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Psaraftis, Harilaos N.

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Harilaos N. Psaraftis
Technical University of Denmark
hnpsar@dtu.dk

Speed Optimization vs Speed Reduction: the Speed Limit Debate

Abstract

The purpose of this paper is to shed some light into the speed limit debate, and specifically whether reducing speed by imposing a speed limit is better than doing the same by imposing a bunker levy. This debate, along with the various issues of speed optimization versus speed reduction, is currently ongoing at the International Maritime Organization (IMO), in the quest to reduce greenhouse gas (GHG) emissions from ships.

Keywords: greenhouse gases; speed reduction; speed optimization; speed limits.

1. Introduction

International shipping is currently at a crossroads. The decision of the 72nd session of the Marine Environment Protection Committee (MEPC 72) of the International Maritime Organization (IMO) in April 2018 to adopt an Initial Strategy for the reduction of maritime green house gas (GHG) emissions (IMO, 2018) epitomizes the last among a series of recent developments as regards sustainable shipping. It also sets the scene on what may happen in the future. Even though many experts and industry circles believe that the MEPC 72 decision is in line with the COP21 climate change agreement in Paris in 2015, others disagree, either on the ground that the target is not ambitious enough, or on the ground that no clear pathway to reach the target is currently visible.

The IMO Initial Strategy is in the form of *Resolution MEPC.304(72)*, and includes, among others, the following elements: (a) the vision, (b) the levels of ambition, (c) the guiding principles, (d) a list of short-term, medium-term and long term candidate measures with a timeline, and (e) miscellaneous other elements, such as follow up actions and others. We briefly highlight some of these elements below.

Vision: IMO remains committed to reducing GHG emissions from international shipping and, as a matter of urgency, aims to phase them out as soon as possible in this century.

Levels of ambition: The Initial Strategy identifies levels of ambition for the international shipping sector noting that technological innovation and the global introduction of alternative fuels and/or energy sources for international shipping will be integral to achieve the overall ambition. Reviews should take into account updated emission estimates, emissions reduction options for international shipping, and the reports of the Intergovernmental Panel on Climate Change (IPCC). Levels of ambition directing the Initial Strategy are as follows:

1) carbon intensity of the ship to decline through implementation of further phases of the energy efficiency design index (EEDI) for new ships

to review with the aim to strengthen the energy efficiency design requirements for ships with the percentage improvement for each phase to be determined for each ship type, as appropriate;

2) carbon intensity of international shipping to decline

to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008; and

3) GHG emissions from international shipping to peak and decline

to peak GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out as called for in the Vision as a point on a pathway of CO_2 emissions reduction consistent with the Paris Agreement temperature goals.

Among the set of short-term measures, those that are to be finalized and agreed to between 2018 and 2023, one can find the following one:

"Consider and analyse the use of speed optimization and speed reduction as a measure, taking into account safety issues, distance travelled, distortion of the market or trade and that such measure does not impact on shipping's capability to serve remote geographic areas"

The a priori rationale for the measure is very simple. Given the non-linear (at least cubic) relationship between ship speed and fuel consumption (and hence emissions, GHG and other), reducing speed looks like a very promising alternative. So "speed reduction" comes naturally as an obvious candidate GHG reduction measure.

It is actually not that simple. In the debate at the IMO prior to MEPC 72, some countries in South America (and most notably Chile and Peru) objected to the use of the term "speed reduction" as a possible emissions reduction measure, on the ground that this may constitute a barrier to their exports to Asia (and particularly to those that involve perishable products such as agricultural products and others). They suggested the use of "speed optimization" instead. In a compromise solution, both wordings were included in the IMO decision text, and hence the above wording. However, what is meant by "speed optimization" in that text is far from clear and hence is subject to different interpretations.

Adding to the complexity of the issue, a recurrent measure that has been and is being promoted by various Non-Governmental Organizations (NGOs) is mandating *direct speed limits*. Since GHG emissions can be reduced by reducing speed, can someone achieve the same desirable outcome by imposing speed limits? This is an argument that is being heard frequently over the last several years. Among various lobbying groups, the Clean Shipping Coalition (CSC), an NGO, advocated at IMO/MEPC 61 that *"speed reduction should be pursued as a regulatory option in its own right and not only as possible consequences of market-based instruments or the EEDI."* However, that proposal was rejected by the IMO at the time. In spite of this decision, lobbying for speed limits has continued by CSC and other groups, and speed limits have been discussed at IMO/MEPC 72 and have succeeded in being included in the roster of potential *short term* measures towards the 50% GHG emissions reduction target. The rationale for speed limits is described in a study by CE Delft (2017).

The study analyzed two cases of exports from South America to the EU. Even with very conservative assumptions about the impacts, the study claims that the economic impacts of slow steaming are modest: Export values will be reduced by a tenth of a percent at most, and the overall economic impact would be well below a tenth of a percent for the whole of South America.

To calculate the emission reduction potential, the cube law is assumed and calculations are performed on a subset of the world fleet, consisting of containerships, crude oil and product tankers, and bulk carriers. These three types accounted for the majority (actually 52%) of the GHG emissions in 2012. No lifecycle emissions are accounted for (the authors find them to range between 4% and 6% of the emissions reductions achievable by slow steaming, without providing a reference on how this number was computed).

Three speed reduction scenarios, 10%, 20%, and 30% are assumed, and for each scenario, CO_2 emissions reductions are estimated. These range from 13% to 33%.

Then there is a section on the potential impact of speed reduction on trade, which is actually restricted to the examination of the trade of just two (2) products, oilcake and chilled beef, both from Buenos Aires to Rotterdam. In the first case they consider a bulk carrier already slow steaming at 12.2 knots, and in the second a containership whose speed is assumed to be equal to an average speed of 16.3 knots (it is not clear where the average comes from and what is the actual speed in that trade). Using these two examples the authors estimate the costs due to increased sailing time and reach the (general) conclusion that impacts of speed limits on trade are minimal.

In short, and although interesting, this is a study that is full of assumptions, some of which cannot be substantiated. It also fails to address some critical issues, including the practical implementation of the speed limits, including enforcement.

In a more recent document submitted to the IMO, CSC (2018) made another pitch at the speed limit option, branding it as a measure that can have an immediate impact on reducing GHG emissions, and as a "bridge" measure until more permanent measures are taken.

The way the measure is supposed to work is by limiting what is called the maximum allowable average speed of a vessel, as a function of ship type and size. So called "baseline speeds" could be set on the basis of the average historical operational speeds of each covered ship type and size using historical automatic identification system (AIS) data. Once the baseline speeds are set, target maximum speeds could be arrived at by applying a percentage (%) reduction, to be determined following an impact assessment, below the baseline per covered ship type and size category.

Some of the numbers in that document, in fact along with the whole scheme, are difficult to comprehend. For instance, if a 10% across-the-board speed reduction target is agreed upon and the 2015 speeds are used as baselines, for a 60,000–100,000 DWT bulk carrier the maximum allowable speed would be 10.40 knots, dropping to 9.96 knots for a 100,000–200,000 DWT ship and rising again to 10.64 knots for a ship larger than 200,000 DWT. Why the intermediate size class has to sail slower than the other two is not clear. The equivalent speed limit for the top tier class of containerships (more than 14,500 TEU) is 15.17 knots. There is no benchmarking for other ship types in that document.

The authors also attempt to explicitly address Chile and Peru's concerns, stating that containerships carrying perishable products would be allowed to not slow down during the export period, so long as they do so in the remainder of the year, on a maximum average per year speed basis. It is clear that such a system would be very difficult to administer and enforce, not to mention the distortions it would create.

The proposers also suggest that specialized reefer ships should be considered to be exempt from ship limits, on the ground that the number of these ships is very small. Again, if this happens, more of these ships (or ships that would label themselves as reefer ships) would be built in the future so as to evade the limit.

Even though it is obvious that ship speed can be reduced by a mandated speed limit, ship speed can also be reduced if the price of fuel goes up. In that sense, imposing a bunker levy can also lead to speed reduction and hence to a reduction of emissions (GHG and other).

A bunker levy comes under the umbrella of Market Based Measures (MBMs). MBMs have been discussed at the IMO between 2010 and 2013 but their discussion was suspended in 2013, mainly for political reasons. For a discussion of that debate see Psaraftis (2012, 2016). MBMs are included in the Initial Strategy as a candidate *medium-term* measure, as follows:

“New/innovative emission reduction mechanism(s), possibly including Market-based Measures (MBMs), to incentivize GHG emission reduction”

A note is important here. The word “possibly” means that the fate of MBMs at the IMO is unclear at best. Because of this, and because of the different timing of these two options within the IMO decision process, it is clear that the bunker levy option is not, at least for the time being, a direct alternative to the speed limit option. In our opinion this is a mistake, which of course does not prevent us to compare these two options.

The purpose of this paper is to shed some light into the speed limit debate, and specifically on whether reducing speed by imposing a speed limit is better than doing the same by imposing a bunker levy. To that effect, it is organized as follows: Section 2 provides some background and Section 3 performs a comparative assessment among the two schemes. Finally Section 4 makes some final remarks.

2. Background

The term "speed optimization" may mean different things to different people. This may create confusion whenever the measure is discussed. To remove the confusion, the following definition can be offered:

- *DEFINITION: "Speed optimization" can be defined as the selection of an appropriate speed profile for the ship so as to optimize a specific objective while meeting various requirements (or constraints) on the ship's operation.*

There are *three planning levels* for which speed optimization can be defined. Not all are necessarily equally relevant for the IMO GHG discussion.

The *operational* planning level (planning horizon of several hours to several days), where speed is optimized along the ship's path (which is also optimized) mainly as a function of prevailing weather conditions. This falls into the realm of *optimal ship weather routing*. It should be noted that in an operational setting optimizing fuel consumption may not necessarily be the only objective. Minimizing transit time or meeting a specified ETA (estimated time of arrival) particularly if schedule is disrupted because of bad weather may be equally or even more relevant.

The *tactical* planning level (planning horizon of several days to several months), in which speed can be optimized for each leg of a ship's route, for instance Far East to Europe, Brazil to Japan, etc. At that level, an existing ship can sail slower than its design speed (slow steaming). Or the ship can sail faster. Slow steaming may involve just slowing down or even 'derating' a ship's engine, that is, reconfiguring the engine so that a lower power output is achieved, so that even slower speeds can be attained. Such a reconfiguration may involve dropping a cylinder from the main engine or other measures. Depending on engine technology, 'slow steaming kits' are provided by engine manufacturers so that ships can smoothly reduce speed at any desired level. In case speed is drastically reduced, the practice is known as "super slow steaming".

Finally we have the *strategic* planning level (planning horizon of the lifetime of the ship), in which a ship's *design speed* is selected (among all ship parameters). For instance, Maersk's Triple-E 18,000 TEU vessels have a design speed of 17.8 knots, down from the 20 - 26 knots range that has been the industry's norm, and will emit 20% less CO_2 per container moved as compared to the *Emma Maersk*, previously the world's largest container vessel, and 50% less than the industry average on the Asia-Europe trade lane. Discussion on this level is relevant when long term measures are discussed, for instance the next generation of ships sailing considerably slower than those now.

What is the objective being optimized, and what are the constraints?

This depends on who pays for the fuel. If the ship owner pays for the fuel (spot charter scenario), a typical objective is to *maximize average per day profit*. If the charterer pays for the fuel (time charter scenario), a typical objective is to *minimize average per day cost*. Of course, it is conceivable that the ship operator may not, for various reasons, act so as to optimize any of the above objectives, or maybe also have additional objectives, secondary or not.

Whereas another conceivable objective (to be minimized) would also be GHG emissions, this would be the objective for society, and no private ship operator is likely to adopt such an objective. Note however that this objective is equivalent to minimizing fuel consumption, or fuel costs, so whenever fuel costs are the predominant operational cost component, a solution that minimizes operational costs is close to a solution that minimizes GHG emissions. In this case we may have a *win-win scenario*, or close to a win-win scenario. By win-win we mean a solution that is optimal both for the ship owner and for society.

Win-win solutions are obviously desirable, however obtaining them may not always be feasible. It is one of the tasks of policy makers, at the IMO and elsewhere, to create the conditions that can make win-win solutions feasible.

Whatever it is, if one talks about "speed optimization," it is self-evident that some sort of objective should be optimized by the shipping company, and it is important that this objective be well defined.

Constraints in speed optimization may include specified deadlines or time windows for loading or unloading the cargo, scheduling or timetabling requirements for serving specific ports or meeting feeder connections (liner markets), and maximum and minimum allowable speeds. We may also have constraints on maximum allowable hull stress and vertical or transverse accelerations for the safety of the ship and of the cargo and for the comfort of the passengers and the crew. All of these constraints would, in distinct ways, define the feasible region for the ship's speed, and may actually even determine the speed itself.

Dealing with ship speed is not new in the maritime transportation literature and this body of knowledge is rapidly growing. In Psaraftis and Kontovas (2013) some 42 relevant papers were reviewed and a taxonomy of these papers according to various criteria was developed. An amended taxonomy, consisting of 51 papers, was presented in Psaraftis and Kontovas (2016), however many additional papers dealing with ship speed appeared after the 2013 paper was published. The 2013 paper's Google Scholar citations as of December 2018 stood at 215, and even included papers in seemingly unrelated journals such as *Meat Science* (Mills et al, 2014). The growing number of references indicates a strong interest of researchers in this topic.

To understand factors that may impact ship speed, Figure 1 is adapted from Gkonis and Psaraftis (2012) and captures the impact of both freight rate and bunker price on optimal speed for a specific Very Large Crude Carrier (VLCC) trading from the Persian Gulf to Japan. Optimal here means maximize average per day profit for the ship owner, and speeds are optimized in both laden and ballast conditions. Two market conditions are shown for the spot rate, one at Worldscale (WS) 60 and one at WS120. Bunker prices (HFO, Heavy Fuel Oil) range from USD400 to USD1,000 per tonne. It can be observed that the impact of both freight rate and bunker price on optimal speed can be quite dramatic, and that the range of optimal speeds can be very broad, depending on the combination of values of these two input parameters. It can be also observed that ballast speeds are typically higher than laden speeds by 1.0 knot in the lower rate scenario and by 1.5 knots in the higher rate scenario.

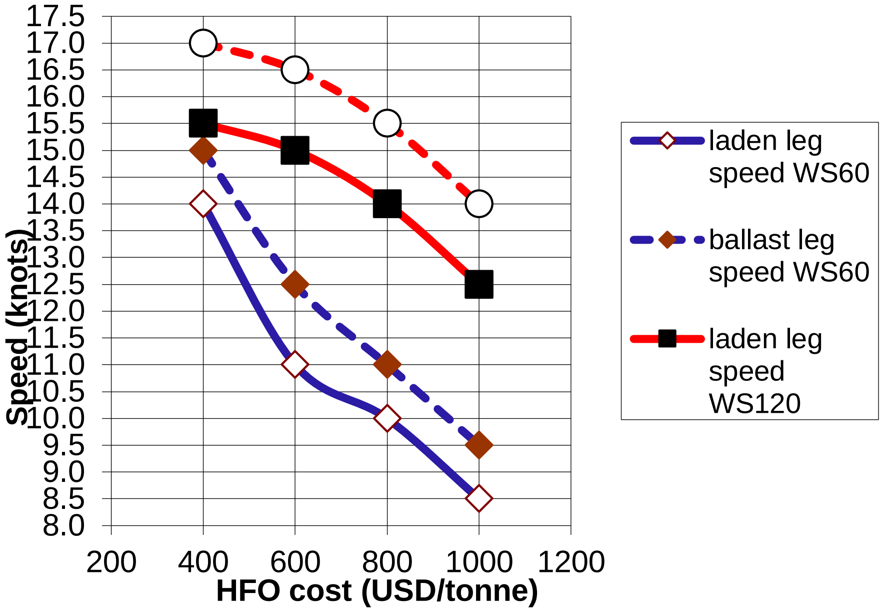

Fig. 1: Optimal VLCC speed as a function of spot rate and bunker price. WS is the WorldScale index. Adapted from Gkonis and Psaraftis (2012).

Psaraftis and Kontovas (2009) investigated, among other things, the option to slow down in Sulphur Emissions Control Areas (SECAs) to reduce the quantity of SO_x produced. Realizing that a reduced speed can not alter the percentage of SOx emissions in a ship's exhaust, it was shown that if the ship speeds up outside the SECA to make up for lost time within the SECA, more emissions will be produced overall, including SO_x. Fagerholt et al. (2015) and Fagerholt and Psaraftis (2015) examined route-speed alternatives for ships operating in and out of Emissions Control Areas (ECAs) and Magirou et al. (2015) developed stochastic optimal control schemes for speed optimization in a dynamic setting.

Another possible side effect concerns effects that speed reduction may have on other modes of transportation, to the extent these are alternatives to sea transportation. This is the situation mosty as regards short-sea trades, in Europe but also in North America. If ships are made to go slower, shippers may be induced to prefer land-based transportation alternatives, mostly road, and that may increase overall GHG emissions. Even in long-haul scenarios such as the Far East to Europe trade, some cargoes may tempted to use the rail alternative (via the Trans-Siberian railway) if the speed of vessels is low enough (see Psaraftis and Kontovas (2010) for a discussion). Such considerations may also be relevant as regards the recent Belt and Road

Initiative (BRI), which aims to promote Chinese trade to Europe via a combination of land-based and maritime corridors.

In short sea shipping, possible modal shifts due to speed reduction and other measures were investigated in Zis and Psaraftis (2017, 2018) in the context of European SECAs and in the Ro/Ro sector. Psaraftis and Kontovas (2015), among other things, provided a discussion on the possible impact of slow steaming on *port operations*. If a port is congested, it would clearly make no sense to sail there at full speed, wasting money on fuel and producing emissions that can be avoided if ship speed were slower. A recent initiative is the so-called 'Virtual Arrival', which has been used in order to manage the vessels' arrival time based on the experience of congestion at some discharging ports. At the same time, Californian ports have been offering monetary incentives for ocean going vessels that reduce speed down to 12 knots in the proximity of the port as an emissions reduction measure (Vessel Speed Reduction Programme – VSRP) which has seen great participation rates (Zis et al., 2014). In separate but related initiatives, Golias et al. (2010) and Du et al. (2011) developed models that combined optimizing berth allocation with reducing associated vessel emissions.

Last but not least, in Giovannini and Psaraftis (2018), a simple model was developed for a fixed route liner shipping scenario which, among other things, incorporates the influence of freight rates, along with that of fuel prices and cargo inventory costs into the overall speed optimization process. The objective to be maximized is the line's average daily profit. Departing from convention, the model was also able to consider *flexible service frequencies*, to be selected among a broader set than the standard assumption of one call per week. It was shown that this may lead to better solutions and that the cost of forcing a fixed frequency can be significant. Such cost is attributed either to additional fuel cost if the fleet is forced to sail faster to accommodate a frequency that is higher than the optimal one, or to lost income if the opposite is the case. The impact of the line's decisions on CO_2 emissions was also examined.

2. Comparison between a bunker levy and a speed limit

As stated above, the speed of ships depends on many factors such as fuel price, freight rate, cargo inventory costs and others, and may actually vary according to the direction of trade.

This is especially so in liner trades, the difference reflecting varying ship load factors and values of cargo. Speed directional imbalances have been manifested in several trades worldwide and have been reported in several publications (see for instance, Cariou (2011), Cheaitou and Cariou (2012), and FMC (2012), among others). Ongoing research by this author and his colleagues in the context of the ShipCLEAN project, has confirmed that liner cargo from South America to Asia moves at a much slower average speed than cargo in the opposite direction, and that at current market conditions (spring and summer 2018), slow steaming was being practised (see also Vilas (2018)).

In fact project ShipCLEAN analyzed a Yang-Ming/Cosco transpacific service that includes these two countries (see Fig. 2 below). Observed were an average eastbound speed of 17.5 knots and an average westbound speed as low as 12.5 knots. Both speeds indicate significant slow steaming, especially in the direction from South America to Asia.

Fig. 2: Transpacific service. Source: Project ShipCLEAN.

The above scenario refers to spring 2018. The situation in the fall of 2018 was not significantly better. A Maersk Line service from Valparaiso, Chile to Yangshan, China for mid-December 2018 (the peak of the cherry export season) would sail the 12,000 nm of distance in 35 days, meaning an average speed of 14.3 knots, still rather slow.

That speeds are already slow from South America to Asia (and surely also elsewhere) is obviously due to market conditions that have to do with the chronic overcapacity in liner trades worldwide and with other factors that are trade-specific. The speed directional imbalance has surely to do with the imbalance in the values of goods and/or load factors in the two directions, both of which are speculated to be significant. Whatever it is, and without any GHG reduction measure being imposed, the speed situation is already one that Chile and Peru characterize as undesirable, raising the question how worse the situation might get by the "speed reduction" that these two countries state that should be avoided. Slow steaming, not so much as a measure, but as an outcome, is already there, and in fact big time. It should be noted that for one of the ships of the ShipCLEAN scenario (a 10,114 TEU vessel whose design speed is about 25 knots), a 12.5 knot speed means sailing at 10% of the ship's maximum continuous rating (MCR), which can achieve significant fuel and GHG emissions savings.

This difference in average speeds is also manifested in the trades between Asia and Europe, with cargoes from Asia to Europe moving faster than cargoes going in the opposite direction. This imbalance is surely due to commercial considerations that take into account, among other things, the difference in the values of the cargo between the two trade directions and the implied difference in in-transit cargo inventory costs.

As ship speeds are the decisions of the carriers and not of the shippers, it is not immediately clear what can be done by South American countries who want their cherries and other agricultural or perishable products to China shipped faster. Our understanding is that these countries are mostly concerned by the conceivable imposition of *speed limits*.

Noting that the speed limit debate is still ongoing at the IMO, the following considerations are important. In addition to difficulties in enforcing such a rule, or in deciding what should be the speed limit as a function of ship type and size, it is clear that slow steaming and speed limits are two different things: the first is *a voluntary response* to market conditions which can dynamically change and the second is *a mandated measure*. If the speed limit is above the optimal speed that is voluntarily chosen, then it is superfluous. This may conceivably alleviate the concerns of Chile and Peru, as no reasonable speed limit is likely to be below actual ship speeds to Asia under the current market circumstances. The question is what happens if or when the speed limit is below the optimal ship speed, as is likely to happen in a boom period. If this happens, a speed limit may cause distortions in the market, and costs that may exceed the benefits of speed reduction. A likely short term effect would be an increase in freight rates due to the contraction of the fleet's annual tonne-km supply curve. This may conceivably render the measure agreeable to some ship owners, however shippers would be hit twice: they would pay more for their cargo and also suffer increased transit times and increased in-transit inventory costs.

We have seen no comprehensive analysis of the possible market distortions of a speed limit. A discussion of some of the issues is in Devanney (2011). Also we note that Cariou and Cheaitou (2012) investigated policy options contemplated by the European Commission and compared speed limits versus a bunker levy as two measures to abate GHGs, with a scenario from the container trades. They concluded that the former measure is counterproductive because it may ultimately generate more emissions and incur a cost per tonne of CO_2 which is more than society is willing to pay and because it is sub-optimal as compared to results obtained if an international bunker levy were to be implemented.

To shed more light on the issue, in the following we shall investigate the comparison of a bunker levy vs speed limits. Both measures would cause speed reduction and hence a reduction in CO_2 and other emissions (GHG and non-GHG). A bunker levy would induce speed reduction, and a speed limit would mandate it. Below we attempt to compare the two measures, in terms of emissions reduction and other attributes.

To investigate the issue, we use a hypothetical and rudimentary scenario in the container sector. A generalization to more realistic scenarios or other shipping markets is straightforward.

A containership of capacity Q (TEU) shuttles between port A and port B, whose interport distance is L (nautical miles-nm). The ship's speed is v (nm/day)[1] which is within the bracket v_{min} and v_{max}.

[1] This is 24 times the speed in knots. The reason we use nm/day instead of knots in the formulas is to avoid having the number 24 in the equations. However, in the tables and results, knots will be used.

Assume that the ship is semi-full in both directions and that the freight rate received by the ship owner is R (USD/TEU), assumed the same in both directions. The assumed load factor of the ship is u ($0 \leq u \leq 1$), again assumed the same in both directions. R is assumed to be on a *per loaded TEU* basis, meaning that if the ship is 75% full (u=0.75), its per (one way) trip income will be 0.75RQ. Assume that the fuel price is p (USD/tonne) and that the fuel consumption function is $FC=kv^3$ (tonnes/day) with k being a constant. Assume finally that miscellaneous other operating expenses (OPEX) are X (USD/day) and that port turnaround times are ignored. Q, L, R, u, p, k, v_{min}, v_{max} and X are assumed known inputs and the sole decision variable is the ship's speed v.

We also note that this analysis assumes that R is an exogenous variable outside the line's control and we do not attempt to estimate R as a function of container capacity supply and demand. In that sense, it is expected that slow steaming or speed reduction, if applied for all ships sailing the given route, will generally increase R, however this is not captured in our model.

Table 1 below shows some hypothetical values for the problem's inputs.

Table 1: Assumed inputs

Input	Value
Q	10,000 TEU
L	20,000 nm
R (base case)	1,500 USD/TEU
u	0.6
p	500 USD/tonne
v_{min}	16 knots
v_{max}	26 knots
X	15,000 USD/day

Finally k is such that FC= 144 tonnes/day when v=22 knots. The value of k for which this is the case is $9.7827*10^{-7}$ (again, v in the formulas is in nm/day).

In this scenario, we can compute various attributes of the round trip, such as

Round trip time $T= 2L/v$ (days)

Round trip TEU throughput $H = 2uQ$ (TEU)

Round trip cost $C= T(pkv^3 +X) = 2(pkLv^2 +LX/v)$ (USD)

Round trip income $I = 2uRQ$ (USD)

Round trip profit $P= I-C = 2(uRQ - pkLv^2 - LX/v)$ (USD)

Average per day profit $P' = P/T = uRQv/L- pkv^3 – X$ (USD/day)

Average per day TEU throughput $H' = 2uQ/T= uQv/L$ (TEU/day)

If the objective of the line is to maximize *average per day profit*, that is, P', the optimal speed can be shown to be as follows.

$v_{opt} = v_{min}$ if $v_{min}>v_0$

$v_{opt} = v_0$ if $v_{min}\leq v_0 \leq v_{max}$

$v_{opt} = v_{max}$ if $v_{max}<v_0$

with $v_0= (uRQ/3pkL)^{1/2}$

Then CO_2 emissions per unit time (tonnes/day) for this ship are equal to

$CO_2 = fkv_{opt}^3$

with f being the carbon coefficient (assumed here equal to 3.11).

For an individual ship, Table 2 below shows the optimal speed and other solution attributes for the above inputs and for selected values of the freight rate R ranging between 500 USD/TEU to 2,000 USD/TEU, with a base case value of 1,500 USD/tonne.

Table 2: Optimal speed as a function of freight rate R, individual ship

R (USD/TEU)	500	1,000	1,500 (base case)	1,800	2,000
v_{opt} (knots)	16.00	18.84	23.07	25.28	26.00

T (days)	104.17	88.47	73.23	65.94	64.10
H (TEU)	12,000	12,000	12,000	12,000	12,000
C (USD)	4,447,589	5,326,987	7,083,480	8,189,078	8,579,871
I (USD)	6,000,000	12,000,000	18,000,000	21,600,000	24,000,000
P (USD)	1,552,451	6,673,013	10,916,520	13,410,922	15,420,129
P' (USD/day)	14,904	75,430	151,131	203,385	240,554
H' (TEU/day)	115.20	135.65	166.13	181.99	187.20
CO_2(tonnes/day)	172.27	281.24	516.67	679.18	739.22

One can see in general that a higher state of the market (higher R) induces a higher speed and hence higher CO_2 emissions for the ship, and vice versa. It should also be noted that in this particular example and for the two extreme cases R= 500 and 2,000 USD/TEU, the optimal speed hits the speed's lower and upper bounds respectively.

To lower CO_2 emissions, one contemplates either a levy q on fuel, or a speed limit equal to V, with q and V being user inputs. Either of those would generally result in a lower speed. The question is, which of these alternatives achieves lower CO_2 emissions. The answer of course depends on the values of q and V. Depending on these values, a levy can achieve lower, the same, or higher CO_2 emissions reductions vis-à-vis those achieved by a speed limit.

Note also that for this comparison to make sense, constant average per day TEU throughput should be maintained, even though speed is reduced. This would necessitate deploying additional ships.

If the initial speed before the levy or the speed limit is v_1 and the final speed after the levy or the speed limit is v_2 ($<v_1$), we define as the "throughput factor" the ratio $r = v_1/ v_2$ (>1). A ratio r=1.20 means that r-1 (in this case 20%) more ships should be deployed on the route so as to maintain the same average per day TEU throughput. These additional ships would generate additional profit and additional CO_2, both of which should be taken into account. To do so, the average per day profit and the average per day CO_2 emissions should be multiplied by r, vis a vis those for an individual ship.

To further investigate the issue, we assume that $v_{min} \leq V \leq v_{max}$ because if V is outside that range, then either the speed limit is superfluous ($V > v_{max}$) or the problem is infeasible ($V < v_{min}$).

The two cases are compared in Table 3 below as follows.

Table 3: Comparison between the speed limit and levy cases, individual ship

	SPEED LIMIT CASE	LEVY CASE
v_0	$(uRQ/3pkL)^{1/2}$	$(uRQ/3(p+q)kL)^{1/2}$
v_{opt}	$v_{opt} = v_{min}$ if $v_{min} > v_0$ $v_{opt} = v_0$ if $v_{min} \leq v_0 \leq V$ $v_{opt} = V$ if $V < v_0$	$v_{opt} = v_{min}$ if $v_{min} > v_0$ $v_{opt} = v_0$ if $v_{min} \leq v_0 \leq v_{max}$ $v_{opt} = v_{max}$ if $v_{max} < v_0$
P'	$uRQv_{opt}/L - pkv_{opt}^3 - X$	$uRQv_{opt}/L - (p+q)kv_{opt}^3 - X$
CO_2	fkv_{opt}^3	fkv_{opt}^3

The superfluous speed limit case occurs if $V \geq (uRQ/3pkL)^{1/2}$, which for our case and for the base case for R means $V \geq 23.07$ knots. If this is the case, v_{opt} is also 23.07 knots.

The non superfluous (binding) speed limit case occurs if $V < (uRQ/3pkL)^{1/2} = 23.07$ knots.

Table 4 shows the results for the base case R, and for selected values of the speed limit V ranging from 18 to 22 knots.

Table 4: Reductions of CO_2 and other attributes as a function of the speed limit V, constant throughput.

V (knots)	**18.00**	**20.00**	**22.00**
v_{opt}(knots)	18.00	20.00	22.00
T (days)	92.59	83.33	75.76
C (USD)	5,040,279	5,757,889	6,590,909

I (USD)	18,000,000	18,000,000	18,000,000
P (USD)	12,959,721	12,242,111	11,409,091
r	1.28	1.15	1.05
P’ (USD/day)	179,418	169,483	157,951
CO_2 (tonnes/day)	314.43	388.18	469.70
ΔCO_2 (tonnes/day)	202.24	128.49	46.97

The last row in the table shows the reductions of CO_2 (in tonnes/day) that can be achieved as a function of the speed limit, vis-à-vis the “no speed limit” case (516.67 tonnes/day). Note that the figures for P’, CO_2 and ΔCO_2 have factored in the effect of the throughput factor r.

In turn, we can investigate what happens if we impose a levy q on bunker fuel. Table 5 shows these results (again base case for R) for selected values of q ranging from 100 to 500 USD/tonne.

Table 5: Reductions of CO_2 and other attributes as a function of the levy q, constant throughput.

q (USD/tonne)	**100**	**300**	**500**
v_{opt}(knots)	21.06	18.24	16.32
T (days)	79.13	91.37	102.15
C (USD/rtrip)	7,186,893	7,370,506	7,532,272
I (USD/rtrip)	18,000,000	18,000,000	18,000,000
P (USD/rtrip)	10,813,107	10,629,494	10,467,728
r	1.10	1.27	1.41
P’ (USD/day)	149,723	147,169	144,880
CO_2(tonnes/day)	430.62	322.94	258.27
ΔCO_2(tonnes/day)	86.05	193.73	258.40

Again, the last row in the table shows the reductions of CO_2 (tonnes/day) that can be achieved as a function of the levy, vis a vis the "no levy" case (516.67 tonnes/day). As before, the figures for P', CO_2 and ΔCO_2 have factored in the effect of the throughput factor r.

Tables 4 and 5 are not directly comparable, in the sense that from these tables no direct conclusions can be drawn as to what is preferrable, a speed limit or a levy. To draw such conclusions, we ask the following question: For a given levy q, what is the value of the speed limit V so that the results are *the same* in terms of CO_2? And once this happens, what are the other differences between the two cases?

It turns out that the speed limit V for which the optimal speed is the same as that with a levy q is as follows.

$V=(uRQ/3(p+q)kL)^{1/2}$

Then the optimal speed is equal to V in both cases.

In this case, and for an individual ship, daily CO_2 is also the same and equal to $fkV^3 = 2fk(uRQ/3(p+q)kL)^{3/2}$

However, daily profit P' is different. With a levy q, it is $P' = uRQV/L - (p+q)kV^3 - X$

With an equivalent speed limit V, and no levy, it is $P'' = uRQV/L - pkV^3 - X$ (>P')

The difference in daily profit is $\Delta P' = qkV^3$

The above are for an individual ship. To maintain the same TEU throughput, the effect of the throughput factor r has also to be taken into account.

This means that for the ship owner, and if the same speed (and hence the same CO_2 emissions) reduction are to be achieved, a speed limit is more profitable than a bunker levy. The ship owner will sail the ship at the same speed as that with a levy, but without paying the levy.

Table 6 shows the values of V, CO_2 and $\Delta P'$ for values of q between 100 and 500 USD/tonne.

Table 6: Equivalent speed limit V, CO_2 and $\Delta P'$ as functions of levy q, constant throughput.

q (USD/tonne)	100	300	500
V (knots)	21.06	18.24	16.32
r	1.10	1.27	1.41
CO_2 (tonnes/day)	430.62	322.94	258.27
$\Delta P'$ (USD/day)	13,902	31,275	41,409

This cuts both ways. The difference in daily profit $\Delta P'$, which is positive for the ship owner, and which possibly reflects an external cost of CO_2 pollution that is not internalized, is a net cost to society. It is money not collected which could be used to achieve out-of-sector emissions reductions[2], or for other noble causes (eg, financial aid to developing countries, research and development, etc). In that sense, and from a societal point of view, a levy is better than an equivalent speed limit.

An equally serious problem with a speed limit is that for ships of different size, a common and uniform levy q will result in different optimal speeds. A larger ship would in general imply a higher optimal speed, everything else being equal. Therefore, achieving equivalence such as the above by a common and uniform speed limit V will be impossible. To do so, one would have to set *size specific* (or maybe even *ship type specific* or *route specific*) speed limits, which will make the whole exercise an administrative nightmare.

Conversely, if a common and uniform speed limit V is imposed, the limit may be superfluous for some ship sizes and binding for some others, depending on the state of the market, the price of fuel, and a host of other parameters. Having the same speed limit in boom market periods and in depressed market periods could create all sorts of distortions. In depressed market

[2] Out-of-sector emissions reductions (or offsets) are emissions reductions that can be realized by investing the monies that are collected by a bunker levy into emissions reduction projects outside the maritime sector, for instance by developing a wind farm in New Zealand or a solar farm in Indonesia.

periods the limit may be superfluous, and in boom market periods the limit would force some ships (likely at the high end of the scale) to slow down whereas others do not. A speed limit may also be superfluous in one route direction (eg, from Europe to the Far East, where ships go slower anyway) and binding in the other direction (ships go faster from the Far East to Europe).

Last but not least, a speed limit would be difficult or impossible to enforce, even if it is the same for all ship sizes or types, and it would hardly serve as an incentive to economize and improve the energy efficiency of ships.

Extensions that are being worked on include consideration of different freight rates, load factors and inventory costs in the two directions, which would result in different optimal speeds. These will be reported in a future publication.

4. Final remarks

This paper has examined a rudimentary scenario comparing speed limits with a bunker levy, in terms of emissions reduction and other attributes. We state again that these two options are not alternatives to one another within the current IMO regulatory process, for reasons mainly connected to the timing of the various options. This is in our opinion a mistake that is mostly due to the reluctance of maritime stakeholders to apply the "polluters pay" principle to reduce GHG emissions. Still, and for the reasons stated in the paper, a conjecture that we can safely make is that a bunker levy is a preferable instrument (as compared to a speed limit) if one wants to reduce maritime emissions.

As this paper was being finalized, the speed limit option was among the set of short term options being considered by the IMO/MEPC in the quest to reduce maritime GHG emissions, and the fate of this option remained by and large unknown. By contrast, the bunker levy option is only obliquely and tentatively mentioned among the set of medium term measures, and interest in it, at least for the time being, appears to be very slim.

More details on this subject can be found in an expanded version of this paper (Psaraftis, 2019).

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