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CHAPTER 1

SHIP EMISSIONS, COSTS AND THEIR TRADEOFFS

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Emissions from commercial shipping are currently the subject of intense scrutiny. Various analyses of many aspects of the problem have been and are being carried out and a spectrum of measures to reduce emissions is being contemplated. However, such measures may have important side-effects as regards the logistical supply chain, and vice-versa. Industry circles have also voiced the concern that low-sulphur fuel in SECAs (the so-called ‘sulphur emissions control areas’) may make maritime transport (and in particular short-sea shipping) more expensive and induce shippers to use land-based alternatives. A reverse shift of cargo from sea to land might ultimately increase the overall level of CO2 emissions along the intermodal chain. This paper takes a look at various tradeoffs and may impact the cost-effectiveness of the logistical supply chain and present models that can be used to evaluate these tradeoffs. One of the key results is that speed reduction will always result in a lower fuel bill and lower emissions, even if the number of ships is increased to meet demand throughput. Another result is that cleaner fuel at SECAs may result in a reverse cargo shift from sea to land that has the potential to produce more emissions on land than those saved at sea. Various examples are presented.

1. Introduction

Air pollution from ships is currently at the center stage of discussion by the world shipping community and environmental organizations. The Kyoto protocol to the United Nations Framework Convention on Climate

Change -UNFCCC (1997) stipulates concrete measures to reduce CO2 emissions in order to curb the projected growth of greenhouse gases (GHG) worldwide. Although some regulation exists for non-GHGs, such as SO_2, NO_x and others, shipping has thus far escaped being included in the Kyoto global emissions reduction target for CO_2 and other GHGs (such as CH_4 and N_2O). Even so, it is clear that the time of GHG non-regulation is rapidly approaching its end, and measures to curb future CO_2 and other GHG growth are being sought with a high sense of urgency and are very high on the agenda of the International Maritime Organization (IMO) and of many individual coastal states. In the forthcoming UNFCCC, which will take place in Copenhagen in December of 2009, shipping is expected to be included in the discussions on future GHG reduction. In that sense, various analyses of many aspects of the problem have been and are being carried out and a broad spectrum of measures is being contemplated. These measures can be considered to fall into three general categories: technical, market-based and operational.

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 (MBIs) are classified into two main categories, Emissions Trading Schemes (ETS) and Carbon Levy schemes (also known as International Fund schemes). Finally, operational schemes mainly involve speed optimization, optimized routing, improved fleet planning, and other, logistics-based measures.

Some of these measures, important in their own right as regards emissions reduction, may have non-trivial side-effects as regards the logistical supply chain. For instance, measures such as (a) reduction of speed, (b) change of number of ships in the fleet, (c) possibly others, will generally entail changes (positive or negative) in overall emissions, but also in other logistics and cost-effectiveness attributes such as in-transit inventory and other costs. Also, industry circles have voiced the concern that the mandated use of lower-sulphur fuel in some regions or globally may make maritime transport (and in particular short-sea shipping) more expensive and induce shippers to use land-based alternatives (mainly road). A reverse shift of cargo from sea to land would go against the drive to shift traffic from land to sea to reduce congestion, and might ultimately increase the overall level of CO_2 emissions along the intermodal chain. In that regard, in Europe one can already see a potential conflict between two policies: (a) the designation of certain areas as "sulphur emissions controlled areas" (or SECAs), such as the Baltic Sea, the North Sea and the English Channel, and (b) the stated Transport Policy goal of shifting cargo off the roads and onto ships and railways.

Typical problems in the maritime logistics area include one or a combination of problems from the following generic list (which is non-exhaustive):

- Optimal ship speed
- Optimal ship size
- Routing and scheduling
- Fleet deployment
- Fleet size and mix
- Weather routing
- Intermodal network design
- Modal split
- Transshipment
- Queuing at ports
- Terminal management
- Berth allocation
- Supply chain management

The traditional analysis of these problems is in terms of cost- benefit criteria from the point of view of the logistics, operator, shipper, or other end-user. Such analysis typically ignores environmental issues. Green maritime logistics tries to bring the environmental dimension into the problem, and specifically the dimension of emissions reduction, by trying to analyze the tradeoffs that are at stake and exploring win-win solutions.

It is also important to realize that two different settings can be analyzed, the strategic setting and the operational one. The distinction between the two is important, and one that is not mentioned frequently. Let us clarify the difference between the two by an example.

A spokesman from Germanischer Lloyd (GL) has been recently quoted as follows: “We recommend that ship-owners consider installing less powerful engines in their newbuildings and to operate those container vessels at slower speeds,” (Lloyds List, 2008a). By ‘slower speeds’ it is understood that the current regime of 24-26 knots would be reduced to something like 21-22 knots. But some trades may go as low as 15-18 knots, according to a 2006 study by Lloyds Register (Lloyds List, 2008b). An obvious reason for suggesting such speed reduction is twofold: fuel costs and emissions.

Implementing the aforementioned speed reduction would only make sense in a strategic setting, by modifying the design of the ship, including hull shape, by installing smaller engines in future newbuildings, by modifying the propeller design, etc. In such a setting however, one would have to also investigate not only differences in emissions produced by these modified lower-speed designs, but also other possible ramifications. These may include emissions differentials by the shipyards that produce these ships, as well as any difference in emissions when these ships would be recycled. This strategic approach to the emissions problem is also known as the ‘life-cycle’ 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.

It is not the scope of this paper to examine all of the problems identified above from an environmental perspective. That will take years to accomplish. Rather, the limited number of models examined in this paper primarily focus on operational scenarios and mainly serve to highlight some of the trade-offs that are at stake in these scenarios, so as to motivate further work in this area.

The rest of this paper is organized as follows. Section 2 reports on relevant background. Section 3 describes some basics on emissions. Section 4 describes a simple logistical scenario to investigate the effects of speed reduction. Section 5 introduces the concept of the cost to avert a tonne of CO2 and Section 6 examines the issue of port time in the quest to reduce emissions. Section 7 examines the effect of speed reduction at

SECAs and Section 8 looks into possible side-effects of cleaner fuels on modal split. Finally Section 9 presents the paper's conclusions.

2. Background

We start by stating that even though the literature on the broad area of ship emissions is immense, the literature on the specific topic (link between emissions and maritime logistics) is scant. There are a number of papers that consider the economic impact of speed reduction especially for container vessels. Andersson (2008) considered the case of a container line where the speed for each ship reduced from 26 knots to 23 knots and one more ship was added to maintain the same throughput. Total costs per container were reduced by nearly 28 per cent. Eefsen (2008) considered the economic impact of speed reduction of containerships and included the inventory cost. Cerup-Simonsen (2008) developed a simplified cost model to demonstrate how an existing ship could reduce its fuel consumption by a speed reduction in low and high markets to maximize profits. Corbett et al. (2009) applied fundamental equations relating speed, energy consumption, and the total cost to evaluate the impact of speed reduction. The paper also explored the relationship between fuel price and the optimal speed.

The situation is similar at the policy level: many activities, but little or nothing relating to the interface between emissions and logistics. Looking at developments at the IMO (International Maritime Organization) level, thus far progress as regards air pollution from ships has been mixed and rather slow. On the positive side, in November 2008 the Marine Environment Protection Committee (MEPC) of the IMO unanimously adopted amendments to the MARPOL Annex VI regulations. The main changes will see a progressive reduction in sulphur oxide (SO_x) emissions from ships, with the global sulphur cap reduced initially to 3.50%, effective 1 January 2012; then progressively to 0.50%, effective 1 January 2020 (IMO, 2008a).

Furthermore, the report of Phase 1 of the update the 2000 IMO GHG Study (IMO, 2000) was presented, which was conducted by an international consortium led by Marintek, Norway (Buhaug, et al 2008). According to this study, total CO_2 emissions from shipping (both domestic and international) are estimated to range from 854 to 1,224 million tons (2007), with a 'consensus estimate' set at 1,019 million tons, or 3.3% of global CO_2 emissions. By comparison, electricity and heat production accounts for 35% of global CO_2 emissions, manufacturing industries and construction 18.2%, and transport (all modes) 21.7%. Among transport modes, road accounts for 51% of all CO_2 emissions, shipping (including fishing) for 25%, aviation for 20%, and rail for 4%. However, in terms of energy use and emissions per tonne-km, shipping ranks as the most environment-friendly transport mode, as can be seen in the following table:

Table 1. Energy efficiency and emissions to the atmosphere (by mode).

Energy Use	**PS -Type container vessel (11,000 TEU)**	**S -Type container vessel (6,600 TEU)**	**Rail - Electric**	**Rail - Diesel**	**Heavy Truck**	**Boeing 747-400**
kWh/tkm	0.014	0.018	0.043	0.067	0.18	2.00
Emissions (g/tkm)	**PS-Type container vessel (11,000 TEU)**	**S-Type container vessel (6,600 TEU)**	**Rail - Electric**	**Rail – Diesel**	**Heavy Truck**	**Boeing 747-400**
Carbon dioxide (CO_2)	7,48	8.36	18	17	50	552
Sulphur oxides (SO_X)	0.19	0.21	0.44	0.35	0.31	5.69
Nitrogen oxides (NO)	0.12	0.162	0.10	0.00005	0.00006	0.17
Particulate matters (PM)	0.008	0.009	n/a	0.008	0.005	n/a

Re. emissions for rail; the complete value chain for el-production is considered.
Source: Network for Transport and the Environment (Sweden)

Among ship types, according to the results of Phase 1, the three top fuel consuming categories of ships (and thus, those that produce most of the CO_2 emissions) are (i) container vessels of 3,000-5,000 TEUs, (ii) container vessels of 5,000-8,000 TEUs and (iii) RoPax Ferries with cruising speed of less than 25 knots. The common denominator of these three categories, which results in a high level of CO_2 emissions, is their high speed, at least as compared to other ship types.

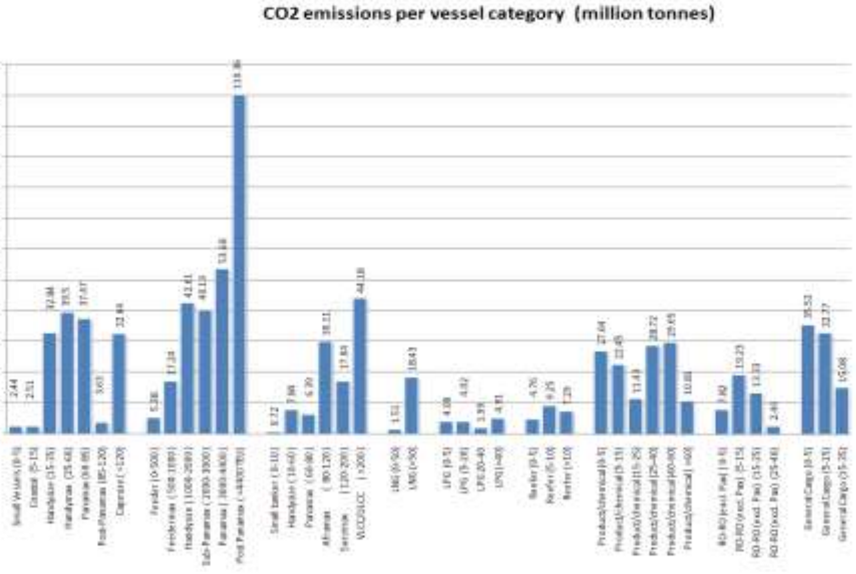

Fig. 1. CO_2 emissions, world fleet (Psaraftis and Kontovas, 2009a).

These findings are in line with those of Psaraftis and Kontovas (2008, 2009a). According to their analysis, containerships are the top CO_2 emissions producer in the world fleet (2007, Lloyds-Fairplay database). Just the top tier category of container vessels (those of 4,400 TEU and above) are seen to produce CO_2 emissions comparable on an absolute scale to that produced by the entire crude oil tanker fleet (in fact, the emissions of that top tier alone are slightly higher than those of all crude oil tankers combined- see Fig. 1 above).

At the latest meeting of IMO's Marine Environment Protection Committee in London last July (MEPC 59) there continued to be a clear split between industrialized member states, such as Japan, Denmark and other Northern European countries, and a group of developing countries including China, India and Brazil, on how to proceed. The latter countries spoke in favor of the principle of "Common but differentiated responsibility" (CBDR) under the UNFCCC. In their view, any mandatory regime aiming to reduce GHG emissions from ships engaged in international trade should be applicable exclusively to the countries listed in Annex I to the UNFCCC, therefore their strong wish is not to be included in any mandatory set of measures.

Due to ‘political’ reasons such as above, progress as regards regulating CO_2 and other GHGs continues to be very slow. In fact, the stated objective to finalize a mandatory Energy Efficiency Design Index (EEDI) of the environmental performance of new ships has not been reached yet. The same is true for the Energy Efficiency Operational Indicator (EEOI), which will be applicable to all ships. As a result, the IMO will not be in a position to have reached a clear position on these two indices in time for the United Nations Framework Conference for Climate Change (UNFCCC) that will be held in Copenhagen in December of this year, when a new climate agreement is expected to be reached, after Kyoto in 1997.

Without going into technical details regarding these two indices, one can state that the first index (EEDI) concerns the design of new ships and the second (EEOI) concerns the operation of all ships, new and existing. Both indices are ratios, in which the numerator is a complex function of all energy consumed by the ship, and the denominator includes a product of the ship’s deadweight (or payload) and the ship’s operational speed. The fact that speed is in the denominator means that the slower the ship goes, the higher both these indices will be, therefore the higher the ship will be ranked in terms of energy efficiency, both for design and for operation. No doubt about it, faster ships will score low as regards these indices.

The implication of this is unknown, other than the fact than in any ranking based on these indices, fast ships will have an unfavorable environmental performance vis-à-vis slower ships of the same capacity. In spite of extensive discussions on this topic, it is still not clear exactly how these indices will be used in future IMO rulemaking. In fact, these indices still have not been finalized, as certain issues still demand discussion and agreement.

Progress as far as other measures to regulate GHG emissions, such as MBIs has been even slower. Reaction to this concept has been even more pronounced, and it is not clear which among two main schemes, the Emissions Trading Scheme (ETS) and the Carbon Levy, will be eventually adopted. Certainly no agreement will be reached before the

Copenhagen UNFCCC conference, and the latest IMO timetable on this issue goes into 2012.

What does slow progress on GHGs mean? And what if no agreement is reached at the IMO any time soon? This will certainly increase the pressure for regional approaches. In fact the European Commission is following IMO developments very closely, and has stated very clearly its intention to act alone if IMO's procedures take longer than previously anticipated. As regards GHGs, the anticipated approach of the Commission is to formulate an ETS, similar to that used in other land-based industries. The Commission has started the procedure for including air transport into its ETS scheme, and many think it will eventually do the same for shipping. Many ship owners' circles have voiced strong concerns that such a scheme would be complicated and unworkable.

Currently, European legislation mainly concerns the sulphur content of marine fuels. The maximum sulphur content for marine fuels according to EU directive 2005/33/EC is in line with MARPOL Annex VI. The implementation dates are differently from those agreed by the IMO under MARPOL Annex VI, but the main point is that currently all vessels sailing in the designated areas (SECAs) should use marine fuels with a maximum of 1.5% by mass content of sulphur. What is different from MARPOL is that the EU Directive sets a limit for all passenger vessels operating on regular service to or from EU ports to a maximum sulphur content of 1.5 % (the same as in SECAs).This limit came into effect on August 11th, 2006 (EU directive 2005/33/EC, Article 4a). Furthermore, according to Article 4b of the same Directive, from January 1st, 2010 a 0.1% limit comes into effect for inland waterway vessels and ships at berth in EU ports with some exemptions.

Perhaps more interesting are developments on the logistics side: the European Commission states in their Freight Transport Logistics Action Plan launched in October 2007 that "*Logistics policy needs to be pursued at all levels of governance*", which is also the reason behind this action plan as one in a series of policy initiatives to improve the efficiency and sustainability of freight transport in Europe. In the Freight Transport Logistics Action Plan a number of short – to medium-term actions is presented that will help Europe address its current and future challenges and ensure a competitive and sustainable freight transport system in

Europe. Among the actions are the "*Green* transport corridors for freight". The Green Corridors are characterized by a concentration of freight traffic between major hubs and by relatively long distances of transport. Green Corridors should in all ways be environmentally friendly, safe and efficient. This is perhaps one of the few EU policy initiatives that aim to establish a clear connection between environment and logistics, even though this activity is still very much at its infancy. It is clear that the maritime mode will be involved in some of these Green Corridors, particularly those involving the Trans European Transport Networks (TEN-T's) and the Motorways of the Sea, and the question is, what ships, what types, what sizes, what speeds, how will they be utilized, and how will tradeoffs will be assessed.

In the United States, the Environmental Protection Agency (EPA) has established a tier-based timeline for implementing NOx emission standards to marine diesel engines that became effective in 2007. These standards are similar to those described in MARPOL Annex VI which has been ratified by the US in October 2008 although the Convention entered into force in May 2005. Canada has not yet ratified Annex VI, however Canada and the United States jointly proposed the designation of an Emissions Control Area (ECA) for specified portions of the US and Canadian coastal waters covering a total o 200 nm. At MEPC 59, the proposal was agreed in principle and will be voted during MEPC 60, scheduled for March 2010. If approved the ECA would enter into force in 2012.

On a local government basis, the State of California which is the home of the two busiest ports in the US has created a special agency, the California Air Resources Board (CARB) which is the primary source for ship emission regulations in California. On July 2008, CARB adopted the regulation "Fuel Sulfur and Other Operation Requirements for Ocean-Going Vessels within California Waters and 24 Nautical Miles of the California Baseline" that sets specific limits on the sulfur content of fuel used within 24 nm of the Californian coast.

In addition, the two busiest ports in the US (Long Beach and Los Angeles) both located in Southern California have introduced a series of voluntary incentive-based programs. On March 2008, the Board of Commissioners of the ports of Los Angeles (POLA) and Long Beach

(POLB) authorized the Low-Sulphur Vessel Main Engine Fuel Incentive program to encourage operators to use cleaner fuels within 40 nm or 20 nm from Point Fermin. The program will pay the operators that will agree to use fuels that contain less than 0.2 % sulphur the price difference between that fuel and IFO 380. Furthermore, the two ports offer a 15% discount on dockage fees to vessels that voluntary comply with the SPBP-OGV1 Vessel Speed Reduction Program and reduce their speed to 12 knots within 20nm of Point Fermin while entering or leaving the ports.

3. Some basics: Algebra of Emissions and Fuel Cost

Before logistical scenarios are examined, some basics have to be established first. Two are the main attributes of any logistical scenario that is viewed from a green perspective: the amount of emissions produced, and the cost.

To calculate CO_2 emissions, one has to multiply bunker consumption by an appropriate emissions factor, F_{CO2} . The factor of 3.17 has been the empirical mean value most commonly used in CO_2 emissions calculations based on fuel consumption (see EMEP/CORINAIR (2002) and Endresen (2007)). According to the IMO GHG study (IMO, 2000), the actual value of this coefficient may range from 3.159 (low value) to 3.175 (high value). The update of the IMO 2000 study (Buhaug et al, 2008), uses slightly lower coefficients, different for Heavy Fuel Oil and for Marine Diesel Oil. The actual values are 3.082 for Marine Diesel and Marine Gas Oils (MDO/MGO) and 3.021 for Heavy Fuel Oils (HFO). According to the report of the Working Group on Greenhouse Gas Emissions from Ships (IMO, 2008b), the group agreed that the Carbon to CO_2 conversion factors used by the IMO should correspond to the factors used by IPCC (2006 IPCC Guidelines) in order to ensure harmonization of the emissions factor used by parties under the UNFCCC and the Kyoto Protocol. In this paper we shall use the original value of 3.17 also used in Psaraftis and Kontovas (2008, 2009a) except for the example in Section 6 where the value of 3.13 has been used, noting that our emissions results will have to be scaled down by up to 5% if a lower emissions factor is used. Table 2 summarizes various emissions factors.

Table 2. Comparison of Emission Factors kg CO2/kg Fuel. (IMO, 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				

As regards SO_2, this type of emissions depends on the type of fuel used. One 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). The factor of 0.02 is exact, and is derived from the chemical reaction of sulphur with oxygen.

Finally, NO_x emissions depend on engine type. 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 fuel cost, one of the most important components of total cost (although by no means the only one). Fuel cost can be estimated by multiplying the amount of bunkers used with the price of fuel. In our analysis we assume that the price of the fuel used by the ship is known and equal to p, assumed constant during the year. Even though it is assumed a constant in our analysis, p is very much market-related, and, as such, may fluctuate widely in time, as historical experience has shown (see Figure 2 below). But this assumption causes no loss of generality, as an average price can be used. Also, as the ship will generally consume different kinds of fuels during the trip and in port, assuming a unique fuel price is obviously a simplification. But this causes no loss of generality either, as the analysis can be readily extended to account for different fuel types on board.

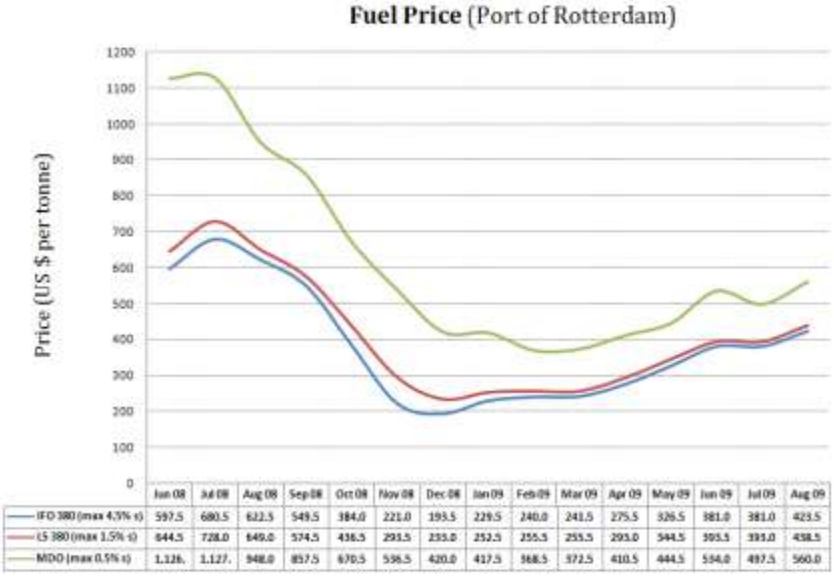

Fig. 2. Average Monthly Fuel Oil Prices (from www.bunkerworld.com).

4. A Simple logistical scenario: factors and tradeoffs

Given that fuel costs and emissions are directly proportional to one another (both being directly proportional to fuel used), it would appear that reducing both would be a straightforward way towards a “win-win” solution. In an operational setting, one of the obvious tools for such a simultaneous reduction is speed: sail slower, and you reduce both emissions and your fuel bill. This may sound simple, but its possible ramifications are not so simple.

Assuming a given ship, and for speeds that are close to the original speed, the effect of speed change on fuel consumption is assumed cubic, that is,

$$\frac{F}{Fo} = \left(\frac{V}{Vo}\right)^3$$

where F (F_0) is the daily fuel consumption at speed V (V_0).

This assumption comes from basic ship hydrodynamics. It means that $F=kV^3$, where k is a known constant, which is a function of the loading condition of the ship and of other ship characteristics (e.g., engine, horsepower, geometry, age, etc). Of course, an implicit assumption in this analysis is that the ship's power plant would still be able to function efficiently if speed is reduced. Speed reduction usually requires reconfiguring the engine so that its operation is optimized at the reduced load.

Also note that the cubic law is only an approximation, and one that is usually valid for small changes in speed. If the speed changes drastically, for instance from 20 to 10 or even 5 knots, one would expect a different relationship between V and F.

Our simplest logistical scenario to investigate tradeoffs between ship CO_2 emissions and other attributes of the ship operation assumes a fleet of N identical ships (N: integer), each of capacity (payload) W. Each ship loads from a port A (time in port $T_{A,}$, days), travels to port B with known speed V_1, discharges at B (time in port T_B, days) and goes back to port A in ballast, with speed V_2. Assume speeds are expressed in km per day. The distance between A and B is known and equal to L (km). Assume these ships are chartered on a term charter and the charterer, who is the effective owner of this fleet for the duration of the charter, incurs a known operational cost of O_C per ship per year. This cost depends on market conditions at the time the charter is signed and includes the charter to the ship owner(s) and all other *non-fuel related* expenses that the charterer must pay, such as canal tolls, port dues, cargo handling expenses, and so on. Not included in O_C are fuel expenses, which are also paid by the charterer, and which depend on the actual fuel consumed by the fleet of ships. The latter depends on how the fleet is used.

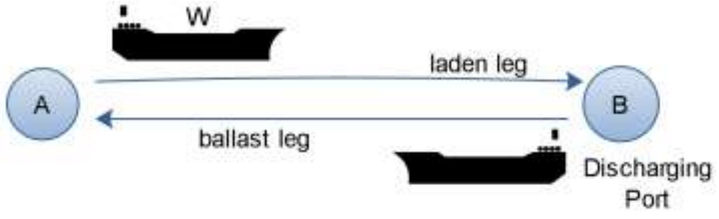

Fig. 3. Ship Route.

Obviously, the above rudimentary scenario (a ship going fully laden one way and on ballast on the return leg) is not the only one that one may encounter in world shipping markets. This scenario is encountered mainly in the charter market and specifically in the tanker trades. Bulk carriers may also be employed likewise; however they are more likely to also trade in triangular routes, depending on the cargoes that are available. Containerships and other ships in the liner market definitely do not use such employment pattern, being engaged in trades that visit many ports. Even though these operational scenarios are different from the one examined above, extending our approach to these other scenarios is straightforward, and the main thrust of our analysis is valid for these scenarios as well.

Assume that each ship's operational days per year are D ($0<D<365$), a known input, and that the total daily fuel consumptions (including both main engine and auxiliaries) are known and are as follows for each ship:
<u>In port</u>: f (tonnes per day)
<u>At sea</u>: F_1, F_2 (tonnes per day) for laden and ballast legs (respectively).

As stated earlier, the effect of speed change on fuel consumption is assumed cubic for the same ship, that is, $F_{new}/F = (V_{new}/V)^3$, or, $F_1=k_1V_1^3$, $F_2=k_2V_2^3$, where k_1 and k_2 are known constants. Also as mentioned in the previous Section, one tonne of fuel burned in the ship's engine room will produce F_{CO2} tonnes of CO_2, where F_{CO2} is the emissions factor.

In addition to the standard costs borne by the charterer, our analysis will also take into account *cargo inventory costs*. The reason is that any conceivable speed reduction to save fuel costs and/or reduce emissions will have as a consequence an increase in inventory costs due to late delivery of cargo and must be taken into account if the analysis is to be complete from a logistical standpoint. These cargo inventory costs are assumed equal to I_C per tonne and per day of delay, where I_C is a known constant. In computing these costs, we assume that cargo arrives in port 'just-in-time', that is, just when each ship arrives. In that sense, inventory costs accrue only when loading, transiting (laden) and discharging. We shall call these inventory costs 'in-transit inventory costs'. Generalizing to the case where inventory costs due to port storage are also considered is straightforward.

If the market price of the cargo at the destination (CIF price) is P ($/tonne), then one day of delay in the delivery of one tonne of this cargo will inflict a loss of PR/365 to the cargo owner, where R is the cost of capital of the cargo owner (expressed as an annual interest rate). This loss will be in terms of lost income due to the delayed sale of the cargo. Therefore, it is straightforward to see that I_C =PR/365.

Based on the above, and on a per ship basis, and after some straightforward algebraic manipulations, we can compute the following:

Round trip duration:

$$d= L/V_1+ L/V_2+ T_{AB},$$

where $T_{AB} = T_A + T_B$ (total port time per round trip)

Number of round trips in a year: n= D/d

Therefore

$n=D/[L/V_1+ L/V_2+ T_{AB}]$ (note that n may not necessarily be an integer)

Total roundtrip fuel consumption: $T_{FC} = T_{AB}f + L(k_1V_1^2+ k_2V_2^2)$

[As a parenthesis, it can be seen here that although the per day fuel consumption is a cubic function of speed, the roundtrip fuel consumption is only a quadratic function of speed, as the slower the ship goes, the more days it stays at sea.]

Total costs in a year:

$$pnT_{FC} + nI_C W\left(T_{AB} + \frac{L}{V}\right) + O_C =$$

$$= np\left[T_{AB}f+L\ \ k_1V_1^2 + k_2V_2^2\ \ \right] + nI_C W\left(T_{AB} + \frac{L}{V_1}\right) + O_C =$$

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

Fuel consumed per tonne-km: T_{FC}/WL

For a fleet of N ships, total fleet costs in a year:

$$\mathrm{pnNT_{FC}} + \mathrm{nNkW}\left(\mathrm{T_{AB}} + \frac{\mathrm{L}}{\mathrm{V_1}}\right) + \mathrm{NO_C} =$$

$$= \mathrm{nNp}\left[\mathrm{T_{AB}f{+}L}\;\; \mathrm{k_1V_1^2} + \mathrm{k_2V_2^2}\;\;\right] + \mathrm{nNI_CW}\left(\mathrm{T_{AB}} + \frac{\mathrm{L}}{\mathrm{V_1}}\right) + \mathrm{NO_C} =$$

$$= \mathrm{DN}\frac{\mathrm{p}\left[\mathrm{T_{AB}f{+}L}\;\; \mathrm{k_1V_1^2} + \mathrm{k_2V_2^2}\;\;\right] + \mathrm{I_CW}\left(\mathrm{T_{AB}} + \frac{\mathrm{L}}{\mathrm{V_1}}\right)}{\frac{\mathrm{L}}{\mathrm{V_1}} + \frac{\mathrm{L}}{\mathrm{V_2}} + \mathrm{T_{AB}}} + \mathrm{NO_C}$$

With this basic scenario complete, we are now ready to investigate the impact of speed reduction.

To investigate what happens if we reduce speed, we assume that we reduce the speed of all ships in the fleet by a common amount[a]. Let this common reduction (initial speed – final speed) be equal to $\Delta V \geq 0$ [b]. To reduce speed and maintain annual throughput constant, we have to add more ships. If these additional ΔN ships are identical in design to the original N ones, ΔN can be determined by equating nNW (the quantity of cargo moved in a year with N ships) with the equivalent expression for N+ ΔN ships. ΔN may not necessarily be an integer, although for illustration purposes one may want to round it to the next highest integer.

It is easy to check that we can compute ΔN from the following equation:

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

Before we proceed, we implicitly assume that these ΔN ships are readily available and can be immediately incorporated into the original fleet at a

---

[a] Reducing speeds by different amounts is a straightforward generalization.

[b] We implicitly assume that we shall not consider a speed increase, or $\Delta V < 0$, even though this may be warranted cost-wise. A speed increase will always increase fuel consumption and emissions, but may actually entail lower other costs, such as inventory or other, leading in turn to lower total costs.

cost equal to O_C per ship per year, the same as that paid to charter the original N ships. However, this may not be the case if there is a lack of supply of available ships, which may have as a result a lower total throughput and/or an increase of charter rates to levels above O_C. Also, and as we investigate an operational setting, we do not take into account long-term effects such as emissions produced by shipyards that would build these extra ships, emissions produced by the ships carrying the additional raw materials to be used to build these ships, and other similar life-cycle quantities.

After some straightforward algebraic manipulations, the difference in total fleet costs (costs after, minus costs before) is equal to

$$\Delta(\text{total fleet costs})= \\ =NL\Delta V\frac{-pD\ \ 2k_1V_1+2k_2V_2-\ \ k_1+k_2\ \ \Delta V\ \ +\frac{I_CWD}{V_1(V_1-\Delta V)}+O_C\left(\frac{1}{V_1(V_1-\Delta V)}+\frac{1}{V_2(V_2-\Delta V)}\right)}{\frac{L}{V_1}+\frac{L}{V_2}+T_{AB}} \qquad [1]$$

Or, in simplified form, if $V_1 = V_2 = V$ (this may not mean that $k_1 = k_2$):

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

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

$$\Delta(\text{total fuel costs})=-NL\Delta V\frac{pD\ \ 2k_1V_1+2k_2V_2-\ \ k_1+k_2\ \ \Delta V}{\frac{L}{V_1}+\frac{L}{V_2}+T_{AB}} \qquad [3]$$

Or, in simplified form,

$$\Delta(\text{total fuel costs})=-NL\Delta V\frac{pD\ \ 2V-\Delta V\ \ k_1+k_2}{2\frac{L}{V}+T_{AB}} \qquad [4]$$

An interesting observation is that fuel cost differentials (and, by extension, total fleet cost differentials) are independent of port fuel consumption f. Even though this may seem counter-intuitive, it can be explained by noting that 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 in port will be the same.

It is also interesting to note that for $\Delta V \geq 0$ and for all practical purposes the differential in fuel costs is always negative or zero, as the term within the square brackets of [3], or the difference $2V-\Delta V$ in [4], is positive for all realistic values of the speeds and of the speed reduction. This means that speed reduction cannot result in a higher fuel bill, even though more ships will be necessary.

The same is true as regards emissions, as these are directly proportional to the amount of fuel consumed:

$$\Delta(\text{total } CO_2 \text{ emissions}) = -F_{CO_2} NL\Delta VD \frac{2k_1V_1 + 2k_2V_2 - \ k_1 + k_2 \ \Delta V}{\frac{L}{V_1} + \frac{L}{V_2} + T_{AB}} \quad [5]$$

Or, in simplified form,

$$\Delta(\text{total } CO_2 \text{ emissions}) = -F_{CO_2} NL\Delta VD \frac{2V - \Delta V \ \ k_1 + k_2}{2\frac{L}{V} + T_{AB}} \quad [6]$$

Total emissions would thus be always reduced by slowing down, even though more ships would be used. The higher the speed, and the higher the speed reduction, the higher this reduction would be.

As a parenthesis we note that mathematically expression [6] achieves its lowest value (that is, emissions reduction is maximized) if $\Delta V = V$. This option is of course only of theoretical value, for if this is the case the fleet would come to a complete standstill and the other cost components (as well as ΔN) would go to infinity.

In the general case, whether Δ(total fleet cost) in expressions [1] or [2] is positive or negative, or reaches a minimum value other than zero, would depend on the values of all parameters involved, for one can see that in-transit inventory costs and ship other operational costs count positively in the cost equation. Both these costs would increase by reducing speed, and this increase might offset, or even reverse, the corresponding decrease in fuel costs. High values of either I_C or O_C (or both) would increase the chances of this happening, and high values of p would do the opposite, as will be seen in the examples that follow.

A closer look at expression [2][c] provides some interesting insights. Expression [2] can be written in the following form:

$$\Delta(\text{total fleet cost}) = \Delta V\left(-A(2V-\Delta V)+\frac{B}{V-\Delta V}\right) \equiv G(\Delta V)$$

where A and B are positive constants given by:

$$A=NLpD\frac{k_1+k_2}{2\frac{L}{V}+T_{AB}} \qquad B=NL\frac{I_C WD+2O_C}{V\left(2\frac{L}{V}+T_{AB}\right)}$$

As we have assumed that $\Delta V \geq 0$, function $G(\Delta V)$ obtains the value of 0 for $\Delta V=0$ and goes to infinity when ΔV approaches V. Its behavior for intermediate values of ΔV depends on the values of all parameters involved. In fact, we distinguish two cases:

Case 1: The derivative of $G(\Delta V)$ at $\Delta V=0$ is ≥ 0 (see Figure 4a below). This is mathematically expressed as $V \leq \sqrt{\frac{B}{2A}}$, or as

$$V \leq V_0 \text{ with } V_0 \equiv \sqrt[3]{\frac{I_C W+2\frac{O_C}{D}}{2p\ \ k_1+k_2}} \qquad [7]$$

Speed V_0 depends on the parameters shown above and can be considered as a cost-benefit ‘speed threshold’. If the original speed of the ship V is at or below that threshold, then any attempt to reduce it to save fuel (and emissions) would entail a net total cost increase, as $G(\Delta V)$ will be monotonically increasing with ΔV [d]. It can be seen that this situation is more likely to occur if I_C and/or O_C are high and/or p is low.

Case 2: The derivative of $G(\Delta V)$ at $\Delta V=0$ is <0 (see Fig. 4b).

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[c] The analysis for expression [1] is similar, but more tedious.

[d] Again, in this case it may be argued that it is best to increase speed, and reduce the number of ships, or that $\Delta V<0$. But this is a case that was excluded from the beginning.

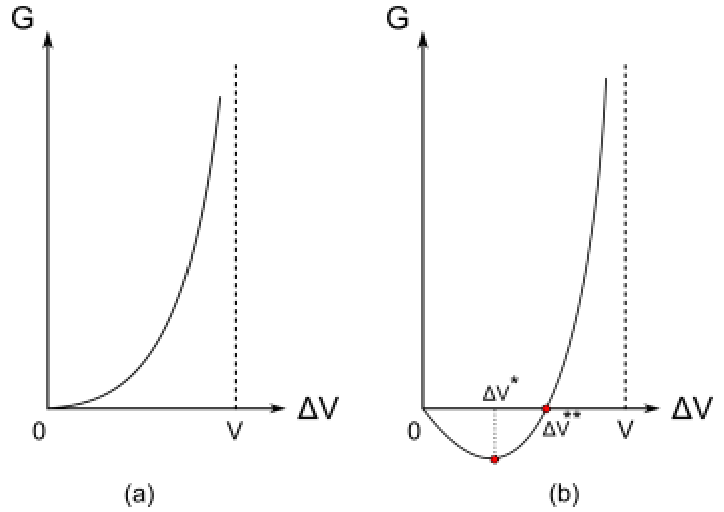


Fig. 4: Possible forms of G(ΔV).

This is mathematically expressed as $V > \sqrt{\frac{B}{2A}}$, or as $V > V_0$ with V_0 defined as in [7] above.

If the original speed of the ship V is above the V_0 threshold, then the option to reduce speed to save fuel (and emissions) could also reduce total costs. This situation is more likely to occur if I_C and/or O_C are low and/or p is high.

In this case, G(ΔV) achieves a minimum (negative) value for some 'optimal' value of ΔV= ΔV*, between 0 and V. In fact, G(ΔV) ≤0 for 0≤ ΔV ≤ ΔV**, and G(ΔV)>0 for ΔV>ΔV**, where ΔV** is the other (nonzero) root of G(ΔV)=0. We note that ΔV**> ΔV*. Both ΔV* and ΔV** depend on the values of all other parameters.

If this is the case, speed reduction would indeed be beneficial, and choosing ΔV= ΔV* would achieve maximum total benefits.

We now present several simple examples to illustrate our approach.

Example 1 – Aframax Tanker Fleet

The first example considers a fleet of N=10 Aframax double hull tankers, each with a DWT of 106,000 tonnes, and payload W=90,000 tonnes, serving the route from Ras Tanura to Singapore, a distance of L=3,702 nm (6,871 km). Other input parameters are as follows:

$V_1 = V_2$ = 15 knots = 668.16 km/day.
$T_A = T_B$ = 4 days
$F_1 = F_2$ = 65 tonnes/day (meaning that $k_1 = k_2 = 2.1791 \cdot 10^{-7}$)
D=350 days
f= 50 tonnes/day
p= $218/tonne (December 2008)
p= $600/tonne (July 2008)

In other words, we examine two variants, one with a low fuel price and one with a high one (all else being equal).

Then we consider reducing speed by one knot, to 14 knots, or 623.62 km/day. It is straightforward to show that we will need 0.60 more ships to be able to cover the same annual throughput. Rounding off to one more ship, we will have (Table 3):

Table 3. Aframax tanker comparison.

Quantity	**10 ships going 15 knots**	**11 ships going 14 knots**
Total fuel consumed for fleet, (tonnes per year)	218,952	201,778
CO_2 for fleet (tonnes per year)	694,077	639,637
Bunker cost for fleet ($/year)		
Fuel price p=218 $/tonne	$7,143,419	$6,630,878
p=600 $/tonne	$19,660,787	$18,250,124

We can see that fuel costs are reduced in both variants, the cost differential being $512,541 in the low fuel price variant and $1,410,663 in the high fuel price variant, both on a yearly basis. CO_2 averted would amount to 54,400 tonnes, even though one more ship is employed.

Still, this does not necessarily mean that total fleet costs will be reduced, as these would also depend on inventory and other operational costs.

Neglecting inventory costs for this example (these will be examined in example no. 3), we consider what the other operational costs might be in each of these variants.

In a market as seriously depressed as in late 2008, ship owners have been said to be willing to charter their ships for a rate of zero, with the charterer paying only for fuel. In this case, variant 1 would continue to be profitable, although the net savings, if expressed per day, would be very meager ($1,404/day).

For the high-market variant however, the $3,865/day savings of fuel costs are well below what an Aframax could command when the market was high. Rates as high as $60,000/day have been observed for this type of ship (or perhaps even higher), meaning that speed reduction during these periods would be non-sensical from a cost-benefit viewpoint.

Example 2 – Panamax Containership Fleet

Our second illustrative example investigates the effect of speed reduction in containerships. As said earlier, containerships are the top CO2 emissions producer in the world fleet (2007 Lloyds-Fairplay database).

Assuming a hypothetical string of N=100 (identical) Panamax containerships, each with a payload of W= 50,000 tonnes, if the base speed is V= 21 knots (both ways) and fuel consumption at that speed is 115 tonnes/day, then for a fuel price of p= $600/tonne (corresponding to a period of high fuel prices, before the slump of 2008), the daily fuel bill would be $69,000 per ship. Running the same type of ship at a reduced speed $V\text{-}\Delta V =$ 20 knots (one knot down), the fuel consumption would drop to 99.34 tonnes/day (cube law vs. 21 knots) and the daily fuel bill would drop to $59,605 per ship, some $10,000/day lower.

Assume these 100 ships go back and forth a distance of 2,100 miles (each way) and are 100% full in one direction and completely empty in the other. This is not necessarily a realistic operational scenario, as containerships visit many ports and as capacity utilizations are typically lower both ways, depending on the trade route. The scenario of trade routes from the Far East to Europe or from the Far East to North America, which are almost full in one direction and close to empty in the other, is probably close to the assumed scenario. However, a generalization of this analysis to many ports and different capacity utilizations in each leg of the trip should be straightforward. For simplicity, assume D=365 operating days per year and zero loading and unloading times. For non-zero port times, the analysis will be more involved but will lead to similar results.

At a speed of 20 knots, we will need 105 ships to reach the same throughput per year. Then we will have:

Table 4. Panamax containership comparison.

Quantity	**100 ships going 21 knots (case A)**	**105 ships going 20 knots (case B)**
Total fuel consumed for fleet, (tonnes per year)	4,197,500	3,807,256
CO_2 for fleet (tonnes per year)	13,306,075	12,069,002
Bunker cost for fleet ($/year)	2,518,500,000	2,284,353,741

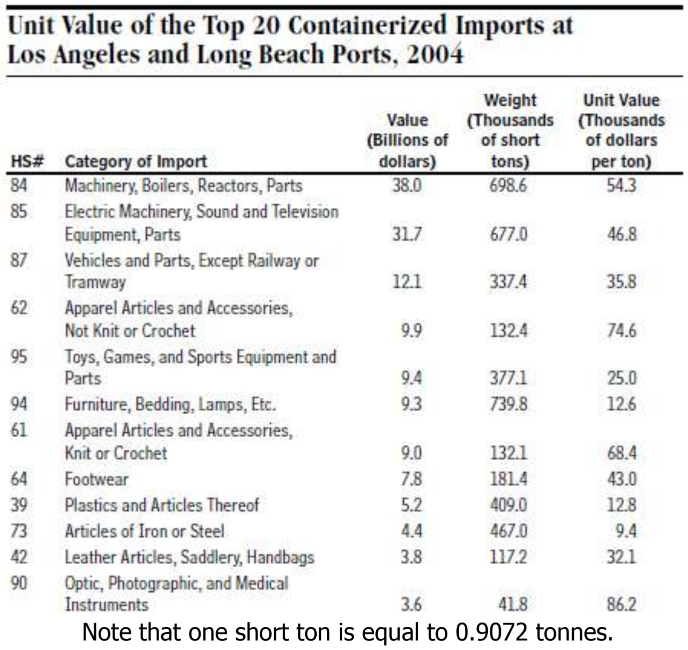
The net reduction of CO_2 emissions (per year) is 1,237,073 tonnes, and the fuel cost reduction (per year) is $234,146,259 for 5 more ships, that is, $46,829,252 per additional ship. Dividing by 365, this difference is $ 128,299 per day.

This means that if the sum of additional cargo inventory costs plus other additional operational costs of these ships (including the time charter) is less than $128,299 a day, then case B is overall cheaper. One would initially think that such a threshold would be enough. But it turns out that this is not necessarily the case if in-transit inventory costs are factored in.

Before we do so, we display Table 5, that illustrates the unit value of the top 20 containerized imports at the Los Angeles and Long Beach Ports in 2004 (see CBO(2006)).

To compute in-transit inventory costs for the above example, we hypothetically assume that cargo carried by these vessels consists of high value, industrial products, similar to those in Table 5, and that its average value at the destination (CIF price) is $20,000/tonne. We also assume the cost of capital being 8%. This means that one day of delay of one tonne of cargo would entail an inventory cost of $I_C = PR/365 = 20,000*0.08/365 = \$4.38$. This may not seem like a significant figure, but it is.

Table 5: Unit Value of Containerized Imports (1,000 $ per short ton).



Unit Value of the Top 20 Containerized Imports at Los Angeles and Long Beach Ports, 2004

HS#	Category of Import	Value (Billions of dollars)	Weight (Thousands of short tons)	Unit Value (Thousands of dollars per ton)
84	Machinery, Boilers, Reactors, Parts	38.0	698.6	54.3
85	Electric Machinery, Sound and Television Equipment, Parts	31.7	677.0	46.8
87	Vehicles and Parts, Except Railway or Tramway	12.1	337.4	35.8
62	Apparel Articles and Accessories, Not Knit or Crochet	9.9	132.4	74.6
95	Toys, Games, and Sports Equipment and Parts	9.4	377.1	25.0
94	Furniture, Bedding, Lamps, Etc.	9.3	739.8	12.6
61	Apparel Articles and Accessories, Knit or Crochet	9.0	132.1	68.4
64	Footwear	7.8	181.4	43.0
39	Plastics and Articles Thereof	5.2	409.0	12.8
73	Articles of Iron or Steel	4.4	467.0	9.4
42	Leather Articles, Saddlery, Handbags	3.8	117.2	32.1
90	Optic, Photographic, and Medical Instruments	3.6	41.8	86.2

Note that one short ton is equal to 0.9072 tonnes.

Computing the in-transit inventory costs for this case gives a total annual difference of $200,000,000 ($4,200,000,000-$4,000,000,000) in favor of case A, which moves cargo faster. This figure is significant, of the same order of magnitude as the fuel cost differential.

Assuming also a time charter rate of $25,000 per day (typical charter rate for a Panamax containership in 2007), the total other operational costs of the reduced speed scenario are $958,125,000 per year for 105 ships, versus $912,500,000 for 100 ships going full speed. Tallying up we find a net differential of $11,478,741 per year in favor of case A, meaning that in-transit inventory and other operational costs offset the positive difference in fuel costs.

Of course, other scenarios may yield different results, and the reduced speed scenario may still prevail in terms of overall cost, under different circumstances. For instance, if the average value of the cargo is $10,000/tonne, and everything else is the same, then the difference in annual inventory costs drops to \$100,000,000, rendering the reduced speed scenario a profitable proposition (with a total cost reduction of \$88,521,259 per year). Actually, speed reduction remains profitable if the value of the cargo is no more than about \$18,800/tonne (which can be considered as a break-even CIF price).

All of the above confirm that the drive to reduce emissions may or may not be a win-win proposition, with the final outcome depending on the specific parameters of the particular scenario (see Psaraftis and Kontovas (2000b) for some additional insights).

We end this section by noting that there are cases where adding more ships may not be necessary. These are cases in which the ship's schedule by design includes an amount of idle time in port. Such cases are typical for RoPax scheduled operations, where there is idle time built into the ship's schedule for various operational reasons. In these cases, any delay due to speed reduction is absorbed by the available idle time and no additional ships are necessary. For a discussion of this scenario, see Psaraftis et al (2009c).

5. The Cost to Avert One Tonne of CO2

What would it take to avert one tonne of CO_2 by speed reduction? Or, put in a different way, as much as the question "what price safety?" is common, let us now ask "what price emissions reduction?" We address this question by noting that in expressions [5] and [6], Δ(total CO_2 emissions) equals minus total CO_2 averted by implementing a speed reduction scheme. We define as the cost to avert one tonne of CO_2 (CATC) the ratio of the total net cost of the fleet due to CO_2 speed reduction divided by the amount of CO_2 averted by speed reduction. Then we will have:

$$\mathrm{CATC{=}NL\Delta V}\frac{\mathrm{-pD}\;\; 2\mathrm{V}-\Delta\mathrm{V}\;\;\; \mathrm{k}_1+\mathrm{k}_2\;\; +\dfrac{\mathrm{I_C WD}}{\mathrm{V(V}-\Delta\mathrm{V)}}+\dfrac{2\mathrm{O_C}}{\mathrm{V(V}-\Delta\mathrm{V)}}}{\mathrm{F}_{\mathrm{CO_2}}\mathrm{NDL\Delta V}\;\; 2\mathrm{V}-\Delta\mathrm{V}\;\;\; \mathrm{k}_1+\mathrm{k}_2}$$

After some algebraic manipulations, this can be rewritten as

$$\mathrm{CATC}=\frac{I_C WD+\dfrac{2O_C}{D}}{F_{CO_2}V\ \ V-\Delta V\ \ \ 2V-\Delta V\ \ \ k_1+k_2}-\frac{p}{F_{CO_2}} \qquad [8]$$

It can be seen that CATC is a positive linear function of both I_C and O_C and a negative linear function of the price of fuel p. It can also be seen that the denominator in the bracket is a cubic function of speed, reflecting the functional relationship between speed and the quantity of CO_2 that is produced.

In addition, the last term in [8], - p/F_{CO2}, where p is the price of one tonne of fuel and F_{CO2} is the CO_2 emissions factor, can be recognized as the cost of the amount of fuel saved (not spent) that would produce one tonne of CO_2. This is an opportunity cost that we will have to subtract from the total cost incurred, as it corresponds to the amount of fuel that would be saved if one tonne of CO_2 is averted.

The CATC criterion can be used whenever alternative options to reduce emissions are contemplated. In that sense, the alternative that achieves the lowest CATC is to be preferred.

The case in which CATC is negative corresponds to the case in which reducing speed is cost-beneficial, that is, to the case the function G(ΔV) of the previous section takes on a negative value.

For the containership example of the previous section, the CATC values for the various scenarios examined are as follows (Table 6):

Table 6. Values of CATC as per containership scenarios outlined earlier.

Scenario	**CATC ($/tonne of CO_2 averted)**
p=$600/tonne P=$20,000/tonne OC=$25,000/day	9.28
p=$600/tonne P=$10,000/tonne OC=$25,000/day	-71.56
p=$250/tonne P=$20,000/tonne OC=$15,000/day	104.94
p=$250/tonne P=$10,000/tonne OC=$15,000/day	24.10

This table confirms that CATC can vary widely. It is also interesting to note that the difference in CATC between the 1st and 2nd scenario is the same as that between the 3rd and 4th scenario ($80.84/tonne in both cases). This is not a coincidence, and can be explained by the structure of expression [8].

In these examples, the influence of in-transit inventory costs in the value of CATC can also be seen clearly. This means that perhaps one of the biggest obstacles that needs to be overcome if emissions are to be reduced, is the unwillingness of the cargo owners to incur inventory costs for their cargoes. Optimized routing, logistics, and other operational measures that would reduce this inventory costs would be important.

As regards what threshold conceivably exists for CATC, that is, under what (positive) value of CATC a speed reduction scheme would still be considered desirable, this issue is currently open and it is not an easy one to address. As much as it is obvious that both the shipping community and society at large wish to reduce CO_2 emissions from shipping, it is far from clear how much they are willing to pay to do so. This is not a surprise, given the fact that there is wide disparity of views on what should be done to curb GHG emissions, and the fact that decisions on the CO_2 front are still pending.

In a conceivable CO_2 Emissions Trading Scheme (ETS) for shipping, a monetary value would be put on a per tonne basis, for instance, $30/tonne of CO_2 averted, and emissions reduction measures would be evaluated against such a threshold. Such market values for CO_2 currently exist for other industries, but not for shipping, for which it is unclear how, or when such a scheme would be implemented.

Figure 5 shows the historic 2009 settlement prices of EU allowances issued under the EU Emissions Trading Scheme and traded at the European Climate Exchange (ECX). One EUA equals one tonne of CO2 (right-to-emit).

Fig. 5. ECX EU Allowances Future Contract Prices
(Source: European Climate Excange).

The concept of CATC, as defined above, can be generalized to measures other than speed reduction, and can be a useful concept for the evaluation of policy or other alternatives.

6. The port time factor

This section focuses on the case where total trip time is kept constant, even though speed is reduced (see Psaraftis et al (2009c) for more details). Given the fact that time at sea increases with slow steaming we must investigate possible ways to decrease time in port. This is not an easy task. The most feasible way to reduce time in port is through operational decisions regarding land-side operations (berth allocation, quay cranes scheduling and vessel stowage). Optimizing terminal operations has received increasing interest over the last years. Vis and de Koster (2003) review the relevant literature and illustrate the main logistics processes in a container terminal whereas Steenken et al.(2004) provide an overview of optimization methods terminal operations. The problem of allocating ships to berths (discrete case) or to quays (continuous case) is dealt among others in Cordeau et al. (2005) and Wang and Lim (2007). The Quay Crane Scheduling Problem (QCSP) which refers to the allocation of cranes and to the scheduling of stevedoring operations can be solved with the use of dynamic programming as proposed in Lim et al (2004) or be addressed with a greedy randomized adaptive search procedure like the one analyzed in Kim and Park (2004). Lee et al. (2006) address a yard storage allocation problem to reduce traffic congestion and Lee and Hsu (2007) present model for container re-marshalling. For a circumstantial review of the operations research literature of problems related to container terminal management the reader could refer among others to Vis and de Koster (2003) and Steenken et al. (2004).

We now present a simple scenario to investigate the impact of speed reduction on ship CO_2 emissions and fuel costs in the case that the total trip time is kept constant.

Assume a ship that loads from a port A, travels to port B (a total distance of L nm from A) carrying a payload W with a known speed of V_0 (in knots), where she discharges the cargo and stays at port before departing again.

The daily fuel consumptions and times that the ship spends at sea and in port are known and are as follows:

At sea:
Fuel consumption F_0 (tonnes per day)
Total time at sea $T_0 = \frac{L}{24 \cdot V_0}$ (days)
In port:
Fuel consumption f (tonnes per day)
Total time in port t_0 (days)

Thus, the total fuel consumption for this trip is $FC_0 = F_0 \cdot T_0 + f \cdot t_0$

Now suppose that the ship operator wants to investigate the scenario of speed reduction. The new speed V will be a fraction of the original speed ($V=aV_0$ where $0<a<1$) and, hence, there will be an increase of the time at sea, $T = \frac{L}{24V} = \frac{To}{a}$

The effect of speed change on fuel consumption is assumed cubic for the same ship (and for speeds that are close to the original speed) as discussed in Section 4. The fuel consumption in port per day will remain the same, but we assume that the new time in port (t) will be reduced in order to keep at least the same total trip time with that before the speed reduction.

For this trip we can compute the difference in fuel consumption as follows:

$$\Delta(\text{Fuel Consumption})=\Delta(\text{consumption at sea}) + \Delta(\text{consumption at port})$$

$$=F\cdot T\text{-}F_0\cdot T_0+f\cdot t\text{-}f\cdot t_0=F\cdot\frac{L}{24\cdot V}\text{-}F_0\cdot\frac{L}{24\cdot V_0}+f\cdot\; t\text{-}t_0\;=$$

$$\overset{V=aV_0}{=}F\cdot\frac{L}{24\cdot aV_0}\text{-}F_0\cdot\frac{L}{24\cdot V_0}+f\cdot\; t\text{-}t_0\;=\frac{L}{24\cdot V_0}\left(F\cdot\frac{1}{a}\text{-}F_0\right)+f\cdot\; t\text{-}t_0\;=$$

$$\overset{\frac{F}{F_0}=\left(\frac{V}{V_0}\right)^3}{=}\frac{L}{24\cdot V_0}\left(\left(\frac{V}{V_0}\right)^3F_0\cdot\frac{1}{a}\text{-}F_0\right)+f\cdot\; t\text{-}t_0=\frac{L}{24\cdot V_0}\left(\left(\frac{aV_0}{V_0}\right)^3F_0\cdot\frac{1}{a}\text{-}F_0\right)+f\cdot\; t\text{-}t_0=$$

$$=\frac{L}{24\cdot V_0}\left(a^3F_0\cdot\frac{1}{a}\text{-}F_0\right)+f\cdot\; t\text{-}t_0$$

Thus, the total fuel consumption for slow steaming is:

$$\Delta(\text{Fuel Consumption})=\frac{L}{24\cdot V_0}F_0\;\; a^2\text{-}1\;\;+f\cdot\;\; t\text{-}t_0 \qquad [9]$$

As one may notice, the first addend is negative since, by definition, parameter ‘a’ lies between 0 and 1 and L, F_0 and V_0 are always positive. It is obvious that if time in port remains the same (t-t_0 equal to 0) there will be a need to add a number of additional vessels (possibly fractional) in order to maintain the same throughput per year. The model in this Section examines assumes that $t < t_0$, and in fact that ‘t’ is such that the total trip time, including time in port, remains the same $T+t=T_0+t_0$.

Furthermore, as discussed in Section 3, to find the equivalent CO_2 emissions reduction, one has to multiply the reduction in bunker consumption by the appropriate emissions factor (F_{CO_2}) from Table 2.

$$\Delta(CO_2\ \text{emissions})=F_{CO_2}\cdot\left[\frac{L}{24\cdot V_0}F_0\;\; a^2\text{-}1\;\;+f\cdot\;\; t\text{-}t_0\right] \qquad [10]$$

Again, the fuel cost reduction can be estimated by assuming a constant fuel price as in the previous examples.

$$\Delta\text{(fuel costs)}=p\cdot\left[\frac{L}{24\cdot V_0}F_0\ \ a^2\text{-}1\ \ +f\cdot\ \ t\text{-}t_0\right] \qquad [11]$$

We now move forward to a realistic example using the following figures that are based on operational data provided by Det Norske Veritas (DNV), see Psaraftis et al (2009c).

A Panamax container-vessel begins its trip at Port A, and then consequently visits ports B and C before going back. The time that she spends at sea and in port and the relating fuel consumptions are as follows:

Depart Port	**Arrive Port**	**Distance (miles)**	**Avg speed (kn)**	**Total TEU**	**Sailing time (hrs)**	**F_0 (tn/day)**	**T_0 (days)**	**f (tn/day)**	**t_0 (days)**
A	B	115	20.18	1892	5.70	91.79	0.24	16.58	1.79
B	C	6068	23.41	2593	259.20	136.81	10.80	3.26	5.45
C	A	6323	22.85	3294	276.70	139.22	11.53	12.15	3.55

Using Eq. 9,10,11 and we can calculate the reductions in fuel cost and emissions for each leg. Note that the emissions factor used in this example is 3.13.

For reasons of simplicity we omit the detailed calculations and we present the resulting total reductions for this round trip in Fig.6.

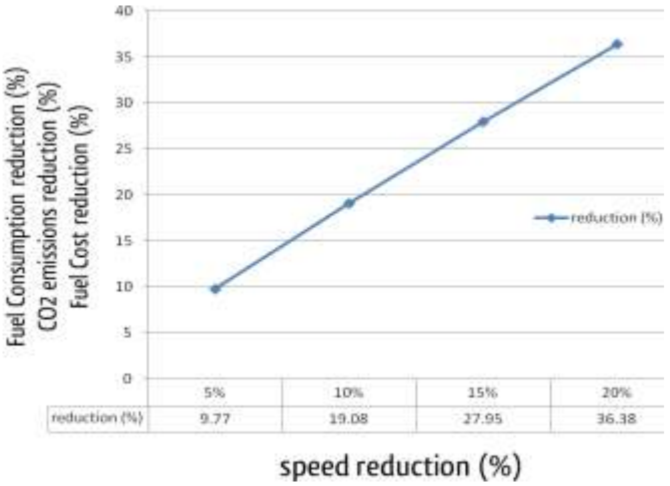


Fig. 6. Reductions in fuel consumption, CO2 emissions and Fuel Costs.

One can observe some significant savings in fuel consumption, CO2 emissions (in fact, all emissions) and fuel cost. However, "there is no free lunch" necessarily. Compensating for a reduced speed will entail either additional ships to maintain the same throughput, or the ability to reduce port time. If the former can be achieved, overall emissions are shown to be reduced, but the overall cost (including cargo in-transit inventory cost) may or may not go down (as per previous section). Emissions can be reduced even further if port time can be reduced so that there is no need for additional vessels. But this may be a more difficult proposition. For instance, in the example illustrated above, when speed is reduced by 5 % , time in port has to be reduced by 11% to maintain a constant total trip time. If this sounds feasible, it is non-trivial nonetheless. For a speed reduction of 15% the total time in port has to be reduced from 10.8 days down to 6.81, which is almost a 37 % reduction. This is a much more difficult proposition, possibly entailing drastic port re-engineering and/or infrastructure improvements

7. Speed reduction at SECAs

All considerations of the previous sections of this paper can be also applied to emissions other than CO_2. For instance, one can compute emissions from other pollutants and also define CATN (the cost to avert one tonne of NOx), CATS (the cost to avert one tonne of SO_2) [e], and so on.

The only difference with the previous analysis is that one would have to substitute for the CO_2 emissions factor the appropriate emissions factor of the pollutant under consideration. For instance if one considers SO_2, one 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). Even though the amounts of SO_2

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[e] Not to be confused with CATS (cost to avert one tonne of spilled oil)- a criterion under discussion in Formal Safety Assessment (in the context of environmental risk evaluation criteria).

produced by ships are substantially lower than CO_2, for SO_2 emissions other considerations are equally important. SO_2 is not a greenhouse gas but as it causes acid rain (among other effects), its reduction is a matter of high priority. To that effect, SO_2 (and generally SO_x) reduction is also high on the IMO agenda, and in fact regulatory progress on this front is more advanced than for the CO_2 front, as exemplified in the latest MEPC 58 Annex VI developments as regards the timetable on SO_x emissions caps.

To reduce pollution by SO_x, special highly sensitive areas have been designated by the IMO as 'Sulphur Control Emissions Areas', or SECAs, where specific limits in SO_x content are set for a ship's exhaust gases. Designated SECAs to date are the Baltic Sea, the North Sea and the English Channel. The IMO does not specify how the SO_x emissions targets should be reached. Among methods contemplated, sea scrubbers are a measure that is offered on the technology front. Fuels cleaner in sulphur content is also a method that is proposed (of which more later).

Among potential operational measures, one question that is relevant is this: Can speed reduction at SECAs work, as a measure to reduce SO_x emissions? This sounds like an easy question to pose, for which however the answer may not be so easy.

First of all it should be noted that speed reduction, in and of itself, will not change the proportion of SO_2 in a ship's exhaust. But it will change the total amount of SO_2 produced, much in the same way as this happens for CO_2. In that sense, speed reduction to reduce SO_2 is worthy of note.

Let us assume a ship that goes from port X to port Y, sailing a total distance of L. At the beginning or the end of the trip, there is a SECA, of distance d (<L).

Assume there are two options: The first (option A) is to sail the entire trip at a constant speed of V. The second (option B) is to reduce speed to v (<V) within the SECA, so as to reduce SO_2 emissions, but go at a slightly higher speed of V* (>V) outside the SECA, so that *total transit time is the same.*

Total transit time is kept the same so that we do not need more ships in the supply chain, and shippers do not lose money on in-transit inventory costs. If total transit time is not the same, we shall have to go through an analysis similar to that of previous sections.

Let us now pose the question, with total transit time being the same, which option burns less fuel, A or B? The one that does so would also cost less, and would also produce less total emissions, not only in SO_2, but also CO_2 and all other pollutants.

The analysis is straightforward and goes as follows:
Let the transit time in both scenarios be T= L/V (in days). If within the SECA the speed is v (<V) for distance d, then

$$\frac{L}{V}=\frac{d}{V}+\frac{L-d}{V^*}$$

Therefore $$V^* = \frac{L-d}{\frac{L}{V}-\frac{d}{v}} > V$$

[the assumption here is that L/V > d/v, otherwise making up the time lost in the SECA would be impossible.]

Again, we assume that fuel consumption per day obeys a cube law, that is, is equal to kV^3. Since we have to multiply by total days, the law becomes quadratic, as total fuel consumption is $T_{FC}=k\,V^3(L/V)=kLV^2$.

Option A: total fuel consumption $T_{FC}(V)= kLV^2$
Option B: total fuel consumption $T_{FC}(V^*,v) = k(L-d)V^{*2} + kdv^2$

Substituting, we get $$T_{FC}(V^*,v) = \frac{k(L-d)^3}{\left(\frac{L}{V}-\frac{d}{v}\right)^2}+kdv^2$$

Define the ratio $$R=\frac{T_{FC}(V^*,v)}{T_{FC}(V)} = \frac{(L-d)^3}{L\left(L-d\frac{V}{v}\right)^2}+\frac{d}{L}\left(\frac{v}{V}\right)^2$$

It can be shown mathematically that always R>1 (assuming again that L/V > d/v). The proof of this is straightforward.

Let us illustrate this with an example:

Let L= 2000 nautical miles
d=200 (SECA)

V= 20 knots
v= 18 knots within the SECA

$$V^* = \frac{1800}{\frac{2000}{20} - \frac{200}{18}} = 20.25 \text{knots} \quad \text{outside SECA}$$

Then

$$R = \frac{1800^3}{2000\left(2000 - 200\frac{20}{18}\right)^2} + \frac{200}{2000}\left(\frac{20}{18}\right)^2 = 0.9226 + 0.081 = 1.0036$$

Other speed and distance combinations will produce other ratios, but all will be >1.

The conclusion from this analysis is this: Speed reduction in SECAs will reduce emissions (of all gases, including SO_x) within the SECA, but result in more total emissions and more total fuel spent if speed is increased outside the SECA to make up for lost time. The reduced emissions within the SECA will be more than offset by higher emissions outside (for all gases). The total fuel bill will also be higher.

Of course, whether or not society may mind polluting the areas outside SECAs more in order to make conditions in SECAs more friendly to the environment is a non-trivial issue that is outside the scope of this paper.

Alternatively, if a lower speed is maintained throughout the ship's journey, then obviously total fuel and total emissions will be reduced, but there will be increased costs in the form of more ships needed to carry the same cargo in a year and more in-transit inventory cost for the shippers (as per previous sections).

8. SECAs continued: Effect on Modal Split

We now make a cursory investigation of the case in which a ship involved in short sea trades uses low- sulphur fuel at a SECA, to reduce SO_x emissions. This fuel is 4-30% more expensive than high-sulphur fuel (see Figure 3). Hence freight rates may go up. Furthermore, according to a document submitted by INTERFERRY to MEPC 58 (doc. MEPC 58/5/11) the rise in fuel prices over the past years and the cost increase for low sulphur fuel will either be passed on to customers or will force some operators out of the market. Increases in fuel prices are cited in this document as key reason for canceling certain ferry routes including those from Newcastle (United Kingdom) to Bergen, or Kristansand (Norway). This may induce shippers to use land transport alternatives (trucking), which will go against stated policies toward shifting cargo from land to sea and increase CO_2 emissions through the logistics chain. The European Community Shipowners' Association (ECSA) has already warned that new sulphur limits agreed at the IMO could push more freight onto the roads in Europe (Lloyds List, 2008a).

In this paper we shall only examine a hypothetical and rudimentary example of this scenario, which goes as follows. A modern Handymax bulk carrier moves a cargo of W=45,000 tonnes from Bergen to Oslo, Norway, a distance of L=371 nm (689 km). The ship sails with a speed of 14 knots and consumes 30 tonnes of HFO per day.

The ship completes the trip in 1.1 days, after consuming a total of 33.13 tonnes of fuel. Thus total CO_2 emissions are 105.01 tonnes, which corresponds to 3.39 grams per tonne-km. Total SO_2 emissions amount to 2.99 tonnes for high-sulphur (4.5%) heavy fuel oil but only to 0.33 tonnes for low-sulphur (0.5%) marine diesel oil, which is the maximum allowable sulphur content effective 1/1/2020. This means that the potential savings in SO_2 emissions by switching to cleaner fuel are 2.66 tonnes (CO_2 would be the same).

We obviously have no way of knowing what the fuel prices will be in 2020, and in particular what the availability of low sulphur fuel might be and how it could impact these fuel prices at that time. However, let us assume that prices (in 2008 US dollars) are as they were in July 2008, when they were high (see Fig. 3). Then the total bunker cost for this trip is $22,545 when using high-sulphur HFO and $37,354 for low-sulphur MDO.

Suppose now that a (yet unspecified) portion, or even the whole amount of this cargo is transported from Bergen to Oslo by road, using a modern and environment-friendly truck with a trailer (long-haul traffic) whose engine emits 2.6 kgr of CO_2 per liter of low-sulphur diesel fuel (10ppm of sulphur).

In this case one truck moves a cargo of 40 tonnes with a speed of 60 km/h and a fuel consumption of 43 liters per 100 km when loaded. Each one-way trip from Bergen to Oslo, a distance of 490 km by road, takes 8.2 hrs or 0.34 days. Total fuel consumption is 0.2107 tonnes per one-way trip, which corresponds to 0.548 tonnes of CO_2 per one-way trip, or 27.95 grams of CO_2 per tonne-km.

We first notice that the comparison is not on a completely equal basis, as the sea trip distance is some 40% longer than the road one. Even so, let us calculate the total CO_2 produced by the road option.

To move the whole cargo of 45,000 tonnes of one shipload one way by road, it would take 1,125 truck trips, bringing the total CO_2 produced by this option to 616.3 tonnes, almost 6 times as much as that produced by the ship, and more than 230 times the amount of SO_2 potentially saved by the cleaner ship fuel. Although comparing the volumes of the two gases may be like comparing apples with oranges, it is important to have these figures in mind (SO_2 produced by the truck fleet is essentially negligible) [f].

Of course, not all of the 45,000 tonnes of cargo may want to shift to road. The proportion that will do so will depend, among other things, on things such as:

(a) the unit fuel costs of each of the two options (both for low-sulphur and for high-sulphur fuel)

(b) how the road option is exercised (e.g., it could be 1,125 trucks doing one trip each, a fleet of 563 trucks doing two trips each, or any other combination)

(c) the transit times of each of the two options

(d) the inventory costs of the cargo.

Regarding (a), we note the differential of \$0.33/tonne of cargo in the price of fuel (or \$14,809 per shipload, or some 66% more). This will translate into a cost increase of the sea mode. The calculation of the impact of this cost increase on the modal split between sea and road (which also depends on points (b), (c) and (d)) was an issue that was open at the time of the writing of this paper.

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[f] This analysis does not take into account the additional CO2 emitted by refineries to produce increased amounts of low-sulphur fuel, or the additional CO2 as a result of the possible congestion by having a large number of trucks on the highway.

9. Conclusions

This paper has taken a look at some of the problems associated with green maritime logistics. Speed reduction was the main focus of the paper and some conditions under which such a scheme would reduce overall cost were identified for some operational scenarios. In addition, some possible ramifications of using speed reduction and cleaner fuels at SECAs were investigated. It was seen that caution should be exercised in proposing measures that may at first glance look environmentally friendly, but in reality they may have negative side effects.

The main conclusions of this paper can be summarized as follows:

- Speed reduction will always result in a lower fuel bill and lower emissions, even if the number of ships is increased to meet demand throughput.
- Due to in-transit cargo inventory costs and other ship costs, total fleet operational costs may or may not decrease with speed reduction, depending on the scenario.
- The cost to avert one tonne of CO2 by speed reduction depends on several factors, being higher for higher-value cargoes.
- Speed reduction to reduce sulphur emissions at SECAs will result in a net increase of total emissions (including sulphur) along a ship’s route, if transit time is to be kept the same.
- Cleaner fuel at SECAs may result in a reverse cargo shift from sea to land that has the potential to produce more emissions on land than those saved at sea.

Future research vis-a-vis the models presented here involves extending these models to more complex logistical scenarios, concerning, among other things, issues such as ship routing and scheduling, maritime and intermodal transport network design, queuing at ports, emissions at ports, and all the others listed at the introductory section. Plus, the broader consideration of such issues in a strategic setting is also important. In the emerging drive for green maritime logistics, investigating such problems would become increasingly important in the future.

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