

The effectiveness and costs of speed reductions on emissions from international shipping

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ABSTRACT

Greenhouse gas emissions from international shipping are an increasing concern. The paper evaluates whether vessel speed reduction can be a potentially cost-effective CO₂ mitigation option for ships calling on US ports. By applying a profit-maximizing equation to estimate route-specific, economically-efficient speeds, we explore policy impacts of a fuel tax and a speed reduction mandate on CO₂ emissions. The profit-maximizing function incorporates opportunity costs associated with speed reduction that go unobserved in more traditional marginal abatement cost analyses. We find that a fuel tax of about \$150/ton fuel will lead to average speed-related CO₂ reductions of about 20–30%. Moreover, a speed reduction mandate targeted to achieve 20% CO₂ reduction in the container fleet costs between \$30 and \$200 per ton CO₂ abated, depending on how the fleet responds to a speed reduction mandate.

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1. Introduction

Global climate change may be one of the most challenging environmental problems facing society; it is global, long term, and its mitigation will involve major social and technological choices (Houghton, 2005; Intergovernmental Panel on Climate Change, 2007). Although international climate agreements such as the Kyoto Protocol directly require nations to consider CO₂ mitigation policy proposals for domestic land-based emissions sources (Intergovernmental Panel on Climate Change, 1998), there has been little progress regarding international aviation and shipping.

Containerships are among the largest maritime emitters of CO₂. There are some 4100 containerships operating throughout the world, about 4% of the registered fleet. Despite their relatively small number, in 2007 they consumed over 70 million metric tons (Mmt) of bunker fuel and emitted over 230 Mmt of CO₂; this represents some 22% of energy consumption and CO₂ emissions from international shipping (Buhaug et al., 2009). Compared to bulk shipping, crude oil tankers, and general cargo ships, CO₂ emissions from containerships are 1.3, 2.2 and 2.5 times greater. Emissions from containerships are expected to be the fastest growing segment of marine shipping (Ocean Policy Research Foundation, 2008).

There are numerous technology-based approaches to improving vessel efficiency and reducing emissions, including propeller re-design, anti-fouling measures for hulls, and improved engine operations. However, limitations of these measures have led to discussions about the potential for behavioral changes (operational changes and demand management) to achieve mitigation targets more cost-effectively (Buhaug et al., 2009). Speed reduction represents one such operational change for potentially reducing CO₂ emissions from international shipping.

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2. Methodology and data

International shipping emits several types of pollutants such as SO_x , NO_x , PM and CO_2 that are a function of the carbon content of the fuel, energy density of the fuel, and combustion efficiency. Marine fuels are a petroleum byproduct with well-understood carbon content, and large marine diesel combustion converts nearly all carbon to CO_2 (with trace amounts of flame-generated black carbon and organic carbon particles); this relationship allows fuel consumption to be used to calculate CO_2 emission rates.

The per-trip fuel use of a vessel is the sum of fuel used by main and auxiliary engines. The per-trip fuel consumption of the main engine follows the so called cubic law of design speed and operational speed. The vessel fuel use per trip is given by Eq. (1).

$$F_{ijk} = \left[MF_k \cdot \left(\frac{s_{1k}}{s_{0k}} \right)^3 + AF_k \right] \cdot \frac{d_{ij}}{24s_{1k}} \quad (1)$$

where i represents the origin port; j represents the destination port; k represents an individual vessel serving the ij route; F_{ijk} represents the fuel consumption per trip; MF_k represents main engine(s) daily fuel consumption; AF_k represents auxiliary engine(s) daily fuel consumption; s_{1k} and s_{0k} represent the operational speed and the design at-sea speed of vessel k respectively in units of nautical miles (nm) per hour; and d_{ij} is the distance between two ports (nm).

MF_k and AF_k are determined by the power of the vessel, fuel consumption rates (g/kWh), and engine load factors. Using the activity assumptions from Wang et al. (2007), we assume the daily main engine fuel consumption rate to be 206 g/kWh and the auxiliary engine fuel consumption rate to be 221 g/kWh; we use an average main engine load factor of 0.8 and average auxiliary engine load factor of 0.5.

Once F_{ijk} is calculated, we multiply this by the fuel's carbon fraction (defined at 86.4%) and a factor for converting carbon to CO_2 (equal to 44/12) to calculate CO_2 emissions in kg per trip. The specific fuel consumption rate is then converted to CO_2 emissions over the fleet as:

$$\text{CO}_2 = (0.8645) \cdot (44/12) \cdot \sum_{i,j,k} F_{ijk} = 3.17 \cdot \sum_{i,j,k} F_{ijk} \quad (2)$$

Inserting Eq. (1) into Eq. (2), we obtain:

$$\text{CO}_2 = 3.17 \cdot \sum_{i,j,k} \left\{ \left[MF_k \cdot \left(\frac{s_{1k}}{s_{0k}} \right)^3 + AF_k \right] \cdot \frac{d_{ij}}{24 \cdot s_{1k}} \right\} \quad (3)$$

One consideration complicating this analysis is whether the frequency of service calls is maintained when ship speeds are reduced or whether the same cargo quantities are delivered at different ship arrival intervals. In other words, a simple reduction in speed implies fewer deliveries to ports. If service is to be maintained, one or a combination of scenarios must occur:

- Scenario 1: Vessels carry more containers to meet constant container demand—this could be done by increasing the capacity factor (where possible) of certain ships or by using more efficient container loading and/or goods packaging systems.
- Scenario 2: Additional ships are added to the route to serve the existing demand without schedule change; the percentage of additional ships needed to maintain cargo flows is inversely proportional to one minus the percent of speed reduction.

Decisions to take policy action can have a role in each of these scenarios. Additionally, cargo logistics and inventory balances may be revised to create reliable and economically-efficient routes that may include less-frequent but scheduled service. Policy instruments may focus on economic factors underlying these types of changes in freight transport demand within the policy-context of demand management (Baumol and Vinod, 1970; Meyer, 1999). We do not address demand management directly but rather construct constant-demand scenarios.

3. Profit seeking behavior and speed reductions

Speed reduction, energy cost, and profits are inexorably linked because energy is an important cost factor to shippers, and because speed reductions save energy across the fleet even when additional ships are needed to maintain service. We construct a profit function specific to containership and route characteristics to model cost changes when fuel prices increase and the cost savings when speeds are reduced in response. The profit function is specified for scheduled liner-service conditions representing the profit-maximizing speed, fuel use and CO_2 emissions when no extra ships are added to the fleet, and when extra ships are added to maintain cargo flow.

The analysis is based on four assumptions. First, the global routes developed over the next decades will change little from past decades. Thus, Asia will still serve North America for the foreseeable future. This assumption allows us to use existing port-pair voyage data. Second, we assume the containerized fleet size profile will change little in the near term; this represents a short-run period that focuses voyage issues on operational measures to optimize profit (different than a mid-run per-

iod during which fleet recapitalization with larger vessels may occur). Although there is no major technological bottleneck for containerships to become bigger, the ports and other infrastructure need time to adjust (Notteboom, 2004). Third, we assume average freight rates across commodities remain generally constant for the period under study. This is consistent with recent-year data (United Nations Conference on Trade and Development, 2007) documenting that average freight rates (\$/TEU) from Asia to the US have remained stable at around \$1600/TEU ($\pm 15\%$) in 2000 prices. Fourth, economic drivers setting freight rates are exogenous to voyage cost, dominantly influenced by commodity price as has been shown in the literature (Hummels et al., 2007); therefore, we assume that freight rates will be unaffected by the cost changes we generate in these scenarios.

Given these assumptions, Eq. (4) generates an annual profit function for a ship k operating from origin i to destination j ,

$$\pi_{ijk} = \left\{ R_{ij} \cdot W_k - \left[C_k + P \cdot \left(MF_k \cdot \left(\frac{s_{1k}}{s_{0k}} \right)^3 + AF_k \right) \right] \cdot \frac{d_{ij}}{24s_{1k}} \right\} \cdot T_{ij} \quad (4)$$

where π_{ijk} represents the profit from the origin i to the destination j per year; R_{ij} , the freight rate in dollars per TEU from the origin i to destination j ; W_k , the number of TEUs per ship in one trip; C_k , the fixed cost per day for ship k including capital costs; P , the fuel price in dollars per metric ton oil; and T_{ij} is the number of trips made by ship k from i to j per year.

The route length and annual trips made per route are calculated based on the Waterway Network Ship Traffic, Energy and Environment Model (STEEM), ship size is estimated based on statistical correlation with engine power, and the freight rate is set to \$1600 per TEU. Defining s_i as the only variable in Eq. (4) and recognizing that marginal profits equals zero when total profit is maximized, we can solve for conditions where shipping companies operate at optimal speed to maximize their profits using the following (taking out the ij subscript):

$$\frac{d\pi_k}{ds_{1k}} = 0 = \left(\frac{C_k}{s_{1k}^2} - \frac{P \cdot MF_k \cdot s_{1k}}{s_{0k}^3} - \frac{P \cdot AF_k}{s_{1k}^2} \right) \quad (5)$$

Therefore, the optimal speed function is:

$$s_{1k} = \left(\frac{(C_k + P \cdot AF_k) \cdot s_{0k}^3}{2P \cdot MF_k} \right)^{1/3} \quad (6)$$

We use the US Entrance/Clearance dataset containing unique ship information (i.e., International Maritime Organization [IMO] number), the origin/destination countries, and origin/destination ports (US Army Corps of Engineers, 2002). This dataset includes over 90,000 records of arrivals and departures involving US ports and ships in foreign commerce. We also consider operating cost data summarized by the US Army Corps of Engineers. Lloyds, 2002 ship registry data are used to match ship identifiers, and selected information specific to containership voyages (Lloyds Maritime Information System (LMIS), 2002). This approach identified 1066 unique routes where more than 2000 unique containerships provide services between US ports and foreign countries totaling 24,545 voyages per year. The distance between origin and destination is based on an empirically derived length of shipping lanes similar to industry port distance calculators from STEEM (Wang et al., 2007).

Table 1 summarizes the vessel data. The table identifies design speed and power for the 25th, 50th and 75th percentile vessels out of the vessel database. Across containerships serving US ports, speed varies across a relatively small range while power has much larger variance.

4. Speed optimization and CO₂ reduction policies

Applying Eq. (6) to determine optimal speed within a profit-maximizing function, we investigate how the shipping firms' motivation for profit maximization may determine or influence ship speed and corresponding CO₂ emissions. Using a reference fuel price of \$150 per metric ton, a typical fuel price in 2001 and 2002 (and prior to a period of steadily increasing prices), Eq. (6) is used to calculate the optimal speed (s_{150}) under the \$150 reference fuel cost for each route, and its corresponding costs. Economically-efficient speeds are evaluated for fuel prices ranging from \$200 to \$1000 per metric ton. Simply, the expected rational behavior of ship operators is simulated by modifying short-run speed behavior in response to higher fuel prices. On average, the distance-weighted average speed at \$150 per ton fuel was 19.57 knots, representing consistency model results with observed route speeds.

Fig. 1 illustrates two deterministic relationships of speed and CO₂ emissions: Scenario 1 assumes less frequent arrivals (longer intervals due to slower speeds), and Scenario 2 assumes speed reductions accompanied by additional vessels to

Table 1

Characteristic speed and power for containership dataset used in this study.

Percentile	Speed (kts)	Power (kW)
25th percentile	20.0	15,636
50th percentile	21.2	23,920
75th percentile	23.7	36,445

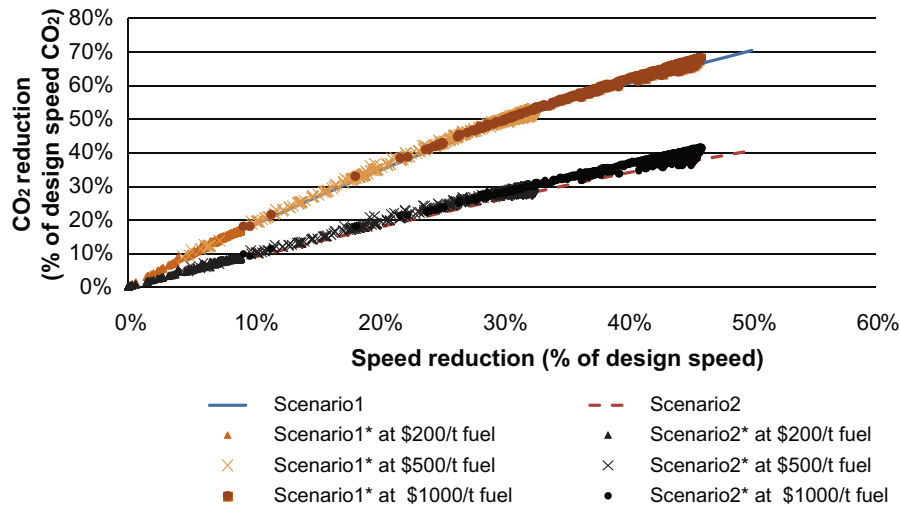


Fig. 1. Comparison of Scenarios 1* and 2* optimal speed reduction and corresponding CO₂ reductions at different fuel prices.

maintain arrival frequency. Overlaid onto these curves are point estimates for each voyage using our optimization analysis (which we label Scenarios 1* and 2* for different fuel prices). The figure presents CO₂ reduction results for the \$200, \$500 and \$1000 per ton price signals for all our voyages in our dataset. As fuel price becomes higher, economic incentives to maximize profit trigger reduced ship speed to avoid fuel consumption, which in turn reduces CO₂ emissions. This figure importantly demonstrates how a given price signal does not result in uniform industry response. Across diverse routes and container-ships, industry can be expected to respond to the same fuel price signal with a range of optimal speeds. The results suggest that the existing fleet would exhibit a range of speed reductions at a price signal of \$500 that is three times the range of a signal of \$200.

Applying Eq. (6), we analyze how fuel taxes could incentivize ships to reduce speed and CO₂. Fig. 2 shows that a \$60 per ton fuel tax can decrease CO₂ between 10% (Scenario 2*) and 20% (Scenario 1*). Compared with a reference price of \$150 per ton baseline fuel price, this represents almost a 40% fuel tax.

Aside from fuel and carbon taxes, authorities may mandate speed reduction. Eq. (6) enables us to calculate the marginal abatement cost (MAC) of CO₂ reductions from marine shipping when speed reductions are mandated by an external authority and when these speed reductions would not normally be profit-maximizing given fuel prices. In such cases, ships are forced to operate at a non-optimal speed, and this creates an opportunity cost equal to the loss in profit from this action. This opportunity cost can improve the estimated values for the MAC of CO₂ through speed reduction over methods that evaluate only fuel cost savings.

To illustrate, Eq. (6) can compute the optimal speed for each route assuming a reference fuel price of \$150 per ton, in line with the cost at which current fleet design speeds are typically profit-maximizing. Let π_{150}^* represent this profit under this case. The loss in profit due to mandated speed reductions is calculated by comparing the profit-maximizing solution (π_{150}^*)

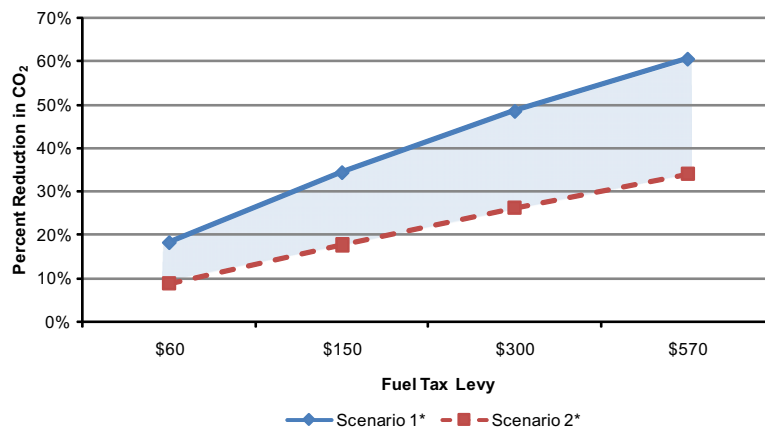


Fig. 2. Impact of a fuel tax on CO₂ reductions.

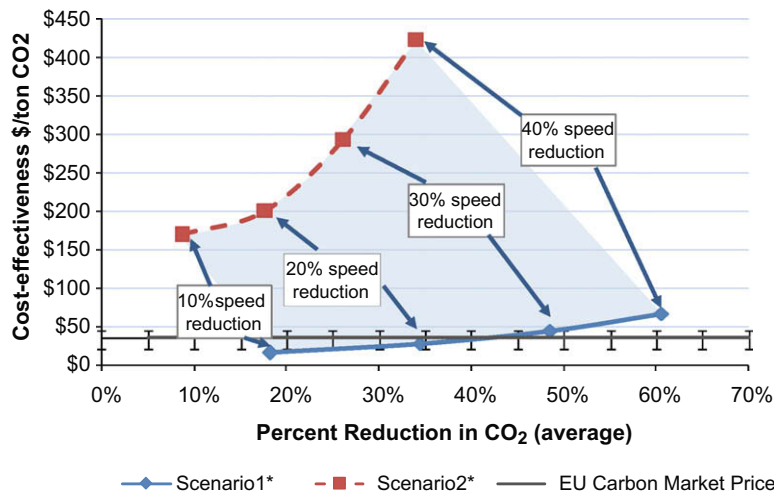


Fig. 3. Marginal abatement cost curve for CO₂ using change in total profit from mandated slower speeds.

with the profit under a speed reduction mandate (π_s). The MAC can be computed by dividing the change in profit by the avoided CO₂ due to speed reductions (ΔCO_2), as shown in Eq. (7). The abatement cost curves in \$/ton CO₂ are shown as Scenarios 1* and 2* in Fig. 3.¹

$$\text{MAC} = \frac{\pi_{150}^* - \pi_s}{\Delta\text{CO}_2} \quad (7)$$

Fig. 3 shows how the costs to an operator increase when ships are required to reduce speeds beyond what is profit-maximizing. When there is no need to add more ships, the marginal cost can be less than the average 2008 price in carbon exchange markets (European Climate Exchange, 2009; Lutsey and Sperling, 2009). However, in cases where speed reduction requires additional service (Scenario 2*), the MAC is often well above market prices for carbon. These results are significantly higher than MACs calculated in other work (Buhaug et al., 2009; Eide et al., 2009). Ignoring profit losses, Eide et al. report a cost savings for a speed reduction from 25 kn to 22 kn in their MAC calculus, whereas we report MAC ranges of \$35–\$200/ton CO₂ for a speed reduction of 20%. Where service frequency is to be maintained with additional ships, this implies that the shipping industry would be a net buyer in a universal cap-and-trade carbon exchange market (at 2008 average current emissions prices) for speed reductions of 20% or greater.

5. Conclusions

The international community is expressing determination to reduce CO₂ emission from marine shipping. Speed reductions would seem from short-run simulations to be able to significantly reduce CO₂ emissions; emissions reduction across a range of container ship routes can be up to 70% when the speed is halved. On average, marginal costs are higher than reported in studies that do not consider lost profit from reduced service. When additional ships are added to maintain scheduled frequency, lower speeds still provide CO₂ reduction on most routes, albeit at less reduction given higher costs. Speed reduction to mitigate CO₂ emissions remains an option that may be preferred by ship operators when there is CO₂ trading, although cost-effectiveness varies with profit-maximizing characteristics among routes.

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¹ Scenario 1* is represented by the lower cost line, and Scenario 2* the higher cost line, unlike previous figures depicting CO₂ reductions; the horizontal line represents the 2008 average carbon price in the European Carbon Exchange and with the bars representing the range of trading prices in 2008.

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