ON THE SPEED OF SHIPS

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ABSTRACT

Ship speed is a parameter that influences the energy efficiency of a ship. For this reason it has been considered as a parameter that could be used to reduce the carbon emissions of the existing and future global fleet of ships. Operational speed is an economic function of market conditions (freight rate) and the costs of operation (e.g., bunker fuel costs, cost of additional ships to meet the equivalent output) because along with the ship size, speed determines the industry's supply. Therefore speed can also be a cost-effective increase in energy efficiency for the ship owner and operator, although the level to which this is attractive will vary over time according to the agent's tradeoffs between revenue and cost. This paper reviews existing literature in order to highlight some of the common assumptions and ideas in the pertinent subject areas: energy efficiency, engineering, economics, environmental impact. Models are developed and their initial results presented, in order to interrogate the sensitivities of some of these assumptions. There is also discussion of the subject of speed in the evolving policy and regulatory discussion at IMO.

Keywords: ship, speed, economics, energy efficiency, policy

1. INTRODUCTION AND BACKGROUND

The average speed that a ship travels on a voyage dictates the journey time of freight or passengers from their origin to their destination. For the customer of the ship's services, the journey time determines when goods arrive at the market, how their value might change over the course of the voyage and how preferable the voyage is relative to alternative routes and modes.

The speed at which a ship travels also has implications for the owner and operators of a ship. Small changes in speed can have significant impacts on the energy efficiency of the ship and therefore its voyage costs, as well as the productivity of the ship and so its revenue.

When a ship is designed and built, its dimensions, hull form, propeller, propulsion and machinery are all selected based on assumptions about the speed at which it will be operated.

More recently, speed and in particular "slow steaming", or traveling at speeds below design speed, has been the focus of attention in the shipping industry. And whilst this paper is focused on ship speed and energy efficiency, the drivers behind the occurrence of slow steaming are often more complicated. For this reason, the paper will also draw attention to the physical, economic and stakeholder relationships mentioned above that are all important components of a systems understanding of shipping industry, and therefore also the potential of this parameter (speed) for increasing the energy efficiency of the global fleet.

1.1 SPEED, DWT AND ENERGY EFFICIENCY

The Admiralty Formula, (1.1), can be used to obtain the first estimate of the propulsive power required to move a vessel of displacement Δ te at speed *V* kts.

$$P = \frac{\Delta^{2/3} V^3}{C} \qquad (1.1).$$

C is a constant specific to ship type (a reflection of hull form and dimensions). From this formula, it can be seen that for a given size and type of ship, speed and power are non-linearly related - a small reduction in speed corresponds to a greater (in proportion) reduction in propulsive power. The output or 'transport supply' (*S*) that a ship provides in a specific time period t is commonly quantified in tenm or tekm – the product of payload carried and distance carried. For 1 hour, this transport supply can be expressed as (1.2).

$$S = dwtVU \qquad (1.2)$$

Where dwt is the deadweight of the ship (approximately the payload capacity) and U is a factor expressing the ships utilization.

A quantification of energy consumption pertinent to ships is their fuel consumption. This is commonly derived as the product of the power of the vessel and the specific fuel consumption *sfc* which is in units of Kg/KWhr. If the energy efficiency, *E* (units of Kg (fuel)/ tenm supply), of a ship is the amount of energy required to produce a unit of output, then taking the definitions obtained from equations (1.1) and (1.2) above, this can be expressed as:

$$E = \frac{sfc\Delta^{2/3} V^2}{CdwtU} \qquad (1.3)$$

This relationship is of a structure common to the EEDI and EEOI formulae, and behind the common assumption that slower ships are more energy efficient than faster ones.

1.2 ENGINEERING AND SAFETY

Ship design is the considered trade off between a number of objectives, one of which is energy efficiency at design speed and so a pure efficiency/speed trade off is rarely executed in practice. However, as voyage costs (fuel costs) are a significant portion of total operating costs of most ship types, optimization for a design condition (clean hull and still water) is commonplace. This optimization means that:

- ships of the same size/type (e.g. Panamax containers ships) that are designed for different speeds will not have the same propulsion, machinery or hullform.
- the same ship operated away from its design point, will to some extent (through propulsion, machinery and hullform) be operating in an off-design condition.

The consequence of being in an off design condition is a deterioration of performance, which can be thought of as a failure to achieve the energy efficiency that is expressed in (1.3). The further away from the design point, the greater the compromise in efficiency. Consequently, (1.3) should only be considered as an upper bound on energy efficiency.

One of the key requirements of a ship is its safety. Ships operate in a harsh environment and accidents resulting in the loss of ships often result in fatalities and significant damage to maritime ecosystems. One cause of these accidents is a ship's inability to manoeuvre to safety in a hazardous seaway. If a ship has insufficient propulsive power, tides, wind and waves can conspire to overcome a ship's manoeuvrability which leave the ship, its cargo and its crew vulnerable to navigational hazards. Speed, or more appropriately installed power, can often therefore be seen as a safety measure and this needs to be taken into consideration when considering speed from an energy efficiency perspective.

1.3 EXISTING LITERATURE

Much of the existing literature on operational speed has focused on determining an "optimum speed." This is defined in the literature as the speed at which the agent(s) (e.g. ship owner, charterer, shipper, consumer) is minimizing costs and/or maximizing profits. However, these optimization models differ with regards to which agents are included in the optimization problem. Most studies focus on the shipowner (Ronen, 1982; Corbett et. al., 2007; Devanney, 2010), finding the optimal speed by maximizing the agent's profits (which in some studies (Corbett et. al., 2007) includes the cost of carbon through a tax). However, this approach ignores the costs to the shipper. For example, a longer time at sea means increased inventory costs due to the time value of the good in transit and a larger required 'safety' stock of goods in warehouses. On the other hand, some shippers may have preferences to green their supply chains and will be more willing to accept slower transit times. Finally, the optimal speed should account for the environmental externality associated with the emissions from the transportation service. Therefore, there are three groups of agents which could be factored into the optimum speed calculation. Eefsen (2010) incorporates the costs of all three groups and finds the optimum speed for a container ship by minimizing the cost. However, there is no modeling of profits so it is most likely not a realistic scenario.

2. SHORT-TERM ECONOMIC OPTIMA AND THE SUPPLY CURVE

2.1 IMPACT OF FUEL COSTS ON THE SUPPLY CURVE OF TANKER FLEET

Focusing on the shipowner in the tanker sector, the optimum operational speed for an individual shipowner is derived by maximizing daily profits. This can be scaled up to create a supply curve for the tanker fleet. The total freight market supply curve is expressed in tonne-miles, which equals (dwt capacity x speed (miles per hour) x 24 x distance (nautical miles)). The optimal speed(s) and supply curve of ships going from the Persian Gulf (A) to Rotterdam (B). The theoretical framework is taken from Ronen (1982) where optimal speed is determined for laden and ballast voyages. The algorithm for the laden voyage will be presented here. The objective for the firm is to maximize daily profit:

$$\pi = [pQ_d - D_p C_r - \frac{DIST_{AB} C_r}{24v} - P_b k \left(\frac{v}{v_0}\right)^3 \frac{DIST_{AB}}{24v}]$$

$$/[D_p + \frac{DIST_{AB}}{24v}]$$

(2.1)

subject to : $0 < v_m \leq v \leq v_0$
where:

p	freight rate
Q_d	quantity of loaded cargo
D_p	days in port
$DIST_{AB}$	distance on route from A to B
V	operating speed in nautical miles
v_0	maximal speed

v_m	minimal cruising speed
$DIST_{AB}/24v$	days at sea
C_r	daily operating costs, excluding fuel
k	daily fuel consumption
P_b	bunker fuel price ($/ton)

The only decision variable is v. Daily profits are maximized by taking the derivative of the profit function with respect to v which gives the cubic function:

$$v^3 + v^2 \frac{DIST_{AB}}{16D_p} - \frac{pQ_d v_0^{\ 3}}{2kP_b D_p} = 0 \qquad (2.2)$$

The optimal speed is the root which maximizes profits, π. It is assumed that the tanker market is a price-taking market with no individual vessel able to influence the freight rate, and therefore price equals marginal cost. It is also assumed that quantity loaded, Q_d, is equal to the *DWT*. From these assumptions, a daily supply curve for a representative sample of the tanker fleet is calculated for each exogenous incremental change in the freight rate. The model solves for optimal speed first as a function of market conditions and then plugs this speed into the supply equation to determine the short-run supply curve. Figure 2.1 provides short-run supply curves for four different heavy fuel oil (HFO) prices which shows that as the HFO price increases, output decreases as ships go slower and some ships drop out of the active fleet.

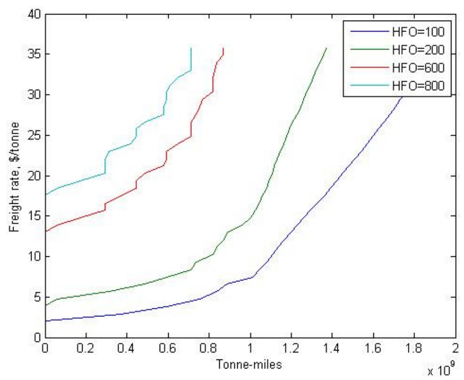

Figure 2.1: Supply curves for the tanker fleet at varying HFO price

2.2 ECONOMIC SURPLUS OF MATCHING SHIPS TO SHIPPERS

An alternative method is to maximize the social welfare of the shippers and shipowners who are looking to potentially trade with each other at each time step. Whereas in 2.1 only the shipowner's profits are taken into account, this method allows for explicit modeling of the profits of the shipper, and important component in determining actual trading patterns. The first step is to define the economic surplus of trading and not trading. This model will look at optimizing for the oil transportation (tanker) sector. There are two types of agent groups: the charterer and the shipowner. The charterer (with Ship 1) has been instructed by an oil trader who has bought X barrels of crude oil which can be dispatched at location A at the current date. The trader will sell the cargo at location B. Ship 1 is located at some location Z which could include location A. The surplus of a match is the profits of the charterer and shipowner as if they were a combined entity. This includes the revenue from the sale of oil and the cost of the shipment (the freight rate gets cancelled out since they are now combined). There are three scenarios that could occur, leading to different surpluses:

The surplus if charterer A and ship 1 match together

The surplus to charterer A if they don't match with a ship

The surplus of a ship that doesn't match with a customer

The match (scenario 1) is comprised of:

(a)The repositioning cost of ship 1 getting from current location Z to location of customer A

(b)The shipment cost: the cost of shipping from location A to B

(c) The expected present value of selling oil shipment at destination at date t, where t is the current date t_0 plus total time required for 1 to travel to A, load shipment, and then travel to destination B

The repositioning cost (a) is:

$$TC_{ZA} = C_f \frac{DIST_{ZA}}{24v} + P_b k (\frac{v}{v_0})^3 \frac{DIST_{ZA}}{24v} \qquad (2.3)$$

where C_f is the daily fixed costs (capital + operating), $P_b k (\frac{v}{v_0})^3$ is the fuel cost, and $\frac{DIST_{ZA}}{24v}$ determines the number of days of the journey, a function of distance and operating speed. The shipment cost (b) is:

$$TC_{AB} =$$
$$C_f (\frac{DIST_{AB}}{24v} + D_p) + P_b k (\frac{v}{v_0})^3 \frac{DIST_{AB}}{24v} + DWELL_{AB}$$
$$+ D_p C_r + P(E_p) E_p$$
(2.4)

The cost of going from A to B includes the port costs, $DWELL_{AB}$ which consists of the cost of using port services and loading and discharging cargo, while $D_p C_r$ is the running cost while in port (C_r daily running cost times number of days in port, D_p). $P(E_p)$ $P(E_p)E_p$ is the expected environmental penalty if the ship is found to be not complying with environmental standards (MARPOL Annex VI), where $P(E_p)$ is the probability of getting inspected. Finally, the expected revenue of oil (c) is:

$$\frac{E(P_{oil}(t))Q_d}{(1+\delta)^n} \tag{2.5}$$

where:

$E(P_{oil}(t))$ = expected price of oil at date *t* which is the future arrival date equal to t_0+n days, where *n* is

$$\frac{DIST_{ZA}}{24v} + \frac{DIST_{AB}}{24v} + D_p$$

Q_d: quantity demanded to be shipped
δ: discount rate
Note Q_d is exogenous to the model.

Combining 2.3, 2.4, and 2.5 gives:

$$\frac{E(P_{oil}(t))Q_d}{(1+\delta)^n} - TC_{AB} - TC_{ZA} \tag{2.6}$$

From 2.6 it is shown that speed enters the equation from 2.3 and 2.4: the costs of fuel to reposition the ship and perform the transportation service. It is also evident that minimizing costs does not necessarily lead to the largest surplus, as it also depends on the revenue from the sale of oil. As the price of oil rises, the percentage increase in transportation costs must rise by a lot more to offset this gain because transportation only accounts for a small fraction of the total price of oil (5% in 2007).

The surplus to charterer A of no match (2) is:

$$\frac{E(P_{oil}(t_{ns}))Q_d}{(1+\delta)^n} - \lambda Q_d - \theta Q_d \tag{2.7}$$

where t_{ns} is the time of next shipment arrival to destination; λ is the per tonne rate of storage and θ is the insurance rate (\$/tonne). Finally, the surplus to the shipowner of not matching Ship 1 with a shipper is:

$$-(C_f n_w + C_r n_w) + E(F_{ns})Q_d \tag{2.8}$$

where n_w is the number of days that the ship waits until it matches with a shipper and $E(F_{ns})Q_d$ is the expected value of trading in the nearest market to Z. This represents an option value of being at location Z.

2.2 HEDONIC PRICE FUNCTION FOR THE TANKER SECTOR

The bottom-up supply curve approach is also limited by the fact that it does not account for the preferences of the shipper and the characteristics of the ships, such as safety and geographic location. These attributes influence the ship-shipper pairs and the freight rate. An alternative approach is to develop a hedonic price function that describes the equilibrium relationship between the economically relevant characteristics of a product or service (i.e., transport) and its price (Nesheim, 2006). In a simple shipping model, the freight rate might describe how the price of the transportation service depends on geographic location, safety, environmental compliance, fixed costs, size, and speed. The hedonic price function describes the equilibrium valuations of the economically relevant characteristics of the product. We can describe the preferences of the shipper in a matrix:

$$X = (A, B, P_{oil}, Q_d)$$

where *A* is the location of dispatch, *B* is the destination of shipment, P_{oil} is price of oil, and Q_d is the quantity demanded for shipment.
Similarly for the shipowner:

$$Y = (Z, S, E, C_f, Size, k, v_0, v)$$

defines the matrix of characteristics:
Z : location of ship
S : safety standard
E : environmental compliance
C_f : fixed costs
Size : capacity, in DWT
k : fuel consumption constant
v_0 : maximum speed
v : operating speed

At a single point in time, there are N_X shippers and N_Y ships. Let

x_i : shipper *i* for all $i = 1 \ldots N_X$
y_j : shipper *j* for all $j = 1 \ldots N_Y$

Denote y_0 as the null ship if shipper *i* doesn't match with ship *i* and similarly x_0 as the null shipper if ship *i* doesn't match with shipper *j.* The objective is to maximize:

$$\sum_{i=1}^{Nx}\sum_{j=1}^{Ny} m_{ij} S(X_i,Y_j) + \sum_{i=1}^{Nx} m_{i0} S(X_i,Y_0) + \sum_{j=1}^{Ny} m_{j0} S(X_0,Y_i)$$
(2.9)

where $S(X_i,Y_j)$ is the economic surplus of a match with m_{ij} defined as the probability of the match occurring. Since not matching is allowed in each period, $S(X_i,Y_0)$ is the surplus of a shipper not matching with a ship with probability m_{i0} and similarly $S(X_0,Y_i)$ is the surplus for the shipowner not matching ship *j* with a shipper with probability m_{j0}. The probability of matching or not is taken to be 0 or 1 such that the objective function subject to the constraint:

$$\sum_{i=1}^{Nx} m_{ij} \leq 1 \forall i$$
$$\sum_{j=1}^{Ny} m_{ij} \leq 1 \forall j$$

and the constraint that allocation can't be a negative amount:

$$m_{i0} \geq 0$$
$$m_{0j} \geq 0$$

The problem can be solved using linear programming which is an optimal transportation problem. The theoretical grounding for this approach includes Gretsky, Ostroy and Zame (1999) and Chiappori, McCann, and Nesheim (2006). The surplus functions are taken from section 2.2 to numerically compute and the probabilities and Lagrangian multiplier (for the constraint) gives the equilibrium price. This linear program can be run for all the possible speeds and the optimal speed is the one that results in the largest value of 2.9.

3. OPERATIONAL AND EMBODIED ENERGY

A further complication to understanding ship speed's potential and impact is the inclusion of life cycle emissions. A ship's CO2 emission can be broken down into:

- an embodied energy CO2 emission, the CO2 associated with the raw materials and manufacture of the ship;

- an operating energy CO2 emission, the CO2 associated with the fuel consumed by the ship during its life.

A change to the design speed of a ship (or operating speed of an existing design) can have a consequence on its energy efficiency. However, assuming that demand for transport is exogenous to the operating speed of the fleet, a reduction in ship speed will result in an increase in the number of ships needed to satisfy a given transport demand. This increase in the number of ships needed will have a consequence on both the operating CO2 emission and the embodied CO2 emission.

The operational CO2 emission per year for a ship is given, to first order, by (3.1):

$$CO_{2op} = C_{ffuel} tpd T_{as}$$

(3.1)

where C_{ffuel} is the fuel carbon factor, and the operational fuel consumption is given by the daily fuel consumption *tpd* and the time (hours) spent at sea T_{as} per year.

The embodied CO2 emission per year is given, to first order, by 3.2:

$$CO_{2em} = \frac{C_{fsteel} lightship}{l} \quad (3.2)$$

where C_{fsteel} is the carbon factor associated with the dominant raw material used for the ship's construction (in this case steel) in te of CO2 per te steel, l is the life of the ship, and the mass of the steel contained within the ship is approximated as the ship's displacement without payload (*lightship*).

The total CO2 emission of a fleet of *n* ships, all the same size and specification and each with embodied and operational emissions given by 3.1 and 3.2 can be given as:

$$CO_{2tot} = \left(CO_{2em} + CO_{2op}\right) n \quad (3.3)$$

A fleet's minimum CO2 can be selected by the calculation of the minimum of this expression. In order to find this minimum, greater definition of the terms in (3.1) and (3.2) is required.

The relationship between power, and therefore by association fuel consumption, and speed for an individual ship is often approximated as a cubic (1.1) and so the operational emissions of a single ship estimated from its fuel consumption can be approximated as a function of its speed:

$$tpd = kv^3 \quad (3.4)$$

where *k* is a constant representative of the resistive forces that a ship's propulsion system must overcome and the specific fuel consumption of the machinery. This is a significant simplification as is discussed in Section 1.2, because a ship's design (geometry and machinery) are optimised for the trade it plies and the speed at which it travels (not least the froude number of the hull form, a function of a ship's speed and length). A high froude number ship, like a 5000 teu containership, would have a different hullform were it optimised for a dramatically lower speed, and so k is in practice a function of v. Further work is therefore required to calculate the error caused by the deployment of the simplification that k is a constant of speed over the speed range that is relevant for the consideration of minimum total CO2 emissions.

Extending (1.2), a fleet of ships fulfils an annualised transport demand to first order, as a function of its payload capacity (approximated as a ship's deadweight (*dwt*)), the number of ships *n*, the number of active days per year D_{aS}, the utilization of the ships and the speed at which those ships travel *V*.

$$S = nT_{aS}dwtUV \qquad (3.5)$$

Assuming the demand for ships and the size of ships fulfilling that demand remains constant, this equation can be rearranged to represent the number of ships required as:

$$n = \frac{S}{T_{aS}dwtUV} \qquad (3.6)$$

Combining 3.4 and 3.6 with 3.3, 3.1 and 3.2 we can write:

$$CO_{2tot} = \frac{\left(\frac{C_{fsteel}lightship}{l} + C_{ffuel}kV^3D_{as}\right)S}{T_{aS}UVdwt} \qquad (3.7)$$

Differentiating wrt v gives:

$$\frac{dCO_{2tot}}{dv} = \frac{\left(2C_{ffuel}kV - \frac{C_{fsteel}lightship}{T_{aS}lV^2}\right)S}{Udwt} \qquad (3.8)$$

which set = 0 can be used to find the speed at which the combination of operational and embodied emissions is minimised :

$$V_{opt} = \sqrt[3]{\frac{C_{fsteel}lightship}{2C_{ffuel}kT_{aS}l}} \qquad (3.9)$$

Taking three examples, a VLCC, a handymax wet/dry bulk carrier, and a panamax container ship, and using data for C_{fsteel} from Gratos et al. The values of *k* are obtained from exemplar ship specifications.

Table 3.1: specifications and minimum speeds for three ships sizes/types

	Handymax bulk	VLCC	Panamax container
Cfsteel (teCO2/te)	2	2	2
lightship (te)	8,000	45,000	25,000
Cffuel (teCO2/te)	3	3	3
k	0.013	0.03	0.012
Das (days)	240	280	250
l (years)	30	30	30
Vopt (kt)	3	4	4.5
Vdes (kt)	13.5	15	24.5

The relationship between total CO2 emitted and speed is of interest as it is instructive of how much potential there is to reduce total emissions for certain ships relative to their design specification. Figure 3.1 plots the ratio of total CO2 at speed V against the total CO2 at the design speed, for a range of values of speed and for all three ships. Based on the simplifications applied in this paper, and using the input data and assumptions in Table 1, the minimum total CO2 for the three ships is approximately 10-20% of the total CO2 associated with their existing design specification.

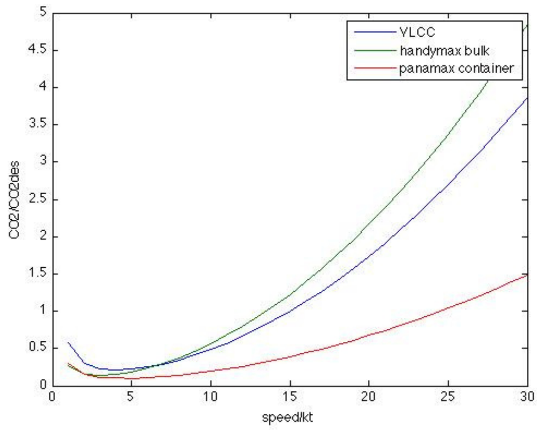

Figure 3.1: relationship between CO2 and speed

However, speed is not the only variable that can be deployed to minimise the total carbon emission of the fleet and independently it is also possible to:

Minimise embodied CO2 by reducing Cfsteel e.g. decarbonisation of land based electricity generation used in the steel industry, using recycled steel, minimising structural weight or considering alternative materials

Minimise operational CO2 by reducing C_{ffuel} e.g. use of biofuels, or reducing k by the use of energy efficiency technologies and operational strategies improving the transport supply of a ship over its lifetime (a given embodied CO2 emission) by increasing TaS or l

To inform the sensitivity of the total CO2 to these variables, let us imagine two arbitrary (yet credible given existing technological options) future scenarios:

Scenario 1 “operational eco lead”:
Cfsteel remains the same, Cffuel reduces by 33% (e.g. biofuel uptake), k reduces by 50% (e.g. technology uptake)

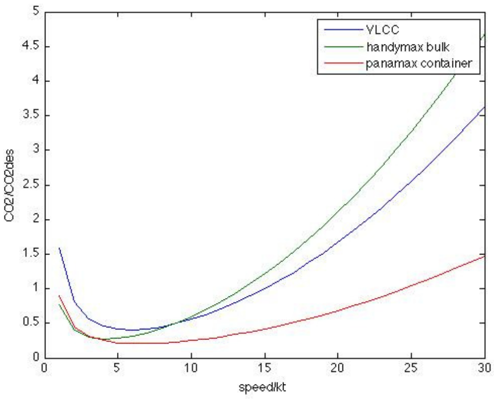

Figure 3.2: scenario 1 relationship between CO2 and speed

Scenario 2 “embodied eco lead”: Cffuel and k remain the same, Cfsteel reduces by 50%, l increases by 33%

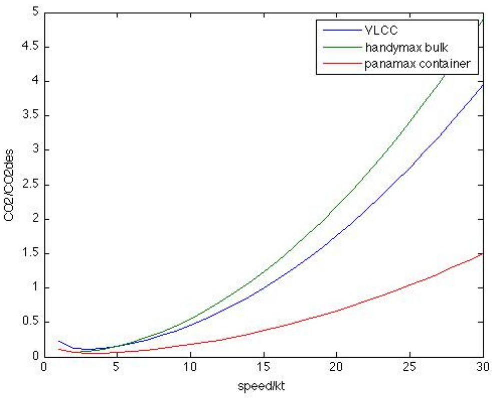

Figure 3: scenario 2 relationship between CO2 and speed

In practice, the future trend could well be some hybrid between these two scenarios, and it is relevant to note, that even taking those trends into consideration, the minimum total CO2 still occurs between 3 and 7 knots, suggesting that current operational speeds represent a significant opportunity for abatement of shipping’s negative externality, providing other issues (logistics, economics, safety etc) can be addressed.

4. REGULATED SPEED

Unlike many freight transport modes, shipping and aviation to date have only faced limited regulation on the subject of speed. Existing ship speed restrictions predominantly apply in surrounding waters of states, typically out to the contiguous zone (i.e. up to 24 miles) and with the aim of protecting sea life and for safety reasons in restricted seaways such as estuaries/canals. For example, the U.S. through the National Oceanic and Atmospheric Association announces seasonal vessel speed restrictions of maximum 10 knots within 20 miles of major ports along the East Coast to protect endangered right whales. Apart from these cases, ship’s design and operational speed has been left to the industry to dictate.

The subject of global mandatory speed limits has been raised at the IMO but gained an unfavorable reception and there are currently no plans to progress this concept further. CSC (2010) urged the IMO to consider speed reduction as a regulatory option in its own right and not just as a possible consequence of market-based instruments or the Energy Efficiency Design Index (EEDI), given the evidence that slower speeds can bring quick and substantial reductions in GHG emissions.

It is likely that if such a global measure is proposed for mandatory application for reducing shipping GHG emissions at the IMO, then following precedents, non Annex 1 member states may raise objection based on the United Nations Framework Convention on Climate Change (UNFCCC) Common But Differentiated Responsibility (CBDR) principle. Just as progression of global agreement on GHG emission reduction regulations at IMO is currently stimulating the development of proposals for regional, unilateral action, it is possible that such action could include speed regulation. At regional/unilateral level a particularly important issue to consider is the issue of enforcement. Though it may be easy to compute a ship’s speed over ground with the use of Automatic Identification Systems (AIS), Long Range Identification and Tracking (LRIT) etc at ports for enforcement, one could argue that this may contravene the rules enshrined in UN Law Of the Sea (UNCLOS). A further problem is that AIS/LRIT does not measure speed through the water, as this is dependent on any current or tides, and it is this and not speed over ground which is the important parameter for the energy efficiency of the ship.

Theoretically, a speed limit in a coastal state’s territorial sea would be possible under the provisions of Article 25.2 of UNCLOS and under Article 56 could be further applied to cover the EEZ as it allows states to enforce pollution regulations. However an average speed limit rule that goes beyond this (reaches the high seas) i.e. where the origin is over 200 miles will give rise to extra-territoriality therefore could be questioned/tested. This situation might arise if, for example, the EU placed an average speed limit regulation from point of origin on all ships arriving in EU ports.

4.1 DESIGN SPEED AND EEDI

The IMO may affect the design speed considerations of new ships through the Energy Efficiency Design Index. The EEDI, if adopted, will mandate a progressive improvement in the energy efficiency of newbuild ships in their design condition. The EEDI formula (4.1) bears some similarities to (1.3) for obvious reasons:

$$EEDI = \frac{C_f sfc P_d}{dwt V_d} \quad (4.1)$$

EEDI is calculated for a ship at its design speed, V_d achieved at the design power P_d, which is assumed to be 75% of the installed power capacity. In order to meet a specified value below the baseline calculated using the existing fleet, the designer of a ship has three options:

- Apply energy efficiency technologies which enable the same speed to be achieved at a lower power, or lower *sfc*.
- Apply abatement options which reduce Cf
- Reduce the design speed of the ship (which as we can see from (1.1) will also reduce P_d

Weighing up these three options, requires an understanding of energy efficiency and abatement options, how costs and revenue might be impacted and different risks and peripheral benefits that might be encountered. It is therefore non-trivial to estimate whether design speeds will change significantly, but given the implementation cost relative to some of the more substantial energy efficiency technologies; it will certainly be an attractive option.

4.2 EEOI AND SPEED IN CHARTERPARTIES

On the operational side, the IMO has developed the Ship Energy Efficiency Management Plan (SEEMP) which could become a mandatory process (as a package with EEDI) for ships. SEEMP incorporates the possibility to use the Energy Efficiency Operational Indicator (EEOI) as a monitoring and benchmarking tool for energy efficient operation. The IMO considers speed optimisation to be one of the best practice measures that should be incorporated in the SEEMP but also recognises that under many charterparties the speed of the vessel is determined by the charterer and not the operator (IMO, 2009).

The optimum operational speed may therefore not be achieved due to barriers that exist within the industry. Standard charter party contracts (e.g. BIMCO Gentime) stipulate that a chartered vessel must sail at 'utmost despatch' without consideration of berth availability at destination ports (Alvarez et al, 2010). This provides the charterer an incentive to instruct the master to sail at full speed to the ports which admit vessels on a first come first serve basis (FCFS). FCFS (and the inability to pre-book berths) is one of the key drivers for charterers to adopt full speed clauses on charterparties. This is further exacerbated due to the divided responsibility between shipowner and charterer for fuel costs. For example on a voyage charter the shipowner pays for bunkers, so has the incentive to reduce speed (slow steam) provided there is no opportunity cost for another voyage but because the charterer dictates the speed of the voyage, the shipowner will ask for a premium on freight cost (therefore pass on the additional cost) for sailing at that speed, thus the actions of both are ultimately at a cost to the environment. In a time charter wherein fuel costs are borne by the charterer, there are also incentives to full steaming due to contractual arrangements with the customers/shippers further down the supply chain, where inventory costs become more of a priority, thus making speed a differentiating/competing factor between services (Stopford, 2009). Furthermore the actions of the party paying for fuel might still be highly dependent on the freight rates and market conditions, which mean that optimal ship speed is seldom achieved.

One of the ways differing incentives of the stakeholders on the issue of speed have been aligned is through development of Just in Time practices (also recommended by IMO, 2009). This tackles the 'utmost despatch' and 'consistent speed/stated speed' clauses in charterparties which normally leads a vessel to full steam and wait at anchorage due to lack of berth or storage shortages at port facilities. An example of a process that removes this known inefficiency is the Virtual Arrival code/agreement developed by OCIMF and Intertanko (Ranheim & Hallet, 2010), whereby a ship's speed is reduced on mutual agreement with all the parties involved, in order to achieve an agreed arrival time at port. Initial trials of this mutual speed reduction on some voyages show reduction of CO_2 emissions by up to 27% (OCIMF & Intertanko, 2010).

5. CONCLUSIONS

This paper shows some of the different perspectives that may be required when thinking about the speed of ships. The paper starts with an estimate for ship speed's impact on energy efficiency, and the simplistic model used to show this relationship is discussed in combination with the engineering and safety consequences of speed change.

The economics of speed selection (given fuel price scenarios) are not trivial because speed has an impact both on revenue and costs, and can also be a customer's (charterer, shipper) preference in its own right. For this reason, a new model for considering the optimization of a combined shipper-operator decision on speed is presented and is the subject of ongoing work and analysis in conjunction with operational data describing ships movements and speed.

Estimates of the consequence of speed change on the embodied energy and associated emissions of the global fleet are used to examine whether when taken in conjunction with the operational emissions there is a net saving to be achieved from speed reduction. A scenario analysis shows that even though many of the input variables to this calculation are uncertain there is a significant potential to reduce the combined emissions if speed is reduced.

In many areas, the models presented in this paper can benefit from further refinement. Engineering considerations (particularly off-design performance) are discussed but not incorporated numerically into the models. This work is ongoing and will be used to ensure that the analysis is not naive to the physical complexity of the ship itself and the environment in which it operates.

Finally, some of the more recent regulatory developments around the subject of speed are presented and discussed, along with the charter party context to the implementation of regulation.

Whilst this paper does not attempt to bring all these different perspectives together to evaluate possible scenarios for future ships and the shipping industry, this is the ambition of the ongoing research project "Low Carbon Shipping – A Systems Approach" through which a global shipping model is being developed, containing all of the components of the system described in this paper.

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