Seatific, Vol. 4, Issue. 2, pp. 48–56, December 2024

Seatific Journal
https://seatific.yildiz.edu.tr
DOI: https://doi.org/10.14744/seatific.2024.0008

Seatific

Research Article

Correlation of the ship speed and carbon dioxide emissions: A study on a Panamax tanker

Levent BİLGİLİ[1*], Volkan ŞAHİN[2]

[1]*Department of Naval Architecture and Marine Engineering, Bandırma Onyedi Eylül University Faculty of Maritime, Balıkesir, Türkiye*
[2]*Department of Marine Engineering, Van Yüzüncü Yıl University Faculty of Maritime, Van, Türkiye*

ARTICLE INFO

Article history
Received: October 07, 2024
Revised: November 15, 2024
Accepted: December 02, 2024

Key words:
Fuel consumption; ship emissions; ship speed; regression analysis

ABSTRACT

The amount of energy needed by the maritime industry is increasing depending on the global energy demand and the increase in commercial activities. Larger ships are expected to create greater challenges in the energy demand and environmental performance issues. Therefore, estimating fuel consumption and emissions are important preliminary steps to avoid these problems. In this study, the relationship between speed and CO_2 emissions is reduced to a single equation. It aims to reach fuel consumption and emission amounts by using only speed input. Since emission calculations are mainly based on fuel consumption data, specific fuel oil consumption methodology is utilized and regression analysis is used to reach a single-variable equation. The equation is calculated with a high accurance (R^2 0.9941). Since the speed input includes RPM, weather and sea conditions, cargo quantity and wave course data, the effects of these data on fuel consumption have been obtained indirectly. In this way, fuel consumption and emissions can be predicted depending on the speed through a simple equation, and the solutions on measurements and route optimization would be much easier.

Cite this article as: Bilgili L, Şahin V. Correlation of the ship speed and carbon dioxide emissions: A study on a Panamax tanker. Seatific 2024;4:2:48–56.

1. INTRODUCTION

Energy efficiency and fuel consumption in ships are considered to be crucial issues in the 21st century, due to the environmental awareness has increased with a growing momentum. Increasing population and developing trade lead the world to bigger ships and larger commercial fleets, forming a bigger energy demand. Thus, it is obvious that fuel consumption and consequently ship emissions would be a bigger problem day by day.

According to the International Energy Agency (IEA) report, when world energy consumption amounts are examined, 122 EJ of energy was spent in the transport sector in 2023 and 11 EJ of this energy was used by the shipping sector. This corresponds to approximately 9% of the energy spent in the transport sector. It is predicted that a total of 132 EJ of energy will be spent in the transport sector in 2030 and 12 EJ of this will be used by the shipping sector. When the world CO_2 emission amounts are examined, it is seen that the total CO_2 emission amount in 2023 is 37723 Mt CO_2. While 8213 Mt CO_2 of this emission amount belongs to the transport sector, 856 Mt CO_2 belongs to the shipping sector. The total CO_2 emission amount in 2030 is estimated to be 36170 Mt CO_2. It is estimated that 8537 Mt of this amount will belong to the transport sector and 900 Mt of CO_2 will belong to the shipping sector (IEA, 2024). On the other hand, even in the most optimistic scenario, fuel demand in the maritime sector is projected to increase by 43.5% in 2050 compared to 2002 (Eyring et al., 2005).

***Corresponding author.**
*E-mail address: lbilgili@bandirma.edu.tr

Published by Yıldız Technical University Press, İstanbul, Türkiye

Ship-related emissions emerge as a separate and important environmental problem. Although ships emit a large number and variety of emissions (Kollamthodi et al., 2008) only a few of them are worth examining in terms of environmental damage and quantity. According to the latest report of the International Maritime Organization (IMO), shipping activities are responsible for 2.4%, 13-15% and 12-13% of global carbon dioxide equivalent (CO_{2e}), sulphur oxide (SO_x) and nitrogen oxide (NO_x) production, respectively (Smith et al., 2014). IMO's recent study has shown that greenhouse gas emissions from the shipping sector increased from 977 million tonnes in 2012 to 1,076 million tonnes in 2018, an increase of 9.6% (IMO, 2020a). In addition, it has been determined that 70% of ship emissions occur at 400 km and closer to the shore (Eyring et al., 2010).

Efforts to estimate emissions and increase energy efficiency are essential to guarantee a greener future. For this purpose, in addition to many local, national and regional studies, many international rules and regulations have been developed under the leadership of the IMO. Under the International Convention for the Prevention of Pollution from Ships (MARPOL), IMO has prepared several annexes for the monitoring, reduction and control of various ship-related pollutants. Annex VI is the supplement where ship air pollutants are evaluated and it includes the assessments on ozone-depleting substances (ODSs), particulate matter (PM), and volatile organic compounds (VOCs). Annex VI came into force on 9 May 2005 and is being developed with various updates annually.

Restrictions imposed by the IMO for NO_x and SO_x are presented in Table 1 and Table 2.

Table 1 presents the minimum requirements for ships to meet NOx criteria. Ship main engines must be manufactured according to Tier II standards in the current situation. Ships cruising in the North American and United States Caribbean Sea Areas must be subject to Tier III restrictions. Table 2 presents the SO_x constraints. Accordingly, under the current situation, the fuel used by a ship cruising in global waters may contain up to 0.5% sulphur by mass. If a ship cruises in an Emission Control Area (ECA) (Baltic Sea, North Sea, North American and United States Caribbean Sea Areas), the ratio is set at 0.1%.

In a recent study on the question of whether Annex VI does not include ship-related CO_2 emissions, it is stated that especially developed countries accept CO2 as a greenhouse gas (GHGs) rather than a polluting agent. In addition, there is a concern that possible additions for CO_2 reduction may lead to "tremendous domestic legal obstacles". Therefore, it was concluded that Annex VI should be left as it is and if necessary, a unique regulation should be prepared for CO_2 (Shi, 2016).

The deleterious impacts of ship-related emissions on human health and the environment are well-studied (Corbett et al., 2007; Eyring et al., 2010; Kollamthodi et al., 2008; Moldanová et al., 2009) and detailed inventories of these emissions on a regional and global scale were calculated (Alver et al., 2018; Jalkanen et al., 2016; Johansson et al., 2017). It is clear that emissions from ships have a wide variety of harmful impacts to human health and the environment. Considering the development of the global economy, trade volume and the maritime industry, it is obvious that ship-related emissions and the energy demand of the maritime sector will pose even more serious problems shortly.

The majority of these studies focused on emission estimates based on fuel consumption or engine power. Some of them calculate the emission by estimating the possible fuel consumption considering the dynamic sea conditions. It is crucial to calculate the emissions at an early stage, especially in terms of compliance with the IMO criteria. Another important issue is to calculate the fuel consumption (energy demand) and emission amounts empirically. For this purpose, various studies have been carried out to find the correlation between speed, which is the most important output of dynamic marine conditions, and fuel

Table 1. The limits for NO_x (IMO, 2015a)

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n=Engine's rated speed (RPM)		
		n<130	**n=130–1999**	**n≥2000**
Tier I	1 January 2000	17.0	$45\times n^{-0.2}$	9.8
Tier II	1 January 2011	14.4	$44\times n^{-0.2}$	7.7
Tier III (ECA)	1 January 2016	3.4	$9\times n^{-0.2}$	2.0

IMO: International Maritime Organization; RPM: Revolutions per minute; ECA: Emission Control Area

Table 2. The limits for SO_x (IMO, 2015b)

Outside an emission control area	Inside an emission control area
4.50% prior to 1 January 2012	1.50% prior to 1 July 2010
3.50% on and after 1 January 2012	1.00% on and after 1 July 2010
0.50% on and after 1 January 2020	0.10% on and after 1 January 2015

IMO: International Maritime Organization consumption/emission. In addition, there are also studies for fuel consumption and emission calculations depending on the dynamic operating conditions.

(Beşikçi et al., 2016) developed a fuel consumption methodology based on ship speed, revolutions per minute (RPM), mean draft, trim, cargo quantity, wind and sea effects data by using the noon reports. The authors used the artificial neural networks method for this purpose. (Bialystocki & Konovessis, 2016) developed a fuel consumption prediction algorithm based on current fuel consumption, draft, weather and surface roughness data. The main point emphasized in this study is the effect of weather conditions on fuel consumption. Utilizing the Least Absolute Shrinkage and Selection Operator (LASSO) regression algorithm, (Shengzheng Wang et al., 2018) developed a fuel consumption prediction methodology based on historical fuel consumption, length overall, beam, speed, trim angle, air and sea conditions and swell height data. (Gkerekos et al., 2019) They studied on estimating fuel consumption by using distance, draft, RPM, daily fuel consumption, ship speed, propeller angle, sea current, wave direction, sea and weather conditions and wind direction data in different machine learning methods. (Kee et al., 2018) developed a fuel consumption prediction formula based on distance, working hours and deadweight data by utilizing multiple linear regression methods. Although they are not included in the formula, ship speed and wind speed are among the inputs used. (Graf von Westarp, 2020) investigated the correlation between fuel consumption and speed for a container ship. As a result, depending on the e-function, a direct equation between speed and fuel consumption was found to be valid in container ships. (Ayudhia P. Gusti & Semin, 2016) examined the correlation between speed and fuel consumption and emission values for a container ship cruising between two ports in Indonesia. (Ayudhia Pangestu Gusti & Semin, 2018) also compiled studies on the correlations between ship speed and emission.

However, none of these studies found a direct correlation between ship speed and fuel consumption for tankers. An equation, which depends on the ship's speed and without any additional calculation or data, would allow the calculation of fuel consumption and emission amount even when the ship is not cruising. In addition, the simpler the fuel consumption and emission estimation can be achieved, the more useful it will be.

In this study, a correlation was developed between the daily speeds and CO_2 emissions. For this purpose, the average daily engine load of the ship was calculated based on the speed, and then the specific fuel oil consumption (SFOC) in this engine load was determined and the amount of fuel expected to be spent was reached. Emission calculations were realized depending on the amount of fuel consumed. Since the dynamic external conditions (RPM, weather and sea conditions, cargo amount, wave course) to which the ship is exposed directly affect the speed, no further calculations were realized, assuming that these conditions are included in the calculation over speed. Although it is a well-known fact that speed is a decisive dependant for emissions, to the best knowledge of the authors, there is no direct link between these two variables. The novelty of this study is to provide a quick equation to measure the relationship of speed and emission.

This study used data from a Panamax tanker. Panamax tankers have maximum dimensions determined by the Panama Canal Authority due to the size of the canal they pass through. These tankers have dimensions of approximately 275 meters (950 feet) in length, 31 meters (106 feet) in width and 11 meters (39.5 feet) in depth (Autoridad del Canal de Panamá, 2022).

2. MATERIALS AND METHODS

Regression analysis is used in many subjects in the maritime industry. (Lepore et al., 2017) used variable selection methods, penalized regression methods, latent variable methods and tree-based ensemble methods regression techniques to analyze the data collected from the shipping industry scenario and C02 emission estimation in their study. (Öztürk & Başar, 2022) used MLRA (multiple linear regression analysis) method in their studies, and estimated ship fuel consumption with RPM, trim, mean draft, weather condition data. (Uyanık et al., 2020) estimated the fuel consumption of a container ship with data such as main engine rpm, main engine cylinder values, scavenge air, shaft indicators using Multiple Linear Regression, Ridge and LASSO Regression, Support Vector Regression, Tree-Based Algorithms, Boosting Algorithms methods. (Cepowski & Drozd, 2023) used data such as rotational speed, draught, trim, hull fouling time, wind speed, wave height, and seawater temperature of a container ship and examined the hierarchical effects of these parameters on fuel consumption using artificial neural networks and multiple nonlinear regression methods. In this study, Microsoft Excel was used to perform regression analysis.

Design speed of the Panamax tanker used in this study is 14 knots and the base SFOC value is 169 g/kWh. These values are obtained from the booklets published by the ship's main engine manufacturer.

Daily speed values for each day were obtained from the logs and the average daily engine load was calculated first. For this purpose, the following equation, which is called as Propeller Law and presented in was utilized:

$$P_2 = P_1 \left(\frac{V_{transient}}{V_{design}}\right)^{\propto} \quad (1)$$

$$LF = \frac{P_2}{P_1} \quad (2)$$

where;

P_2 : Coefficient

P_1 : Engine power (kW)

$V_{transient}$: Daily speed (knots)

V_{design} : Design speed (knots)

α : Constant (Assumed as 2.7)

LF : Engine load (%)

Table 3. Sample set

No	Speed (knots)	P2	LF (%)	$SFOC_{relative}$	SFOC (g/kWh)	Fuel consumption (t)	CO_2 (t)
1	13.7	11224	0.943	1.015	171.6	49.0	152.6
2	13.2	10152	0.853	1.005	169.9	48.5	151.1
3	13.2	10152	0.853	1.005	169.9	48.5	151.1
4	13.0	9742	0.819	1.010	170.7	48.8	155.3
5	13.5	10787	0.906	1.004	169.6	48.4	151.8
…	…	…	…	…	…	…	…

P2: Coefficient; LF: Engine load; SFOC: Specific fuel oil

SFOC values were calculated in accordance with these engine loads after engine loads, which were calculated depending on daily speed. For this, the equation, which is presented below, obtained from the study below (Moreno-Gutiérrez et al., 2015) was utilized:

$$SFOC_{relative}=0.455LF^2-0.71LF+1.28 \quad (3)$$

where;

$SFOC_{relative}$: Relative engine load

LF : Engine load (%)

After that, SFOC value is calculated based on the related engine load with the help of the following equation. The $SFOC_{base}$ value is given by the main engine manufacturer and has been measured as 169 g/kWh for the ships used in this study.

$$SFOC = SFOC_{relative} \times SFOC_{base} \quad (4)$$

Thus, firstly, the engine load depending on the average speed value of that day and then the SFOC value of the ship can be calculated depending on the variable engine load. Then, the total fuel consumption can be calculated.

After calculating the fuel consumption, emission estimates can be estimated. In this study, only CO_2 emissions were evaluated. Emission estimations can be calculated via the following equation (Trozzi, 2010):

$$E_{Trip}=FC\times EF \quad (5)$$

where;

E_{Trip} : Estimated emission amount (t)

FC : Fuel consumption (t)

EF : Emission factor (t/t fuel)

The emission factor for CO_2, which is 3114 g/kg fuel for LSHFO, was taken from (IMO, 2020a).

Thus, based on the fuel consumption data obtained with the help of the equations presented above, the estimation of mentioned emissions can also be realized. These fuel consumption and emission data were processed with the help of regression analysis and formulas were developed to calculate the fuel consumption and emission amounts depending on the speed variable.

Regression analysis is to explain the relationship between two variables with the help of a mathematical formula. For this purpose, first, a dependent variable symbolized by y and an independent variable symbolized by x is determined (Rawlings et al., 1998). The mathematical expression of regression analysis is given by (Ye et al., 2017) as follows:

$$y=\beta_0+\beta_1 x+\beta_2 x^2+\beta_3 x^3+e \quad (6)$$

where;

β_0 : Constant

β_1, β_2, β_3 : Linear, quadratic and cubic coefficients

e : Error

The main purpose of such equations established in the regression analysis is to explain one variable through other variables. Regression analysis is a method developed to find the correlation or relationship between dependent or independent variables by finding the coefficients expressed by β (Bilgili, 2018).

3. RESULTS AND DISCUSSION

3.1. Results

A sample set of data and results used in the study is presented in Table 3. In Table 3, only CO_2 is given as an example of emission to save space and other emissions may also be examined within the scope of the study. The sample set consists of 3080 rows. Only the operational phase is included, thus, manoeuvres, canal transits, and other operational conditions such as berthing or anchoring are excluded, which can be considered a limitation of the study. No split of data was applied as train and test. The minimum and maximum values of the dataset are 153 and 195.9, respectively. Median and mean values are presented as 154.8 and 156.6. The values for 1st and 3rd Quartiles are 154.04 and 156.86, respectively.

The data presented in Table 3 is just a sample and the data of an entire voyage was processed. Figure 1 and Figure 2 show the graphs obtained for fuel consumption and CO_2 emissions, respectively.

Figure 1 and Figure 2 have a slope that is compatible with the SFOC graphics presented by the ship's main engine manufacturer. Accordingly, as speed decreases, fuel consumption and emissions decrease to a certain level. However, although the speed continues to decrease after a certain level, an increase in fuel consumption and emissions

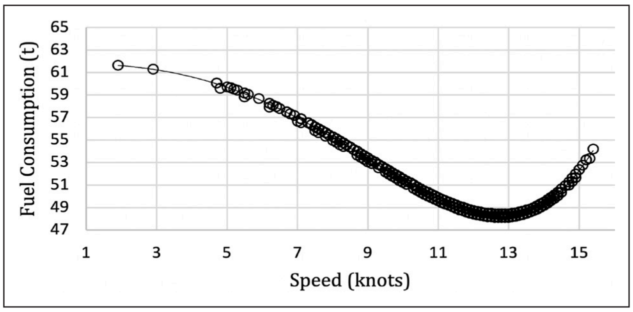

Figure 1. Speed-fuel consumption relationship.

is observed. The reason for this is the engine load-SFOC relationship, as the main engine manufacturer presents. The figures clearly show that the relationship between speed and fuel consumption does not change exponentially or linearly. This relationship has a unique graph type.

In Table 4, the formulas obtained through the regression analysis are presented.

In Table 4, while y value means the dependent variable, the value of x means speed. The R^2 value (not adjusted) of all equations was obtained as 0.9941, which is a very close value to 1. Considering that $R^2=1$ is the perfect condition, it is seen that the obtained equations express the relationship between speed-fuel consumption/emission quite successfully.

When the speed is replaced with the x value in the equations, results of how much fuel a Panamax tanker will consume at the current speed can be obtained. Besides, the other equation will present the CO_2 emissions produced.

4. DISCUSSION

(Graf von Westarp, 2020) carried out a study on the data of 3 ships, searching for a general speed-fuel consumption formula based on dynamic variable conditions. According to the results of the study, the relationship between speed and fuel consumption was found exponential. Accordingly, the results of the study conducted by the current study and the results of (Graf von Westarp, 2020) are partially compatible. The graphics obtained in the current study (Fisg. 1, 2) are almost exactly compatible with the SFOC curves presented by the ship's main engine manufacturer. The data from the main engine manufacturer shows that SFOC values are decreasing rapidly to a certain level, but then the acceleration reverses and fuel consumption starts to increase although the speed continues to decrease. For this reason, the results obtained in the current study do not change in any way either exponentially or linearly, but as a peculiar graphic. (Moreira et al., 2021) showed that it is possible to predict the ship speed and fuel consumption using only sea conditions data without using variables

Figure 2. Speed-CO_2 relationship.

such as RPM and torque using an artificial neural network. (Pelić et al., 2023) investigated the effects of slow steam on fuel consumption and CO_2 emissions in their study. They calculated the reduction in fuel consumption between 72.36% and 76.25% at a speed of 12 knots. When compared to a speed of 23 knots, CO_2 emissions were found to be four times less. (Taskar et al., 2023) calculated fuel savings using the speed optimization algorithm for two case ships in different seasons at three different ship speeds. It was observed in the study that fuel savings of up to 6% could be achieved. It was stated that combining slow steaming with speed optimization would support higher fuel savings and emission reductions.

In addition, various studies have been carried out to realize cost estimations, which is the second important issue affected by fuel consumption. These studies generally focus on estimating to perform realistic cost calculations by considering the relationship between speed and fuel consumption. (Notteboom, 2006) assumed that fuel consumption increased with the increase in speed. This increase is exponential and more consistent with the results of (Graf von Westarp, 2020). (Ronen, 1982) conducted a study on the effect of fuel prices on the optimum speed of the ship and examined the effects of optimum speed on fuel cost instead of developing a speed-fuel consumption formula. Similarly, (Corbett et al., 2009; Psaraftis & Kontovas, 2010; Ronen, 2011) studies have also focused on fuel costs and route optimization, mostly through the relationship between speed optimization and fuel consumption.

5. CONCLUSION

Increasing commercial activities and energy demand are accelerating a process that results in the growth of the number and size of ships. Energy demand for ships means more need for fuel. Depending on this energy demand, ship emissions, which are already known to be a major problem, are expected to increase shortly if adequate measures are not taken. Therefore, estimating fuel consumption and emissions and determining whether these values comply with international restrictions have gained great importance.

Table 4. Speed-dependent fuel consumption and emission formulas

Variable dependent	Equation	R^2
Fuel consumption	$y = 7E\text{-}05x^5 - 0.0005x^4 - 0.0078x^3 - 0.0491x^2 + 0.0338x + 61.803$	0.9941
CO_2	$y = 0.0002x^5 - 0.0015x^4 - 0.0247x^3 - 0.1559x^2 + 0.1074x + 196.47$	

In addition, estimating the fuel consumption as simply as possible depending on the dynamic conditions will provide important preliminary data to the relevant subjects such as route and speed optimization by providing accurate and realistic calculations of the fuel costs during the operation. In particular, the relationship between speed and fuel consumption has been studied in several studies, and despite some important progress, it has not been possible to develop a direct and effective correlation. The emission estimation is based on a well-known and frequently applied method, which includes SFOC calculations and utilization of emission factors. The reason for using regression analysis method is to reach a single-variable equation to estimate the target values.

This study aims to calculate fuel consumption on a single variable (speed) that is indirectly linked to other variables (RPM, air and sea conditions, cargo amount, wave course). In addition, emissions from fuel consumption can also be achieved depending on speed (Table 4). The evaluation criteria for the success of this study is to reach a reliable equation to estimate the speed-emission relationship. The equation has a R^2 value as 0.9941, which means the expected success is met. Employing this equation, when the estimated speed of the ship is determined, average fuel consumption and emissions can be calculated. In this way, the speed-fuel consumption relationship, which has not been answered clearly for a long time, has become evident and simple equations, which are ready for use, have been developed. The results are also compatible with the engine load-SFOC curves given by the ship's main engine manufacturer.

DATA AVAILABILITY STATEMENT

The published publication includes all graphics and data collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

USE OF AI FOR WRITING ASSISTANCE

No AI technologies utilized.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

REFERENCES

Agrawal, H., Malloy, Q. G. J., Welch, W. A., Wayne Miller, J., & Cocker, D. R. (2008). In-use gaseous and particulate matter emissions from a modern ocean going container vessel. *Atmospheric Environment, 42*(21), 5504–5510. [CrossRef]

Alver, F., Saraç, B. A., & Alver Şahin, Ü. (2018). Estimating of shipping emissions in the Samsun Port from 2010 to 2015. *Atmospheric Pollution Research, 9*(5), 822–828.

Autoridad del Canal de Panamá. (2022). Vessel Requirements. In *OP Notice to Shipping No. N-1-2022* (Vol. 1, Issue 1).

Beşikçi, E. B., Kececi, T., Arslan, O., & Turan, O. (2016). An application of fuzzy-AHP to ship operational energy efficiency measures. *Ocean Engineering, 121*, 392–402. [CrossRef]

Bialystocki, N., & Konovessis, D. (2016). On the estimation of ship's fuel consumption and speed curve: A statistical approach. *Journal of Ocean Engineering and Science, 1*(2), 157–166. [CrossRef]

Bilgili, L. (2018). *Estimation of operation gaseous emissions in ship life cycle with machine learning method* [Doctorial Thesis]. Yildiz Technical University.

Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J. H., & Klimont, Z. (2004). A technology-based global inventory of black and organic carbon emissions from combustion. *Journal of Geophysical Research: Atmospheres, 109*(14), 1–43. [CrossRef]

Burgard, D. A., & Bria, C. R. M. (2016). Bridge-based sensing of NOx and SO2 emissions from ocean-going ships. *Atmospheric Environment, 136*, 54–60. [CrossRef]

Capaldo, K., Corbett, J. J., Kasibhatla, P., Fischbeck, P., & Pandis, S. N. (1999). Effects of ship emission on sulphur cycling and radiative climate forcing over the ocean. *Nature, 400*, 743–746. [CrossRef]

Cepowski, T., & Drozd, A. (2023). Measurement-based relationships between container ship operating parameters and fuel consumption. *Applied Energy, 347*, Article 121315. [CrossRef]

Cooper, D. A. (2003). Exhaust emissions from ships at berth. Atmospheric Environment, 37(27), 3817–3830. Cooper, D. A., & Andreasson, K. (1999). Predictive NO(x) emission monitoring on board a passenger ferry. *Atmospheric Environment, 33*(28), 4637–4650. [CrossRef]

Corbett, J. J., & Koehler, H. W. (2004). Considering alternative input parameters in an activity-based ship fuel consumption and emissions model: Reply to comment by Øyvind Endresen et al. on "Updated emissions from ocean shipping". *Journal of Geophysical Research D: Atmospheres, 109*(23), 1–8. [CrossRef]

Corbett, J. J., Wang, H., & Winebrake, J. J. (2009). The effectiveness and costs of speed reductions on emissions from international shipping. Transportation Research Part D: *Transport and Environment, 14*(8), 593–598. [CrossRef]

Corbett, J. J., Winebrake, J. J., Green, E. H., Kasibhatla, P., Eyring, V., & Lauer, A. (2007). Mortality from ship emissions: A global assessment. *Environmental Science and Technology, 41*(24), 8512–8518. [CrossRef]

De Meyer, P., Maes, F., & Volckaert, A. (2008). Emissions from international shipping in the Belgian part of the North Sea and the Belgian seaports. *Atmospheric Environment, 42*(1), 196–206. [CrossRef]

De Ruyter De Wildt, M., Eskes, H., & Boersma, K. F. (2012). The global economic cycle and satellite-derived NO2 trends over shipping lanes. *Geophysical Research Letters, 39*(1), 2–7. Deniz, C., & Durmuşoğlu, Y. (2008). Estimating shipping emissions in the region of the Sea of Marmara, Turkey. *Science of the Total Environment, 390*(1), 255–261. [CrossRef]

Doney, S. C., Fabry, V. J., Feely, R. A., & Kleypas, J. A. (2009). Ocean acidification: The other CO2 problem. *Annual Review of Marine Science, 1*(1), 169–192. [CrossRef]

Eyring, V., Isaksen, I. S. A., Berntsen, T., Collins, W. J., Corbett, J. J., Endresen, O., Grainger, R. G., Moldanova, J., Schlager, H., & Stevenson, D. S. (2010). Transport impacts on atmosphere and climate: Shipping. *Atmospheric Environment, 44*(37), 4735–4771. [CrossRef]

Eyring, V., Köhler, H. W., Lauer, A., & Lemper, B. (2005). Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. *Journal of Geophysical Research D: Atmospheres, 110*(17), 183–200. [CrossRef]

Gkerekos, C., Lazakis, I., & Theotokatos, G. (2019). Machine learning models for predicting ship main engine Fuel Oil Consumption: A comparative study. *Ocean Engineering, 188*, Article 106282. [CrossRef]

Graf von Westarp, A. (2020). A new model for the calculation of the bunker fuel speed–consumption relation. *Ocean Engineering, 204*, Article 107262. [CrossRef]

Gusti, Ayudhia P., & Semin. (2016). The effect of vessel speed on fuel consumption and exhaust gas emissions. *American Journal of Engineering and Applied Sciences, 9*(4), 1046–1053. [CrossRef]

Gusti, Ayudhia Pangestu, & Semin. (2018). Effect of ship speed on ship emissions. *Asian Journal of Scientific Research, 11*(3), 428–433. [CrossRef]

Henningsen, R., Skjolsvik, K., Andersen, A., Corbett, J., & Skjelvik, J. (2000). *Study of Greenhouse Gas Emissions from Ships Final Report to the International Maritime Organization*. International Maritime Organization

IEA. (2024). *World Energy Outlook*. IEA.

IMO. (2020a). Fourth IMO Greenhouse Gas Study: Executive Summary. In *IMO Greenhouse Gas Study*. IMO.

IMO. (2015b). *Nitrogen Oxides (NOx) – Regulation 13*. https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx Accessed on Dec 11, 2024.

IMO. (2015c). *IMO Sulphur Regulation*. https://www.imo.org/en/OurWork/Environment/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx Accessed on Dec 11, 2024

Isakson, J., Persson, T. A., & Selin Lindgren, E. (2001). Identification and assessment of ship emissions and their effects in the harbour of Göteborg, Sweden. *Atmospheric Environment, 35*(21), 3659–3666. [CrossRef]

Jalkanen, J. P., Johansson, L., & Kukkonen, J. (2016). A comprehensive inventory of ship traffic exhaust emissions in the European sea areas in 2011. *Atmospheric Chemistry and Physics, 16*(1), 71–84. [CrossRef]

Johansson, L., Jalkanen, J. P., & Kukkonen, J. (2017). Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution. *Atmospheric Environment, 167*, 403–415. [CrossRef]

Kågeson, P. (1999). Economic instruments for reducing emissions from sea transport. In *Air Pollution and Climate Series* (Vol. 11), European Federation for Transport and Environment.

Kee, K.-K., Lau Simon, B.-Y., & Yong Renco, K.-H. (2018). Prediction of Ship Fuel Consumption and Speed Curve by Using Statistical Method. *Journal of Computer Science & Computational Mathematics, 8*(2), 19–24. [CrossRef]

Kesgin, U., & Vardar, N. (2001). A study on exhaust gas emissions from ships in Turkish Straits. *Atmospheric Environment, 35*(10), 1863–1870. [CrossRef]

Kollamthodi, S., Brannigan, C., Harfoot, M., Skinner, I., Whall, C., Lavric, L., Noden, R., Lee, D., Buhaug, Ø., Martinussen, K., Skejic, R., Valberg, I., Brembo, J. C., Eyring, V., & Faber, J. (2008). Greenhouse gas emissions from shipping: Trends, projections and abatement potential: Final report to the Committee on Climate Change (CCC). In *AEA Technology* (Issue 4).

Lang, J., Zhou, Y., Chen, D., Xing, X., Wei, L., Wang, X., Zhao, N., Zhang, Y., Guo, X., Han, L., & Cheng, S. (2017). Investigating the contribution of shipping emissions to atmospheric PM2.5 using a combined source apportionment approach. *Environmental Pollution, 229*, 557–566. [CrossRef]

Lepore, A., dos Reis, M. S., Palumbo, B., Rendall, R., & Capezza, C. (2017). A comparison of advanced regression techniques for predicting ship CO2 emissions. *Quality and Reliability Engineering International, 33*(6), 1281–1292. [CrossRef]

Matthias, V., Bewersdorff, I., Aulinger, A., & Quante, M. (2010). The contribution of ship emissions to air pollution in the North Sea regions. *Environmental Pollution, 158*(6), 2241–2250. [CrossRef]

Millero, F. J. (1995). Thermodynamics of the carbon dioxide system in the oceans. *Geochimica et Cosmochimica Acta, 59*(4), 661–677. [CrossRef]

Moldanová, J., Fridell, E., Popovicheva, O., Demirdjian, B., Tishkova, V., Faccinetto, A., & Focsa, C. (2009). Characterisation of particulate matter and gaseous emissions from a large ship diesel engine. *Atmospheric Environment, 43*(16), 2632–2641. [CrossRef]

Moreira, L., Vettor, R., & Soares, C. G. (2021). Neural network approach for predicting ship speed and fuel consumption. *Journal of Marine Science and Engineering, 9*(2), 1–14. [CrossRef]

Moreno-Gutiérrez, J., Calderay, F., Saborido, N., Boile, M., Rodríguez Valero, R., & Durán-Grados, V. (2015). Methodologies for estimating shipping emissions and energy consumption: A comparative analysis of current methods. *Energy, 86*, 603–616. [CrossRef]

Notteboom, T. E. (2006). The Time factor in liner shipping services. *Maritime Economics and Logistics, 8*(1), 19–39. [CrossRef]

Öztürk, O. B., & Başar, E. (2022). Multiple linear regression analysis and artificial neural networks based decision support system for energy efficiency in shipping. *Ocean Engineering, 243*, Article 110209. [CrossRef]

Park, R. J., Jacob, D. J., Chin, M., & Martin, R. V. (2003). Sources of carbonaceous aerosols over the United States and implications for natural visibility. *Journal of Geophysical Research Atmospheres, 108*(12), Article 4355. [CrossRef]

Pelić, V., Bukovac, O., Radonja, R., & Degiuli, N. (2023). The impact of slow steaming on fuel consumption and CO2 emissions of a container ship. *Journal of Marine Science and Engineering, 11*(3), Article 675.

Psaraftis, H. N., & Kontovas, C. A. (2010). Balancing the economic and environmental performance of maritime transportation. *Transportation Research Part D: Transport and Environment, 15*(8), 458–462. [CrossRef]

Quinn, P. K., Bates, T. S., Baum, E., Doubleday, N., Fiore, A. M., Flanner, M., Fridlind, A., Garrett, T. J., Koch, D., Menon, S., Shindell, D., Stohl, A., & Warren, S. G. (2008). Short-lived pollutants in the Arctic: Their climate impact and possible mitigation strategies. *Atmospheric Chemistry and Physics, 8*(6), 1723–1735. [CrossRef]

Raven, J., Caldeira, K., Elderfield, H., Hoegh-Guldberg, O., Liss, P., Riebesell, U., Shepherd, J., Turley, C., & Watson, A. (2005). *Ocean acidification due to increasing atmospheric carbon dioxide*. The Royal Society.

Rawlings, J. O., Pantula, S. G., & Dickey, D. A. (1998). Applied Regression Analysis: A Research Tool. In G. Casella, S. Fienberg, & I. Olkin (Eds.), *The American Statistician* (2nd ed.). Springer-Verlag. [CrossRef]

Richter, A., Eyring, V., Burrows, J. P., Bovensmann, H., Lauer, A., Sierk, B., & Crutzen, P. J. (2004). Satellite measurements of NO2 from international shipping emissions. *Geophysical Research Letters, 31*(23), 1–4. [CrossRef]

Ronen, D. (1982). The effect of oil price on the optimal speed of ships. *The Journal of Operational Research Society, 33*(11), 1035–1040. [CrossRef]

Ronen, D. (2011). The effect of oil price on containership speed and fleet size. *Journal of the Operational Research Society, 62*(1), 211–216. [CrossRef]

Saxe, H., & Larsen, T. (2004). Air pollution from ships in three Danish ports. *Atmospheric Environment, 38*(24), 4057–4067. [CrossRef]

Schrooten, L., De Vlieger, I., Int Panis, L., Styns, K., & Torfs, R. (2008). Inventory and forecasting of maritime emissions in the Belgian sea territory, an activity-based emission model. *Atmospheric Environment, 42*(4), 667–676. [CrossRef]

Schrooten, L., De Vlieger, I., Panis, L. I., Chiffi, C., & Pastori, E. (2009). Emissions of maritime transport: A European reference system. *Science of the Total Environment, 408*(2), 318–323. [CrossRef]

Shi, Y. (2016). Are greenhouse gas emissions from international shipping a type of marine pollution? *Marine Pollution Bulletin, 113*(1–2), 187–192. Smith, K. R. (2000). National burden of disease in India from indoor air pollution. *Proceedings of the National Academy of Sciences of the United States of America, 97*(24), 13286–13293. [CrossRef]

Smith, T. W. P., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S., O'Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D. S., Ng, S., Agrawal, A., Winebrake, J. J., Hoen, M, … & Pandey, A. (2014). *Third IMO GHG Study 2014*. International Maritime Organization (IMO).

Smith, T. W. P., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S., O'Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D. S., Ng, S., Agrawal, A., Winebrake, J. J., & Hoen, M., A. (2014). *Third IMO Greenhouse Gas Study*. In International Maritime Organization (IMO).

Solomon, S., D., Qin, M., Manning, Z., Chen, M., Marquis, K. B., Averyt, M. T., Miller HL, Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., & Miller, H. L. (2007). Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In Cambridge University Press..

Streets, D. G., Carmichael, G. R., & Arndt, R. L. (1997). Sulfur dioxide emissions and sulfur deposition from international shipping in Asian waters. *Atmospheric Environment, 31*(10), 1573–1582. [CrossRef]

Streets, D. G., Guttikunda, S. K., & Carmichael, G. R. (2000). The growing contribution of sulfur emissions from ships in Asian waters, 1988-1995. *Atmospheric Environment, 34*(26), 4425–4439. [CrossRef]

Styhre, L., Winnes, H., Black, J., Lee, J., & Le-Griffin, H. (2017). Greenhouse gas emissions from ships in ports – Case studies in four continents. *Transportation Research Part D: Transport and Environment, 54*, 212–224. [CrossRef]

Taskar, B., Sasmal, K., & Yiew, L. J. (2023). A case study for the assessment of fuel savings using speed optimization. *Ocean Engineering, 274*, Article 113990. [CrossRef]

Trozzi, C. (2010). Emission estimate methodology for maritime navigation. *US EPA 19th International Emissions Inventory Conference*. https://www3.epa.gov/ttnchie1/conference/ei19/ Accessed on Dec 05, 2024.

Tyrrell, T. (2008). Calcium carbonate cycling in future oceans and its influence on future climates. *Journal of Plankton Research, 30*(2), 141–156. [CrossRef]

Tzannatos Ernestos, E. (2010). Ship emissions and their externalities for Greece. *Atmospheric Environment, 44*(18), 2194–2202. [CrossRef]

Uyanık, T., Karatuğ, Ç., & Arslanoğlu, Y. (2020). Machine learning approach to ship fuel consumption: A case of container vessel. *Transportation Research Part D: Transport and Environment, 84*, Article 102389. [CrossRef]

Wang, Shengzheng, Ji, B., Zhao, J., Liu, W., & Xu, T. (2018). Predicting ship fuel consumption based on LASSO regression. *Transportation Research Part D: Transport and Environment, 65*, 817–824. [CrossRef]

Williams, E. J., Lerrier, B. M., Murphy, P. C., Herndon, S. C., & Zahniser, M. S. (2009). Emissions of NOx, So2, CO, and HCHO from commercial marine shipping during Texas Air Quality Study (TexAQS) 2006. In *Journal of Geophysical Research Atmospheres, 114*(21), Article D21306. [CrossRef]

Winther, M. (2008). New national emission inventory for navigation in Denmark. *Atmospheric Environment, 42*(19), 4632–4655. [CrossRef]

Ye, X., Kang, Y., Zuo, B., & Zhong, K. (2017). Study of factors affecting warm air spreading distance in impinging jet ventilation rooms using multiple regression analysis. *Building and Environment, 120*, 1–12. [CrossRef]