO greenhouse gas study was published. The study estimated that ships in international trade in 1996 contributed about 1.8% of the world total anthropogenic CO_2 emissions. By 2009, the principles for a mandatory Energy Efficiency Design Index (EEDI) and a Ship Energy Efficiency Management Plan (SEEMP) were agreed upon, and by 2011 the EEDI and SEEMP were adopted as part of the MARPOL Convention. According to the Second IMO GHG study (Buhaug et al., 2009), maritime transport emitted 3.3% of global anthropogenic CO_2 emissions. These shipping emission estimates have been updated and reduced to 3% (Smith et al., 2014). More importantly, both these reports assume that maritime CO_2 emissions will increase by 150–250% through 2050 if no action is taken.

The EEDI uses a formula to evaluate the CO_2 emitted by a vessel per unit of transport based on a fully loaded vessel as a function of vessel type and size. The standards do this in a way that does not reward vessel size (Lindstad et al., 2012), but the building of mores slender vessels is stimulated (Lindstad et al., 2013b, 2014).

Making the EEDI thresholds stricter can entice the industry to build more slender vessels, and hence reduce emission, but the results of the present study indicates that such policies miss out importantly if failing also to stimulate the greater use (and recruiting) of larger vessels. A warning from the literature, also supported by our study, is that a focus on standards may be excessively rigid, and among the consequences will be too little attention to operative decisions – such as speed. Another warning is that focus on standards indeed may improve the performance of new-buildings, but possibly at a cost of slowing down fleet renewal compared to if emission costs were driving these developments. Emission costs would as we show here slow down vessels. They would also, at high levels, shape the fleet as well as vessel retirements, giving vessels that are larger, slender and energy efficient a greater role.

In addition to the EEDI and the SEEMP, IMO has been discussing market based measure's (MBM) in the form of emissions trading, a fuel levy, or a combination of the two. While the EEDI only will reduce emissions through new vessels (which suggests that even after 12–15 years, only half of the fleet will be improved), the MBM's will have an immediate effect, and our study here shows the important and cost effective results of how the current fleet is operated. The MBM are based on the assumption that higher fuel prices will incite operators inter alia to reduce speeds and – thus – CO_2 price levels of 20–50 USD per ton are often commonly indicated as being what's required to reduce CO_2 emissions significantly. The result from this study indicate that a CO_2 price level of 100 USD per ton will reduce emissions in the range of 10% through speed reductions alone, and other responses will add to this. Fleet composition changes toward larger and more slender vessels will take longer time, but will give large additional emission reductions at modest or zero costs. Anger et al. (2010) indicates that a CO_2 price of 1000 USD per ton would be required to reduce emissions with 50%.

To summarize, our results indicate that the emission reduction potential in this industry is substantial, and at modest costs. Admittedly, our analysis does not include portside costs. An interpretation of the observation that at current prices, larger and more slender vessels will save costs (and thus save energy and emissions at negative costs) is that there in many instances will be costs or inconveniences at portside and in canals (dredging, larger storage capacities), and even in some cases prohibitive costs). But the savings offered to those who go through these inconveniencies and costs will be higher at greater emission costs, so changes toward size and slenderness can be expected, in addition to speed reductions. Sizeable emission costs will not only induce given vessels to go more slowly, but also ask the world to use vessels that are more slender and larger. Including these responses, emission reductions will be larger, still performing the same amount of transportation work.

The estimations done in this paper use crude oil carriers as examples. Other trades will be different, but the general ideas carry over: close to cubic consumption functions, speed, size, slenderness. Most shipping markets have a distribution of vessel sizes, but constraints as well as freedoms with respect to speed and slenderness will vary. Emissions and energy consumption per unit of output will fall with speed with about a factor of two – this follows from a cubic consumption function – and speed reductions are facilitated by drawing in more capital in the form of ships and cargo at sea. Technological change – in engines, in fuels, etc. – will also be important, and add to the changes we emphasize here.

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