

# Ship speed vs power or fuel consumption: Are laws of physics still valid? Regression analysis pitfalls and misguided policy implications

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## ARTICLE INFO

### Keywords:

Ship fuel consumption  
Ship speed  
Greenhouse gas emissions  
Regression analysis

## ABSTRACT

There have been a number of recent papers in the literature that investigate the relationship between ship speed and required power, or between ship speed and fuel consumption. Using regression analyses for selected case studies these papers show that in many cases the traditional “cube law” is not valid, and exponents lower than 3 (and in some cases lower than 2 or even below 1) are more appropriate. Perhaps more important, they use these results to derive implications on the validity (or lack thereof) of policies to reduce greenhouse gas (GHG) emissions from ships through slow steaming. This paper reviews some of these papers and shows that their results are partially based on pitfalls in the analysis which are identified. Policy implications particularly on the quest to reduce GHG emissions from ships are also discussed.

## 1. Introduction

In the quest to reduce greenhouse gas (GHG) emissions from ships, the role of speed reduction is paramount. Due to the non-linear relationship between ship speed and required power, or between speed and fuel consumption, a reduction of speed by  $x\%$  usually translates to an equivalent reduction of fuel consumption (and hence of emissions, GHG or other) that is greater than  $x\%$ .

As this may have important policy ramifications, particularly with regard to the Initial IMO Strategy (IMO, 2018), it is obviously very important to correctly understand how much fuel consumption can be reduced for any assumed reduction of speed. Practically all of the thus far adopted or contemplated policies at the International Maritime Organization (IMO) and/or the European Union (EU) critically depend on the role ship speed may play in reducing fuel consumption and hence emissions. Conversely, an incorrect understanding of the issue can conceivably lead to misleading economic implications and misguided policies.

There have been a large number of papers in the literature that investigate the relationship between ship speed and required power, or between ship speed and fuel consumption. Using regression analyses for selected case studies, some of these papers purport to show that in many cases the traditional “cube law” (also known as “propeller law”) is not valid. The cube law derives from hydrodynamic principles and states that a reasonable approximation for a ship’s required power (and also

daily fuel consumption) is that it is proportional to the speed of the ship through water raised to the 3rd power. Yet, the aforementioned papers claim that exponents lower than 3 (and in some cases lower than 2 or even lower than 1) are more appropriate. Perhaps more important, they use these results to draw implications on the validity (or lack thereof) of policies to reduce GHG emissions from ships.

The purpose of this brief paper is to take a look at some of these papers and show that their results are partially based on pitfalls in the analysis which are identified. The main contribution of this paper is that the identification of such pitfalls may conceivably prevent their replication in future research efforts and their possible misuse on critical regulatory decisions.

Given the above, it is not the scope of this paper to be encyclopedic on ship fuel consumption models. For recent surveys of such models, the reader is referred to Yan et al. (2021) and to Fan et al. (2022). In the first paper, models that optimize ship operations based on fuel consumption prediction results are presented and discussed, and current research challenges and promising research questions on ship performance monitoring and operational optimization are identified. In the second paper, current ship fuel consumption models are classified into three types: white, black, and grey boxes. Considering the different types of models, the advantages and disadvantages, accuracy improvement methods, and verification methods are analysed in the paper, and the influencing factors of these models are investigated.

The rest of this paper is organized as follows. Section 2 presents some

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basics, mainly based on hydrodynamic theory. Section 3 reviews the papers in question and explains the possible pitfalls in their analyses. Section 4 discusses some additional points, mainly focusing on policy issues.

## 2. Basics

A typical assumption, which is widely used in naval architecture and which is based on hydrodynamic principles, is the so-called “cube law” (or “propeller law”), which states that a good approximation for the relationship between a ship’s required power and ship speed is cubic. That is, required power can be reasonably approximated by the following formula:

$$P(v) = kv^3 \quad (1)$$

where  $v$  is the ship’s speed through water (knots)  $P(v)$  is the ship’s required power, including main engines, boiler and auxiliary engines (kW) and  $k$  is a constant.

More advanced forms can also be considered, for instance

$$P(v, w) = m(A + w)^{2/3}v^n \quad (2)$$

where  $w$  is the ship’s payload (tonnes)  $A$  is the light ship weight (tonnes)  $n$  is an exponent, typically  $\geq 3$  and  $m$  is another constant.

Eq. (2) is also known as the “modified admiralty formula” (Barass 2004), and the power of  $2/3$  in which the ship’s displacement  $\Delta = A + w$  is raised is due to the fact that  $\Delta^{2/3}$  is a quantity which can be considered as a proxy to (or proportional to) the ship’s wetted area of the hull, which enters the hydrodynamic calculations to compute  $P$ , as will be seen below.

Last but not least, the function  $P$  may not be available in closed form, but can be the output of a routine that can calculate it as a function of many inputs, including ship geometry, laden condition, speed, weather conditions, and others.

That the exponent of speed  $n$  in the above calculations cannot be less than 3 comes from basic hydrodynamic principles, which in turn are based on the laws of physics. Indeed, a ship’s *calm water* resistance  $R_T$  can be calculated as a function of the total drag coefficient  $C_T$ , the density of water  $\rho$ , the speed through water  $v$ , and the total wetted area  $S$  of the hull, as follows:

$$R_T = (1/2)\rho C_T v^2 S \quad (3)$$

The total drag coefficient  $C_T$  is the sum of the frictional coefficient  $C_F$  and the residual drag coefficient  $C_R$ . In general both components of the *calm water* resistance of a specific ship are quadratic functions of the ship’s speed through water  $v$ . However, the coefficients of proportionality are not constant. The frictional resistance is quadratic with speed, since  $C_F$  is essentially constant for a given ship size. The residual resistance is mainly due to wave making and is generally roughly proportional to  $v^4$ . See Schneekluth and Bertram (1998) and Newman (2018) for more information.

The above means that the ship’s *calm water* resistance in the best case cannot have a ship speed exponent lower than 2. By “best case” we mean cases of low ship speed, where residual resistance is low and frictional resistance is the predominant component of the resistance.

If now we multiply both sides of eq. (3) with  $v$ , we get the ship’s required power in the left hand side, as follows:

$$P = vR_T = (1/2)\rho C_T v^3 S \quad (4)$$

Notice the similarity between Eqs. (2) and (4). In fact, if in eq. (2) we put  $n = 3$ ,  $(A + w)^{2/3} = S$ , and  $m = (1/2)\rho C_T$ , we get eq. (4). Again, in the best case (low ship speeds),  $P$  is proportional to the cube of speed  $v$ , and the speed exponent can be higher in the general case. The exponent being lower than 3 cannot be justified on hydrodynamics (or laws of physics) grounds.

The above results also pertain to the relationship between ship speed and (daily at sea) fuel consumption. Moving from required power to fuel consumption involves multiplying the various power requirements (main engine, auxiliary engines, boilers) by the respective specific fuel oil consumptions (also known as SFOCs). The SFOC is in general not a constant but a function that varies with ship speed  $v$ , depending on the characteristics of the main engine and the ship-propeller-engine configuration (Prpić-Oršić et al. (2016), MAN Diesel (2018)). However, the same behavior with respect to  $v$  is generally expected, and the same functional form that is assumed for speed vs power in eqs (1) to (3) is assumed in many studies for speed vs daily at sea fuel consumption. Again, an exponent lower than 3 cannot be justified on hydrodynamics (or laws of physics) grounds.

All of the above concern *calm water* resistance, which is only part of the story. Extra resistance will be generated by sea waves along the ship’s route. This extra resistance is called *added resistance* and it is heavily non-linear. Estimating *added resistance* is a complex process, as this generally depends on hull shape, seakeeping characteristics of the ship, the sea spectrum and other parameters. For the calculation of the *added resistance* we refer to the seminal work of Salvesen (1978) using strip theory approximation. Other important papers on *added resistance* include Kwon (2008), Panigrahi et al. (2012), and Cai et al. (2014).

Corroborating the above, it is interesting to note that both the 3rd and the 4th IMO GHG studies (IMO 2014, 2020) assume the speed exponent to be equal to 3, in order to estimate the required power  $\dot{W}_i$  for ship  $i$  as follows:

$$\dot{W}_i = \frac{\delta_w W_{ref} \left( \frac{t_i}{t_{ref}} \right)^m \left( \frac{v_i}{v_{ref}} \right)^n}{\eta_w \eta_f} \quad (5)$$

Here  $\dot{W}_{ref}$  is the reference power of a ship as given in the world fleet database,  $t_i$  and  $v_i$  are the instantaneous drafts and speeds respectively as these are provided by AIS (the ship’s Automatic Identification System). The reference draft ( $t_{ref}$ ) and speed ( $v_{ref}$ ) are also from the world fleet database. The draft ratio exponent  $m$  is assumed to be 0.66 (approximately  $2/3$ - see again eq. (2), while the speed ratio exponent  $n$  is assumed to be 3. In the denominator,  $\eta_w$  represents the weather modifier to the ship’s propulsive efficiency (the value corresponding to a 15% sea margin is 0.867) and  $\eta_f$  is the fouling modifier. A correction factor,  $\delta_w$ , to  $\dot{W}_{ref}$  is applied to certain ship types and sizes to adjust the speed-power relationship, as provided by the fleet database. It is noted that the speeds in eq. (5) are speeds over ground as opposed to speeds through water, which entails an approximation as it ignores the effect of tides and currents. Notice again the similarity between eq. (2) and eq. (5).

On the operational side, shipping companies tend to measure vessel’s energy efficiency by combining data on their early performance at a newbuilding/sea trial stage with data retrieved during normal operations. As the vessel’s hull gets fouled and weather conditions can vary significantly from voyage to voyage, a good practice it to compare the attained speed, power and fuel consumption data with a benchmark at the newbuilding phase. Furthermore, shipping operators measure indices such as the “slip of the propeller” to document external factors affecting the propeller’s performance and thus the loss of attained speed. The slip is a good indicator on realizing how external factors such as the sea state, sea currents and the intensity of the wind affect the vessel’s performance.

## 3. Enter regression analysis

Laws of physics notwithstanding, there have been a number of recent papers in the literature that investigate the relationship between ship speed and required power, or between ship speed and fuel consumption, using *regression analyses* for selected case studies. Some of these papers purport to show that in many cases the traditional “cube law” is not valid, and exponents lower than 3 (and in some cases lower than 2 or

even in some other cases lower than 1) are more appropriate.

Perhaps more important, some of these papers use these results to derive implications on the validity (or lack thereof) of policies to reduce GHG emissions from ships. If these results are correct and can be generalized to other ship types, all known global shipping GHG estimates (for instance, those by the 3rd and 4th IMO GHG studies, IMO (2014, 2020), see eq. (5) above) are completely wrong, and so are policies that aim to reduce GHG emissions from shipping via speed reduction.

Before we go over these papers, we note that one should be very careful about how regression analyses are used. A regression analysis does not prove a cause-and-effect relationship among the selected variables, but tries to establish a statistical correlation among the variables to be investigated. Care should be exercised on the relationship among these variables, otherwise results may be misleading. The same is true if important variables are omitted from the regression, or if independence is assumed among variables that depend on one another.

To state one example in which misleading conclusions can be drawn if the results are not interpreted correctly, Kontovas and Psaraftis (2011) performed a regression analysis of about 4,000 container vessels built from 1999 to 2010 and provided by the IHS Fairplay online Sea-Web database. Based on this regression, the installed power  $P$  needed to sail at a design speed  $V$  (after removing statistical outliers) was found to be given by the following formula:

$$P = 0.00311V^{5.1465} \text{ with } R^2 = 0.947 \quad (6)$$

Note that the speed exponent of this regression is much greater than 3. Does this mean that the above formula can describe the relationship between required power and operational speed for a specific vessel? The answer is no. First of all, the above regression was performed over a diverse population of about 4,000 containerships, ranging from very small to very large. Therefore it is not valid for any specific and fixed ship size. Second,  $V$  in the above formula is *not the operational speed, but the design speed* of the vessel. Operational speed can vary depending on a variety of parameters and is not necessarily equal to design speed. As design speeds generally increase with vessel size (Efsen and Cerup-Simonsen, 2010), in the above formula vessel size enters the formula implicitly and its effect on required power is twofold, one directly and one indirectly: (a) there is a positive correlation between vessel size and design speed, and (b) required power is an increasing function of both vessel size and design speed. That the exponent is higher than 3 in the above formula is due to the above fact.

Table 1 is an extension of a related table from Zis et al. (2020) and provides a sample of frequently used speed exponents as found in the literature.

We note that Table 1 is not encyclopedic. In fact in the “speed taxonomy” paper of Psaraftis and Kontovas (2013) one of the parameters of the taxonomy was the form of the fuel consumption function. Of all

papers surveyed in that paper (some 40 of them), about half examined a cubic function ( $n = 3$ ), and the rest examined a general function or a non-linear function. None reported a function for which  $n < 3$ .

Of course, many additional speed-related papers have been published, especially after the above survey was published. For instance, papers that specifically included weather as a parameter in their ship fuel consumption analyses but did not postulate a speed exponent lower than 3 included Lindstad et al. (2011), Prpić-Oršić et al. (2016), Lee et al. (2018), Safaei et al. (2018), Işikli et al. (2020), and Fam et al. (2022).

Without claiming completeness, we have picked the last three papers of Table 1 as characteristic examples of papers using regression analysis to derive speed exponents lower than 3, and we base the rest of our analysis on these three papers.

Looking first at the paper of Bialystocki and Konovessis (2016), the paper performs a regression analysis of the fuel consumption and speed relationship based on 418 noon reports of a pure car or a pure truck carrier. The influence of the ship’s draft and displacement, weather force and direction, hull and propeller roughness on fuel consumption are calculated. Among other results, the paper finds that for the proposed speed, a wind force of Beaufort (BF) 4 decreases resistance by 3.1% as compared to wind force of BF 5. The regression yields a *quadratic* relationship between daily fuel consumption and speed, that is,  $n = 2$ . This implies a *linear* relationship between ship speed and resistance, something that violates the laws of physics. It is fair to recognize that the paper makes some corrections in the regression to account for the influence of some exogenous parameters including weather. The correction to account for weather is by shifting all data points from BF 4 and BF 6 to a “common denominator” wind force of BF 5. Even though this may make sense, this correction leaves open what happens to data for BF below 4 or above 6, which could be quite common.

Perhaps more interesting from a policy perspective is the paper by Adland et al. (2020). The authors examine data for a set of 16 tankers and perform a series of regression analyses. They then conclude that the cube law is valid only near the ship’s design speeds and not valid elsewhere. In fact, exponents much lower than 3 (and in some cases lower than 2) are calculated in most of the cases. Even though most of this paper is of a technical nature, the authors also make some statements that are more of a policy nature. For instance they say in the abstract: “Our results can be used to question the economic and environmental benefits of slow-steaming and fuel levies.” This is a highly “political” statement challenging the view that a bunker levy can be a useful policy instrument to reduce GHG emissions in the short run. Papers that show that a bunker levy or a higher “fuel price to spot rate” ratio can achieve GHG emissions reductions via the speed reduction they can induce include Gkonis and Psaraftis (2012) and Lagouvardou et al. (2022), among others.

The above political statement is not new. In an earlier paper, Adland and Jia (2018), after an analysis of fuel prices and ship speed data obtained via detailed satellite AIS information, reach the conclusion that no correlation between fuel prices and ship speed could be found. Indeed, they find that “owners do not appear to adjust vessel speeds based on freight market conditions and fuel prices, as argued in classical maritime economic theory” and as a result reach the policy conclusion to the effect that “From a policy point of view, the results actually suggest that higher fuel prices do not contribute to a reduction in vessel speeds and emissions.”

However, there are some important caveats to that conclusion, the most important of which is that the model used does not take weather information into account (“The poor model fit may be due to factors outside our model, such as weather conditions and contractual limitations”). Indeed, a low AIS speed may be due to bad weather and not to a voluntary slow down by the ship operator (more on this point below). Further, that paper uses detailed AIS data for 2011 and 2012. However, the 3rd and 4th IMO GHG studies claim that before 2012, due to insufficient AIS coverage the derived data were highly untrusted and not consistent. In addition, average global fleet speeds (and GHG emissions) have dropped as a result of the 2008 economic crisis and the ensuing overcapacity in

**Table 1**  
Speed exponent values used in the literature (sample).

Vessel type/scenario	Speed exponent	Source
Tanker, product	$3.2 < n < 3.8$	MAN Diesel (2018)
Bulk Carrier	$3 < n < 3.6$	MAN Diesel (2018)
Container Ship (1FPP)	$3.2 < n < 3.4$	MAN Diesel (2018)
Container Ship (2FPP twin skeg)	$3.1 < n < 3.3$	MAN Diesel (2018)
Ro-pax	$3.4 < n < 4.8$	MAN Diesel (2018)
Sample of 2259 containerships	3.3	Notteboom and Cariou (2009)
Based on a linear regression model on historical data	$2.7 < n < 3.3$	Wang and Meng (2012)
Sample of 419 noon reports of pure car and truck carriers	2	Bialystocki and Konovessis (2017)
Sample of 16 tankers	$< 3$ and sometimes $< 2$	Adland et al. (2020)
Sample of 50,000 noon reports from 88 tankers	$\ll 3$ at low speeds ( $< 2$ , or even $< 1$ )	Berthelsen and Nielsen (2021)

many shipping markets, and there is widespread evidence in the literature and in practice showing that, whenever fuel prices go up or the market is depressed, ships tend to slow down and vice versa.

In fact, the apparent conclusion of the paper that owners do not adjust speeds based on freight market and fuel conditions are contradicted by historical evidence, and there are many examples supporting that fact. According to the 3rd IMO GHG study (IMO, 2014), the reduction of global maritime CO<sub>2</sub> emissions from 885 million tonnes in 2007 to 796 million tonnes in 2012 is mainly attributed to slow steaming due to the serious slump in the shipping markets after 2008. When fuel prices collapsed in the spring of 2020 due to the Covid19 pandemic, it was cheaper for containerships on the Far East to Europe route to sail the much longer route around Africa at higher speeds than paying the Suez canal tolls. And as reported in Lagouvardou et al. (2022), the observed reduction of average tanker speeds between 2012 and 2018 coincided with a corresponding decrease of the spot rate to fuel price ratio over the same period.

Coming back to the Ådland et al (2020) paper, the authors discover considerable noise in their data. See for instance Fig. 2 of the paper, an extract of which is shown in Fig. 1 below.

The noise is due to factors other than speed that vary across the data sample under study. Weather is the most important factor contributing to such variation, even though some other factors, for instance hull condition, trim, and others may also vary. This noise is not a surprise, and we can name a number of other papers that have shown considerable noise as well (see for instance Lindstad et al (2019), Polakis et al. (2019), and Panagakos et al. (2019)). Noise is also shown in the reports of the European Maritime Safety Agency (EMSA) on the statistics of the EU MRV (Monitoring, Reporting and Verification) scheme (EMSA, 2020).

The regression lines are calculated by the following formula:

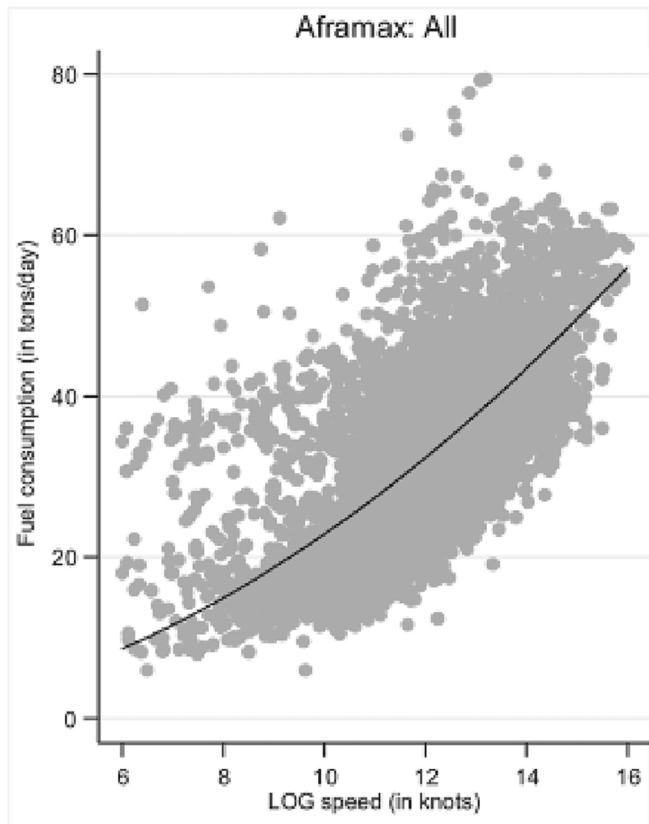


Fig. 1. Fuel consumption vs speed, Aframax laden tankers. Source: Ådland et al. (2020).

$$\ln C_{it} = \ln \alpha + \beta \ln S_{it} + \delta \ln X_{it} + \varepsilon_{it} \quad (7)$$

where

$C_{it}$  is the daily fuel consumption,

$\alpha$  is a constant, an output of the regression.

$S_{it}$  is the vessel speed,

$\beta$  is the speed exponent, another output of the regression.

$X_{it}$  is a set of observable parameters that influence fuel consumption, including weather variables,

$\delta$  is the associated coefficient, yet another output of the regression, and,

$\varepsilon_{it}$  is other noise.

As stated above, one of the outputs of the set of regression analyses is the speed exponent  $\beta$ . The paper shows that  $\beta$  is way below 3, and sometimes even below 2. These results violate basic hydrodynamics laws, as per section 2.

How can these results be explained? A basic observation in this analysis is that vessel speed ( $S_{it}$ ) and weather ( $X_{it}$ ) can not be considered independent variables as they are assumed in the regression equation (eq. (7)). There is an obvious cross-correlation between the two, which surely skews the results of the regression as regards all outputs including  $\beta$ . In fact this is precisely the reason values lower than 3 for that coefficient are estimated. A low speed in the data may be due to bad weather (which would make the ship consume more fuel to maintain that speed) and not necessarily to a deliberate choice to slow down. But the above formula cannot distinguish between a low speed that is deliberately chosen (due to market conditions) and a low speed that a ship is forced to use as a result of bad weather. As a result, this model ends up with a  $\beta < 3$  (and sometimes  $\ll 3$ ), which overestimates fuel consumption at lower speeds and underestimates fuel consumption at higher speeds.

One can better understand this in Fig. 2, plotting FC, the daily at sea fuel consumption, versus ship speed  $V$ . The dashed curve corresponds to the case the vessel is forced to slow down due to bad weather, but still has a considerable fuel consumption at that (low) speed to maintain it. The shape of that curve at lower speeds implies that  $\beta < 3$ , which yields a higher fuel consumption at these speeds versus the solid curve, which corresponds to the case  $\beta$  greater than 3.

Of course a low value of  $\beta$  would also have ramifications as regards how the optimal speed changes as a function of fuel price or as a result of a bunker levy. As a result of a lower  $\beta$ , the authors of the paper found a less pronounced speed reduction from a bunker levy (as compared to  $\beta = 3$  or  $\beta$  greater than 3), hence the “political” statement in their paper.

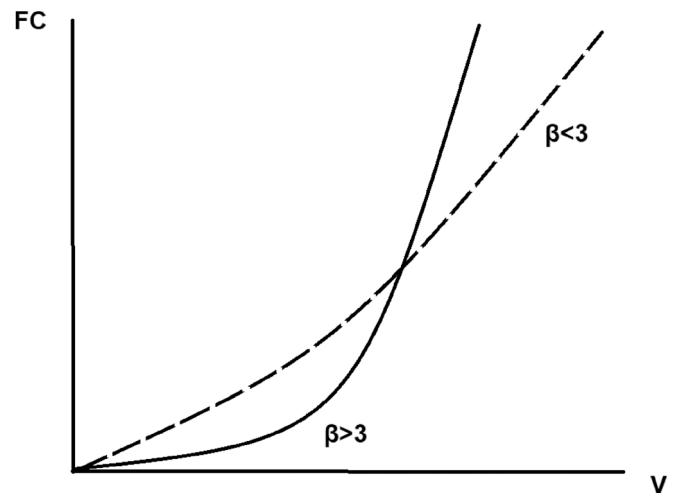


Fig. 2. A higher fuel consumption at lower speed that is due to bad weather implies  $\beta < 3$  (dashed curve).



The aforementioned paper also includes an analysis with a variable  $\beta$ . This is surely more accurate, however the issue of dependency between speed and weather is still valid.

Similar observations can be made on the [Berthelsen and Nielsen \(2021\)](#) paper. The authors investigate the speed-power relationship of ships, and the paper is based on a combined econometric and naval architectural data-driven model fed with operational data from more than 50,000 noon reports obtained from 88 tankers. Even though a different method is used, and one which embeds naval architecture principles instead of being solely based on econometrics, the results of the paper are very similar with those of the [Ådland et al \(2020\)](#) paper. Thus, the speed-power exponent is calculated as being lower than 3 at speed intervals below the design speed. According to that paper's [Table 1](#), exponents lower than 2 and even in some cases lower than 1 are calculated for some scenarios. As an extreme case, the speed exponent that was calculated for one of the scenarios was 0.35, indicating a highly sub-linear relationship between speed and power for that particular scenario. Note that if the required power to propel a ship grows as ship speed to the 0.35 power, ship resistance would grow as ship speed to the minus 0.65 power, that is, would be a decreasing function of speed.

Obviously such a result is non-sensical from a laws of physics perspective. It can only be explained by the fact that, as in the [Ådland et al \(2020\)](#) paper, the model used by the authors is unable to detect if a low vessel speed is chosen deliberately or is a consequence of bad weather. Note that weather information does not enter explicitly the paper's regression model, however, according to the authors, some kind of correction of the power output due to added resistance in waves is applied before the regressions are run.

As in the [Ådland et al \(2020\)](#) paper, a corollary in the [Berthelsen and Nielsen \(2021\)](#) paper is policy-related: it is the implication that slow steaming will not be as effective as often stated. As such, the latter paper claims that speed optimization, rather than speed reduction, should be used in the political and environmental debate focused on the reduction of carbon emissions from shipping. Precisely how that can be done is left open. For a paper that discusses the speed reduction vs speed optimization debate at the IMO, and also compares speed limits with a bunker levy, see [Psaraftis \(2019\)](#).

What can be done to fix this problem? Our suggestion is threefold.

First, avoid the use of regression analysis altogether, at least for these kinds of problems. It is a tool that one should be extremely careful to deal with, and the risks of misuse or abuse are always there. So if one can solve the problem without regression, for instance using direct measurements, model tests, or computational fluid dynamics (CFD), methods that all respect the laws of physics, this would be in our opinion preferable.

Second, if one absolutely has to use regression analysis, drop the assumption that weather and vessel speed are independent variables, because they are not. Instead, vessel speed should be considered as a dependent variable, a function of the vector of weather variables, the power of the main engine, the heading of the vessel, the seakeeping properties of the vessel, and other parameters, for instance hull fouling and others. The considerations of [Section 2](#) on added resistance are relevant here.

Third, to draw any meaningful conclusions, the fuel consumption vs speed curves for a specific vessel class and lading condition should be established with a constant weather as a parameter (eg at calm weather, at 5 BF, at 9 BF, etc). If the weather is not constant and is implicitly mixed in these scenarios and is cross-correlated with speed, one will not get a very accurate picture and regression results may be misleading.

#### 4. Discussion

It would seem self-evident that any scientific study, in whatever field, must be based on methodologies that do not contradict the laws of physics. This is all the more important if these results are used to put forward recommendations that may have important policy

ramifications. For the subject under study in our paper, it is also self-evident that policies on the best measures to reduce GHG emissions from ships should be based on sound scientific principles. We believe that this paper has identified some of the pitfalls in some analyses and that by doing so, the chance that similar pitfalls can be seen in future analyses is hopefully reduced.

As far as speed reduction is concerned, and until alternative, low carbon fuels can find their way and become economically viable, speed reduction is surely a tool for reducing GHG emissions from ships, and perhaps it is the main tool. In fact and as argued below, all GHG related regulatory action by the IMO and the EU thus far has implications on ship speed, either at the design or at the operational level.

Indeed, both ship speed and fuel consumption enter into ship energy efficiency indices such as EEDI (Energy Efficiency Design Index) and EEXI (Energy Efficiency Existing Ship Index), as well as into carbon intensity indicators (CII) such as EEOI (Energy Efficiency Operational Indicator) and AER (Annual Efficiency Ratio). Being more compatible with IMO's Data Collection System (DCS) on ship fuels, AER is currently the IMO designated metric on how to compute CII, however there are voices advocating the use of EEOI. All of these indices are associated with the only (thus far) IMO mandated measures to reduce CO<sub>2</sub> emissions from shipping, and they can have significant implications on both ship design and operation. Even though the intent behind all these indices is to incentivize more energy efficient propulsion systems, optimized hulls and other technologies and alternative fuels that would reduce CO<sub>2</sub> emissions, it is no secret that speed reduction is a central tool to achieving compliance in all of these indices, and perhaps the easiest to implement solution. Thus, from a design perspective, installing a smaller engine to achieve EEDI compliance will inevitably lead to a lower design speed and to lower operational speeds. Implementing Engine Power Limitation (EPL) to achieve EEXI compliance will also lead to lower speeds. From an operational perspective, achieving and maintaining a good CII rating would very likely involve the ship sailing slower.

In addition, the possible implementation of Market Based Measures (MBMs) by the IMO and the impending inclusion of shipping into the EU ETS (Emissions Trading System of the European Union) may also have implications on the operational speed of ships in the short to medium term. See [Psaraftis \(2019\)](#), [Lagouvardou et al. \(2022\)](#) and [Lagouvardou and Psaraftis \(2022\)](#) for some related studies.

However, it is fair to say that finding the best way that speed reduction can be used so that it becomes an efficient and effective "bridge" until low carbon fuels can be widely used is still open and subject to discussion. For instance, it is not clear if and to what extent being EEDI or EEXI compliant would reduce the absolute level of CO<sub>2</sub> emissions, and the same can be said for ships attempting to reduce their CII and maintain a good CII rating. In fact, and as [Wang et al. \(2021\)](#) have shown, one could manipulate CII to achieve compliance, but increase CO<sub>2</sub> in the process.

An example that shows the possible role of speed in reducing GHG emissions is the following (see also [Gkonis and Psaraftis \(2012\)](#) and [Lagouvardou et al \(2022\)](#)). An analysis of ship speeds conducted for the tanker market indicated that if laden leg ship speeds are not constrained by charter party speed clauses, lower laden ship speeds are possible, leading to lower GHG emissions. In such lower GHG emissions scenarios, the laden speed is typically lower than the ballast speed, whereas if laden speeds are constrained by charter party clauses, the laden speed is higher than the ballast speed and GHG emissions are higher. A charter party agreement specifying a prescribed speed, explicitly or implicitly, might entail significant costs, both in terms of additional fuel (which is a private cost matter) and in terms of additional emissions, GHG and other (which is a cost to society). A similar situation can be manifested in the drybulk market or even in the liner market, where commercial considerations may dictate different speeds in the two directions of a route (see [Psaraftis \(2019\)](#) for an example).

It is obvious that more GHG emissions will be produced if the ship sails faster in the leg in which the ship is more laden than in the less-

laden leg. However, if speed is to be reduced somewhere, this should rather be done in the laden leg than in the ballast or less-laden leg. *This is exactly the opposite of current practice*: ballast or less-laden legs are where slow steaming is predominantly manifested. Higher speeds are typically seen whenever the ship is closer to full and lower speeds are encountered whenever load factors are low. Commercial factors are the main reason for such a situation. Higher load factors induce higher speeds.

What kind of regulatory action to prevent the above from happening can be taken? Prescriptive measures, for instance an outright ban of charter party speed clauses or a speed limit that is a decreasing function of the ship's load factor, would be very difficult to be agreed upon let alone be verifiable for compliance. Thus far, the only IMO action that we think may be relevant here is the recently adopted combined EEXI/SEEMP/CII short-term measure, which is a goal-based measure (SEEMP stands for Ship Energy Efficiency Management Plan). Compliance with EEXI via EPL (see above) will have a much larger speed reduction effect in the laden, rather than in the ballast condition. Also, compliance with CII would likely induce owners or charterers to sail slower in the laden condition than in ballast. However, how exactly all this will play out in the years ahead remains to be seen.

Last but not least, a substantial levy on fuel or a carbon levy would penalize laden legs and higher speeds much more than ballast legs or lower speeds and could be a solution. However, and in spite of the support of such a measure by various IMO delegations, the road before its eventual adoption at the IMO is foreseen to be a difficult one.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

## Acknowledgments

This paper is the outcome of unfunded research collaboration between the authors. They wish to thank two anonymous reviewers, as well as Harry Bingham, Jack Devanney, Jasmine Lam, and Panos Zachariadis for their comments on earlier versions of the paper. All of these comments helped improve the paper.

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