

SHIP EMISSIONS: LOGISTICS AND OTHER TRADEOFFS

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ABSTRACT

This paper takes a look at various tradeoffs that are at stake in the goal for reduced ship emissions and may impact the cost-effectiveness of the maritime logistics chain and presents some models that can be used to evaluate these tradeoffs. The reason for investigating such tradeoffs is that measures to reduce such emissions may possibly have ramifications as regards the logistical supply chain, and vice-versa. The broad spectrum of measures that are involved in the drive to reduce emissions generally depends on the type of emissions that are studied. In this paper we focus on operational measures that have a direct link to logistical operations, and investigate related tradeoffs. The focus is mainly on CO₂ and SO₂ emissions. Measures such as reduction of speed, change of number of ships in the fleet, and 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. Industry circles have also voiced the concern that low-sulphur fuel in SECAs (these are the so-called 'sulphur emissions control areas' that exist in some parts of the world- for instance the Baltic and the North Sea) may make maritime transport (and in particular short-sea shipping) more expensive and induce shippers to use land-based alternatives (mainly road), even though shifting cargo from land to sea is an important policy goal. A reverse shift of cargo from sea to land might ultimately increase the overall level of CO₂ emissions along the intermodal chain. Models to investigate such problems are developed and some examples are presented.

Our main conclusions 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.*

KEY WORDS

Ship Emissions; Green Logistics; Cost to Avert One Tonne of CO₂; Speed Reduction

INTRODUCTION

Emissions from commercial shipping are currently the subject of intense scrutiny by the world shipping community and society at large. According to the Kyoto protocol to the United Nations Framework Convention on Climate Change - UNFCCC (1997), definite measures to reduce CO₂ emissions are necessary in order to curb the projected growth of

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greenhouse gases (GHGs) worldwide. Shipping has thus far escaped being included in the Kyoto global emissions reduction target for CO₂ and other GHGs. But it is clear that the time of non-regulation is rapidly approaching its end, and measures to curb future CO₂ growth are being sought with a high sense of urgency. CO₂ is the most prevalent of these GHGs, and it is therefore clear that any set of measures to reduce the latter should primarily focus on CO₂. In parallel, the broader analysis of other greenhouse gases (such as CH₄ and N₂O) and other, non-greenhouse gases, such as SO₂, NO_x and others is already very high on the International Maritime Organization's (IMO) agenda. Various analyses of many aspects of the problem have been and are being carried out and a spectrum of measures are being contemplated.

At the latest meeting of IMO's Marine Environment Protection Committee (MEPC 58), held in London in October 2008, progress as regards air pollution from ships was mixed. On the positive side, 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, 2008).

At the same meeting, 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). The objectives of Phase 1 have been as follows: (1) to undertake an assessment of present day CO₂ emissions from international shipping; (2) to estimate future shipping emissions towards 2050; (3) to compare shipping emissions with other transportation modes; and (4) to assess climate impacts from shipping. Phase 1 is followed by Phase 2 which also addresses GHGs other than CO₂ and possibilities and mechanisms for emissions reductions.

On the negative side, it became clear at MEPC 58 that the stated objective to establish a mandatory Energy Efficiency Design Index of the environmental performance of new ships by MEPC 59 in July 2009 will not be reached. In fact, MEPC 58 failed to reach a consensus on GHG emissions and deferred further action for an intersessional meeting in the spring of 2009. Due to procedural reasons, this delay means that the IMO will not be in a position to have reached a decision by MEPC 59, and, in turn, a clear position at the UN Climate Change Conference in Copenhagen in late 2009, when a new climate agreement is expected to be reached. Much of the discussion thus far has centered on the definition and proposed amendments of an Energy Efficiency Design Index for new ships, and there seems 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 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.

It is also interesting to point out that 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 Emissions Trading Scheme (ETS), similar to that used in other industries. However, industry circles have voiced concerns that such an approach would be difficult or impossible to implement.

Looking at the literature on the broad area of this paper (including both scientific work and regulation-related documents), it is no surprise that the relevant material is immense. MEPC 57 alone had some 65 submissions, MEPC 58 had 45 submissions and the GHG intersessional group meeting in Oslo, Norway in June of 2008 had some 20 submissions. Among the number of related IMO documents, perhaps the most seminal one from 2000 to mid-2008 was IMO (2000). Outside IMO documents, detailed methodologies for constructing fuel-based inventories of ship emissions have been published by Corbett and Köhler (2003), Endresen et al (2003; 2007), Eyring et al (2005), and in EMEP/CORINAIR (2002). In Table 1 we reproduce one of the main results of the most recent IMO-sponsored study, Buhaug et al (2008).

Table 1: Consensus estimate 2007 CO₂ emissions (million tonnes CO₂). Source: Buhaug et al (2008)

	Low bound	Consensus estimate	High bound	Consensus estimate % Global CO₂ emissions
Total ship emissions ¹	854	1019	1224	3.3
International shipping ²	685	843	1039	2.7

¹ Activity based estimate including domestic shipping and fishing, but excluding military vessels.

² Calculated by subtracting domestic emissions estimated from fuel statistics from the activity based total excluding fishing vessels.

Table 2 is from Psaraftis and Kontovas (2009) and shows a comparison of bunker consumption estimates among a broad set of studies, based on the comparison made in Buhaug et al (2008). Bunker consumption is relevant as it is directly proportional to CO₂ emitted. In order to allow a proper comparison, which is difficult anyway because of different modeling assumptions, various adjustments were applied.

Table 2: Comparison of Bunker Consumption Results of Various Studies. Source: Psaraftis and Kontovas (2009)

	Base year	Total (Mt)	Adjusted Total	2007 est. (Mt)
Eyring et al., 2005	2001	280	277	361
Corbett et al. 2003	2001	289	254	339
Endresen et al, 2007	2000	195	210	282
IMO Expert Group	2007	369	369	369
IEA total marine sales	2005	214	214	234
EIA bunker	2004	225	225	260
Buhaug et al., 2008	2007	333	333	333
Psaraftis and Kontovas, 2008	2007	298	283	283

In a general sense, the drive to reduce emissions entails a broad spectrum of measures, and these generally depend on the type of emissions that are studied. Some of these measures are technical, and some are operational. In this paper we shall focus on operational measures that have a direct link to logistical operations, and investigate related tradeoffs. The focus will mainly be on CO₂ and SO₂ emissions. The reason for investigating such tradeoffs is that measures to reduce such emissions may possibly have ramifications as regards the logistical supply chain, and vice-versa. For instance, measures such as (a) reduction of speed, (b) change of number of ships in the fleet, (c) and 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. Industry circles have also voiced the concern that low-sulphur fuel in SECAs (these are the so-called ‘sulphur emissions control areas’ that exist in some parts of the world- for instance the Baltic and the North Sea) may make maritime transport (and in particular short-sea shipping) more expensive and induce shippers to use land-based alternatives (mainly road), even though shifting cargo from land to sea is an important policy goal. A reverse shift of cargo from sea to land might ultimately increase the overall level of CO₂ emissions along the intermodal chain.

Before we proceed with our analysis, we first note that even though the literature on the broad area of this paper (ship emissions) is immense, the literature on the specific topic of this paper (link between emissions and maritime logistics) is scant. There are however 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 containerhips 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.

It is important to realize that if one wishes to investigate measures for reducing ship emissions, 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, 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. However, it is outside the scope of this paper.

In this paper we examine an operational setting, one that is connected with the logistics of the ship operation. This examines possible effects of measures to reduce emissions that are implemented on a known type of ship. For that ship, no design or other major changes (e.g., an engine change) are assumed to be taking place, but solutions on how to best exploit a given design are sought.

The rest of this paper is organized as follows: The section that follows deals with the algebra of CO₂ emissions. The next section investigates the effect of speed reduction. The following three sections introduce the concept of the cost to avert a tonne of CO₂, investigate the effect of speed reduction at SECAs, and provide some insights on the potential ramifications of low sulphur fuels on modal split. The final section presents the paper's conclusions.

ALGEBRA OF CO₂ EMISSIONS

Our simplest scenario to investigate tradeoffs between ship CO₂ 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 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 the 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.

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, it is our opinion that extending our approach to these other scenarios is straightforward, and that 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 daily fuel consumptions are known and are as follows for each ship:

In port: f (tonnes per day)

At sea: F_1, F_2 (tonnes per day) for laden and ballast legs (respectively)¹.

The effect of speed change on fuel consumption is assumed cubic for the same ship, that is, $F_{\text{new}}/F = (V_{\text{new}}/V)^3$, or, $F_1 = k_1 V_1^3$, $F_2 = k_2 V_2^3$, where k_1 and k_2 are known constants. These are functions of the loading condition of the ship and of other ship characteristics (e.g., engine, horsepower, geometry, age, etc).

One tonne of fuel burned in the ship's engine room will produce F_{CO_2} tonnes of CO₂, where F_{CO_2} is the CO₂ emissions factor. Several past studies, including IMO (2000), EMEP/CORINAIR (2002), and Endresen (2007), among others, have used the value of 3.17 for F_{CO_2} , irrespective of fuel type and engine type. However, more recent studies, for instance Buhaug et al (2008), have used slightly lower coefficients, different for Heavy Fuel Oil (HFO) and for Marine Diesel Oil (MDO) and Marine Gas Oils (MGO). The actual values are 3.082 for MDO/MGO and 3.021 for HFO. In this paper we shall use the original value of 3.17, also used in Psaraftis and Kontovas (2008, 2009), noting that our emissions results will have to be scaled down by up to 5% if a lower emissions factor is used.

Assume finally 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 time-wise, as historical experience has shown².

¹ Total fuel consumption is assumed here, including from both main engine and auxiliaries. The extension to individual fuel consumptions (by fuel type) is straightforward.

² Constancy during the year may be patently false, as recent events have demonstrated, 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 for auxiliary engines, low sulphur fuel for emissions control areas, etc, assuming a unique fuel price is obviously a simplification. But this causes no loss of generality either, as an average price can be assumed for the general case.

In addition to the standard costs borne by the charterer, this 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 but is outside the scope of this paper.

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:

$$\begin{aligned} pnT_{FC} + nI_C W \left(T_{AB} + \frac{L}{V} \right) + O_C &= np \left[T_{AB}f + L(k_1V_1^2 + k_2V_2^2) \right] + nI_C W \left(T_{AB} + \frac{L}{V_1} \right) + O_C = \\ &= D \frac{p \left[T_{AB}f + L(k_1V_1^2 + k_2V_2^2) \right] + I_C W \left(T_{AB} + \frac{L}{V_1} \right)}{\frac{L}{V_1} + \frac{L}{V_2} + T_{AB}} + O_C \end{aligned}$$

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

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

$$\begin{aligned} pnNT_{FC} + nNk W \left(T_{AB} + \frac{L}{V_1} \right) + NO_C &= \\ &= nNp \left[T_{AB}f + L(k_1V_1^2 + k_2V_2^2) \right] + nNI_C W \left(T_{AB} + \frac{L}{V_1} \right) + NO_C = \\ &= DN \frac{p \left[T_{AB}f + L(k_1V_1^2 + k_2V_2^2) \right] + I_C W \left(T_{AB} + \frac{L}{V_1} \right)}{\frac{L}{V_1} + \frac{L}{V_2} + T_{AB}} + NO_C \end{aligned}$$

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

EFFECT 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 amount³. Let this common reduction (initial speed – final speed) be equal to $\Delta V \geq 0$ ⁴. To reduce speed and maintain annual

³ Reducing speeds by different amounts is a straightforward generalization.

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 $N + \Delta N$ 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:

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

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

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

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

$$\Delta(\text{total fleet costs}) = NL\Delta V \frac{-pD(2V - \Delta V)(k_1 + k_2) + \frac{I_c WD + 2O_c}{V(V - \Delta V)}}{2\frac{L}{V} + T_{AB}} \quad [2]$$

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

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

Or, in simplified form,

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

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:

⁴ 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.

$$\Delta(\text{total CO}_2 \text{ emissions}) = -F_{\text{CO}_2} NL \Delta V D \frac{(2k_1 V_1 + 2k_2 V_2 - (k_1 + k_2) \Delta V)}{\frac{L}{V_1} + \frac{L}{V_2} + T_{AB}} \quad [5]$$

Or, in simplified form,

$$\Delta(\text{total CO}_2 \text{ emissions}) = -F_{\text{CO}_2} NL \Delta V D \frac{(2V - \Delta V)(k_1 + k_2)}{2\frac{L}{V} + T_{AB}} \quad [6]$$

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 $\Delta(\text{total fleet cost})$ 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.

A closer look at expression [2]⁵ 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:

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

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 1a below).

This is mathematically expressed as $V \leq \sqrt{\frac{B}{2A}}$, or as

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

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 ⁶. 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 Figure 1b).

⁵ The analysis for expression [1] is similar, but more tedious.

⁶ 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.

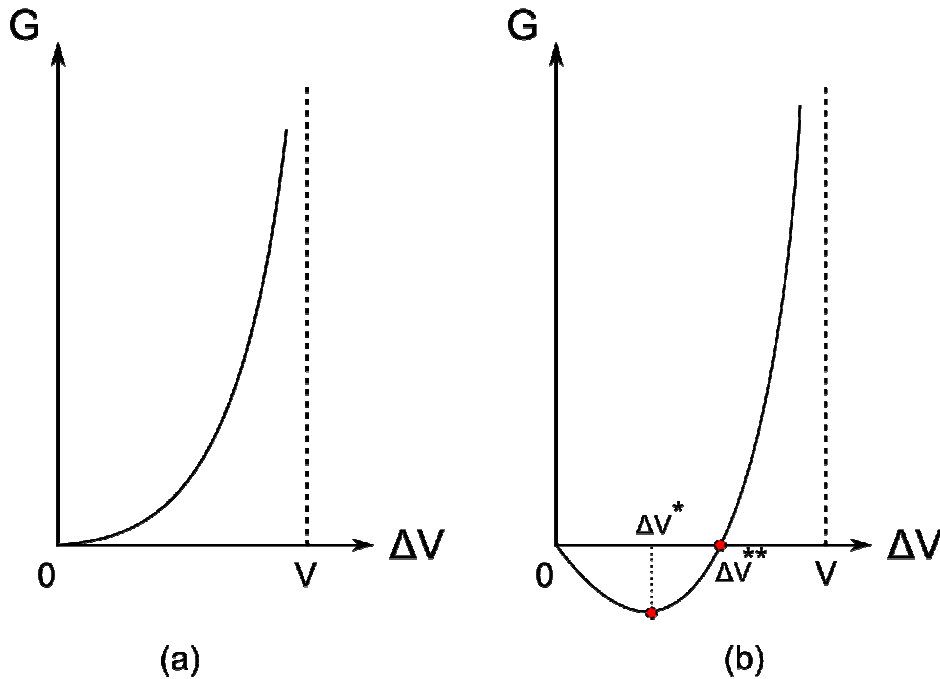


Figure 1: Possible forms of $G(\Delta V)$

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, $G(\Delta V)$ achieves a minimum (negative) value for some 'optimal' value of $\Delta V = \Delta V^*$, between 0 and V . In fact, $G(\Delta V) \leq 0$ for $0 \leq \Delta V \leq \Delta V^{**}$, and $G(\Delta V) > 0$ for $\Delta V > \Delta V^{**}$, where ΔV^{**} is the other (nonzero) root of $G(\Delta V) = 0$. We note that $\Delta V^{**} > \Delta V^*$. 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 $\Delta V = \Delta V^*$ would achieve maximum total benefits.

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 RPM.

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, with 106,000 DWT, 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
- $p = \$218/\text{tonne}$ (December 2008)
- $p = \$600/\text{tonne}$ (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 per ship (tonnes per trip)	1,534	1,365
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. CO₂ 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 Bulk Carrier Fleet

The second example considers a fleet of N=10 Panamax double hull bulk carriers, with 70,000 DWT, and payload W=66,000 tonnes, carrying coal from Newcastle, Australia to Japan, a distance of L=4,287 nm (7,957 km). Other input parameters are as follows:

- V₁ = 13.5 knots = 601.34 km/day
- V₂ = 14 knots = 623.62 km/day.
- T_A=T_B = 4 days
- F₁ = 32.5 tonnes/day (meaning that k₁= 1.4946·10⁻⁷)
- F₂ = 30 tonnes/day (meaning that k₂= 1.2370·10⁻⁷)
- f= 3.5 tonnes/day HFO
- p= \$218/tonne (December 2008)
- p= \$600/tonne (July 2008)

Then we consider reducing speed by one knot, to 12.5 knots, or 556.80 km/day. Again it is straightforward to show that we will need one more ship to be able to cover the same annual throughput. Then we will have (Table 4):

Table 4: Panamax Bulk Carrier comparison

Quantity	10 ships going 13.5 knots	11 ships going 12.5 knots
Total fuel consumed per ship (tonnes per trip)	827	713
Total fuel consumed for fleet (tonnes per year)	96,490	85,667
CO ₂ for fleet (tonnes per year)	305,873	271,565
Bunker cost for fleet (\$/year)		
Fuel price p=218 \$/tonne	\$1,768,182	\$1,488,848
p=600 \$/tonne	\$4,866,556	\$4,097,747

We can see that fuel costs are reduced in both variants, the cost differential being \$279,334 in the low fuel price variant and \$768,809 in the high fuel price variant, both on a yearly basis. CO₂ averted would amount to 34,308 tonnes, even though one more ship is employed.

If we factor in other operational costs, we will have results similar with those of the Aframax tanker case.

Example 3 – Panamax Containership Fleet

Our third illustrative example investigates the effect of speed reduction in containerships. According to Psaraftis and Kontovas (2009), containerships are the top CO₂ 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 CO₂ 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. 2 below).

CO2 emissions per vessel category (million tonnes)

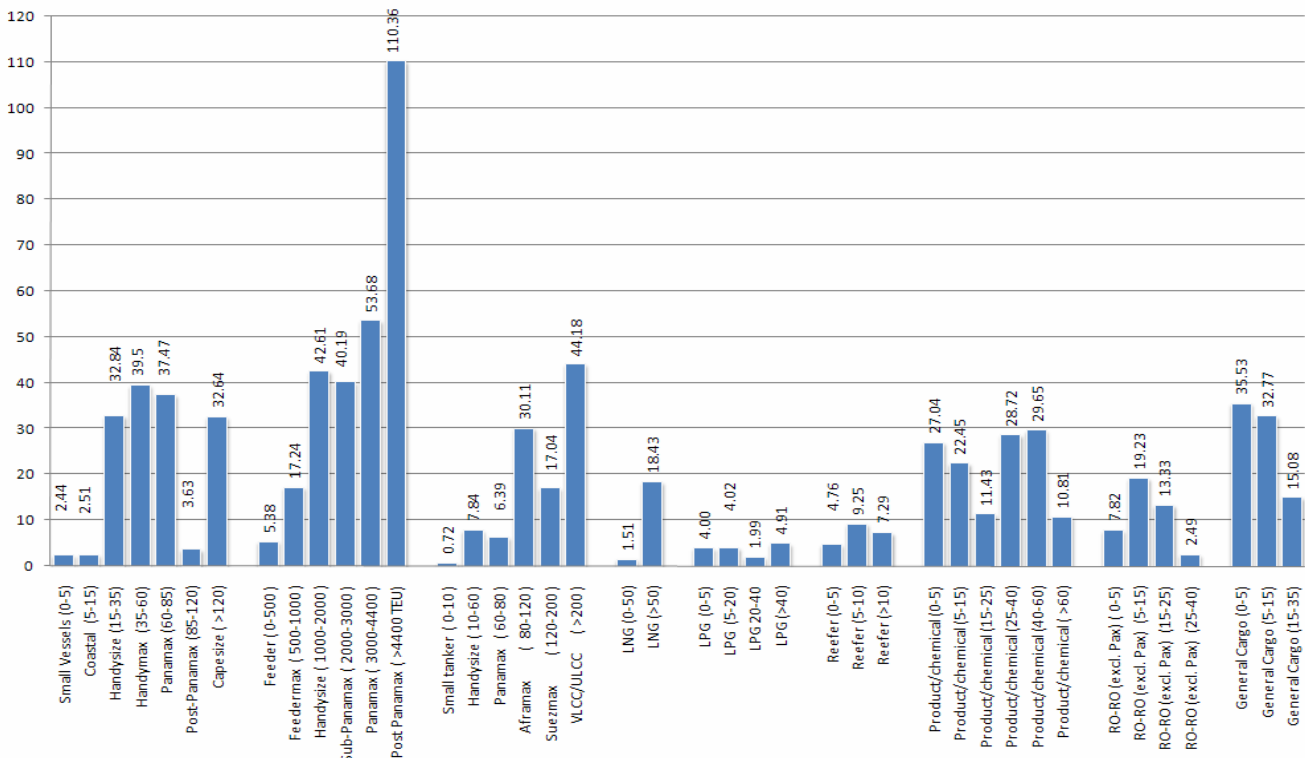


Figure 2: CO₂ emissions, world fleet (Psaraftis and Kontovas, 2009)

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 the fuel consumption at that speed is 115 tonnes/day, then for a fuel price of $p= \$600/\text{tonne}$ (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 $V-\Delta V = 20$ 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.

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 route⁷. 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.

Then we will have:

AT FULL SPEED (case A):

Total fuel burned/year/ship: 115 tonnes/day*365 = 41,975 tonnes
For 100 ships = 4,197,500 tonnes
Total annual fuel cost ($\times \$600$) = \$2,518,500,000.

AT REDUCED SPEED (case B):

To reach the same throughput of cargo per year, we will need 105 ships.
Total fuel burned/year/ship: 99.34 tonnes/day*365 = 36,259 tonnes
For 105 ships = 3,807,256 tonnes
Total annual fuel cost for 105 ships ($\times \$600$) = \$2,284,353,741 (reduced vis-à-vis case A).

Reduction of CO₂ emissions (per year): 1,237,073 tonnes.

Fuel cost difference (per year) = \$234,146,259 for 5 more ships, that is, \$46,829,252 per additional ship. Dividing by 365, this difference is \$128,000 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.

To compute in-transit inventory costs for this case, we hypothetically assume that cargo carried by these vessels consists of high value, industrial products (e.g., computers, luxury cars, or similar), whose 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 \times 0.08/365 = \4.38 . This may not seem like a significant figure, but it is.

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 1, 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).

⁷ 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.

Many other variants of this scenario can be studied. For instance, we can investigate the effect of reduced fuel prices and reduced time charter rates (as was the situation in late 2008). If the price of fuel drops to \$250/tonne and the daily charter rate drops to \$15,000 a day, this speed reduction scheme is unprofitable for both the \$20,000/tonne and the \$10,000/tonne CIF cargo prices, perhaps reflecting the reduced potential for savings in fuel costs if fuel prices are low. In this scenario, the break-even CIF price of the cargo (below which reducing speed is profitable) will drop to about \$7,000/tonne.

Interesting also is an investigation of:

- (a) what is the ‘speed threshold’ V_0 (obtained by expression [7])
- (b) what is the optimal speed reduction ΔV^* (obtained iteratively)

The results are shown in Table 5, for each of the scenarios examined above.

Table 5: V_0 and ΔV^* (knots) for the containership example

Scenario	V_0 (vis-à-vis V)	ΔV^*
p=\$600/tonne P=\$20,000/tonne OC=\$25,000/day	20.83<21	0.175
p=\$600/tonne P=\$10,000/tonne OC=\$25,000/day	17.50<21	3.50
p=\$250/tonne P=\$20,000/tonne OC=\$15,000/day	27.17>21	0
p=\$250/tonne P=\$10,000/tonne OC=\$15,000/day	22.40>21	0

For the last two scenarios, $V < V_0$ and hence speed reduction is unprofitable for any $\Delta V > 0$ (that is why $\Delta V^* = 0$)⁸.

For the second scenario, $V > V_0$ and the optimal speed reduction ΔV^* was found to be about 3.50 knots (by iterations). At that speed (17.5 knots), a total of 20 more ships would be needed, achieving a maximum net total cost reduction of \$187,041,667 per year.

Perhaps more interesting of all is scenario 1, which, even though was found unprofitable overall (see earlier in this section), nevertheless has $V > V_0$, implying the opposite. This seems like a contradiction, but can be explained by the fact that in this case $\Delta V^* = 0.175$ knots only, for which case a net total cost savings of \$518,592 is realized. The range of speed reduction for which $G(\Delta V) < 0$ is rather narrow, and $G(1 \text{ knot})$ is positive. For a 0.175 knots speed reduction, 0.84 more ships would be needed.

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.

THE COST TO AVERT ONE TONNE OF CO₂

What would it take to avert one tonne of CO₂ 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], $\Delta(\text{total CO}_2 \text{ emissions})$ equals minus total CO₂ averted by implementing a speed reduction scheme. We define as the cost to avert one tonne of CO₂ (CATC) the ratio of the total net cost of the fleet due to CO₂ speed reduction divided by the amount of CO₂ averted by speed reduction. Then we will have:

$$\text{CATC} = \frac{N \Delta V \left[-pD(2V - \Delta V)(k_1 + k_2) + \frac{I_c WD}{V(V - \Delta V)} + \frac{2O_c}{V(V - \Delta V)} \right]}{F_{\text{CO}_2} N D L \Delta V (2V - \Delta V)(k_1 + k_2)}$$

⁸ One can make the case here that $\Delta V^* < 0$ (speed increase), but this has been excluded from our analysis.

After some algebraic manipulations, this can be rewritten as

$$\text{CATC} = \frac{I_c W D + \frac{2O_c}{D}}{F_{\text{CO}_2} V(V - \Delta V)(2V - \Delta V)(k_1 + k_2)} - \frac{p}{F_{\text{CO}_2}} \quad [8]$$

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], $-p/F_{\text{CO}_2}$, where p is the price of one tonne of fuel and F_{CO_2} 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 $G(\Delta V)$ 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 CO₂ currently exist for other industries, but not for shipping, for which it is unclear how, or when such a scheme would be implemented.

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.

SPEED REDUCTION AT SECAs- EFFECTS OF SPEED REDUCTION

It is important to state that all considerations of the previous sections of this paper can be also applied to emissions other than CO₂. For instance, one can compute emissions from other pollutants and also define CATN (the cost to avert one tonne of NO_x), CATS (the cost to avert one tonne of SO₂)⁹, and so on.

The only difference with the previous analysis is that one would have to substitute for the CO₂ emissions factor the appropriate emissions factor of the pollutant under consideration. For instance if one considers SO₂, emissions depend on type of fuel, and so does F_{SO₂}. To find F_{SO₂}, 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 SO₂ emissions (in tonnes per day). The factor of 0.02 is exact, and comes from the chemical reaction between sulphur and oxygen.

Even though the amounts of SO₂ produced by ships are substantially lower than CO₂, for SO₂ emissions other considerations are equally important. SO₂ 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, SO₂ (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 CO₂ 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 SO₂ in a ship's exhaust. But it will change the total amount of SO₂ produced, much in the same way as this happens for CO₂. In that sense, speed reduction to reduce SO₂ 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 SO₂ 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 SO₂, but also CO₂ and all other pollutants.

⁹ 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).

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 $T_{FC} = kV^3(L/V) = kLV^2$.

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

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

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).

EFFECT OF HIGHER FUEL PRICES 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 CO₂ 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 CO₂ emissions are 105.01 tonnes, which corresponds to 3.39 grams per tonne-km. Total SO₂ 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 SO₂ emissions by switching to cleaner fuel are 2.66 tonnes (CO₂ 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 CO₂ 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 CO₂ per one-way trip, or 27.95 grams of CO₂ 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 CO₂ 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 CO₂ 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 SO₂ 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 (SO₂ produced by the truck fleet is essentially negligible)¹⁰.

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%

¹⁰ 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.

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. Research on this matter is ongoing and will be reported in a future paper.

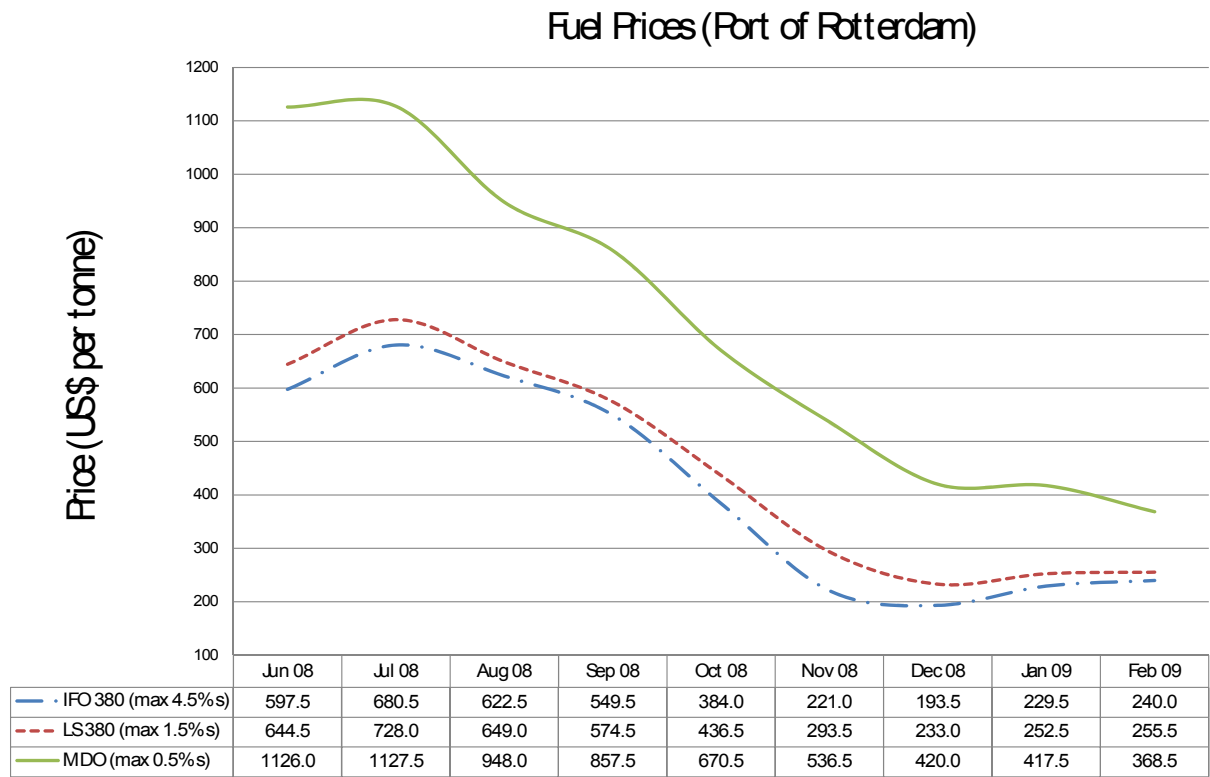


Figure 3: Average Monthly Fuel Oil Prices (from www.bunkerworld.com)

CONCLUSIONS

This paper has taken a look at various tradeoffs that are at stake in the goal for greener shipping and may impact the cost-effectiveness of the logistics chain and has presented some models that can be used to evaluate these tradeoffs. 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.

Clearly, the models presented here can be extended to more complex logistical scenarios, involving, among other things, issues such as ship routing and scheduling, maritime and intermodal transport network design, queuing at ports, emissions at ports, and the like. 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.

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