On the estimation of ship's fuel consumption and speed curve: A statistical approach

Nicolas Bialystocki[a], Dimitris Konovessis[b],*

[a] Technical Department, Antares Shipping Ltd., Israel
[b] School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

Abstract

When fuel efficiency is at stake, along with the reduction of the environmental foot print of air pollution, a need is presented to estimate a ship's fuel consumption for a forthcoming voyage, and means for decision making and for cost saving. This paper suggests an operational approach for obtaining an accurate fuel consumption and speed curve, on the basis of major factors affecting it, namely, ship's draft and displacement, weather force and direction, hull and propeller roughness. A statistical analysis on 418 noon reports of a Pure Car and Truck Carrier case ship is carried out and the influence of the above factors is calculated. As expected, stronger wind and head weather increases the fuel consumption, and the difference between several weather conditions could be quantified. A simple and accurate algorithm is proposed in order for ship owners, managers and operators to be in a position to apply the suggested method on their fleet. Finally, applications of the structured algorithm are introduced with examples, in estimating the fuel consumption of the case ship for a future voyage, and also the same for a sister ship. Furthermore, voyage planning in several scenarios is proposed in order to assist the stakeholders with decision making aimed to fuel saving and environmental friendliness of their ships.

1. Introduction

In recent years, fuel efficiency of ships is a major topic addressed by every private, national and international body related to shipping, receiving considerable attention due mainly to fuel cost increase, and environmental deterioration, in particular air pollution.

Fuel onboard ships, commonly referred to as "bunkers", has become the largest cost item of a ship's Operational Expenses (OPEX), accounting today almost 50% of a voyage cost, even greater than crew wages [21]. The level of interest in designing a fuel efficient ship is linearly related to the fuel price [24]. Between 1970 and 1980 fuel oil price increased significantly (nearly ten-fold), leading to ships with high fuel consumption being laid up. During the period 1985–2000 prices of fuel oil fell, with research and development on energy efficiency not receiving particular attention by the maritime industry. However, from 2000 onwards, the crude oil cost started to climb again, which pushed engine manufacturers, shipyards and designers to re-investigate design and operational solutions for reduced fuel consumption and energy efficiency.

Shipping is no different than other industries, and is highly affected by fuel prices. However, there is, to a certain extent, a control on the ship's fuel consumption by means of technical innovation fitted or by a better ship operation such as weather routing, trimming, slow steaming, etc. [8].

Even though oil price decreased for a brief period of time after the 2008 recession, today is again at record high levels, meaning that ship operators cannot ignore this expense as in the past, or just embody it into the price of the commodities carried, but there is a need to design and operate more efficient ships, consuming less fuel per carrying capacity.

Furthermore, the intense focus on environmental protection, supported by considerable research findings, has led the International Maritime Organization (IMO) to take concerted measures towards this direction, in limiting the environment foot print of ships significantly.

In particular, one of the top environmental topics is global warming due to increasing Green House Gases (GHG) in the atmosphere. The shipping industry contributed about 4% of the world carbon dioxide (CO_2) emissions in 2007 [19]. The aim to reduce CO_2 emissions comes hand in hand with the increasing fuel price, and is leading towards the adoption of technological and operational innovations in order to decrease fuel consumption.

In order to set means to improve ship's fuel efficiency, it is initially required to define the prevailing fuel consumption rate. For this purpose, the importance of carrying out a full scale ship performance analysis is highlighted in several publications as offering benefits to the designers and the operators. The aim of such an analysis can, for example, be the prediction of the required propulsion power [18], or monitoring of the hull resistance due to fouling [1]. Boom et al. [6] suggested that since sensors are already found onboard, along with equipment to transmit the information, continuous monitoring can be achieved with an adequate analysis.

The research presented in this paper, uses a similar approach, with the well-defined goal of plotting accurate speed and fuel consumption curves from relevant operational data, whilst overcoming intermediate factors normally taken into account, e.g. power and SFOC [14]. Applications of the derived method are also presented and discussed.

2. Factors affecting ship's fuel consumption

Typically a ship's power vs. speed curve is prepared during the delivery sea trials. Power is a more stable parameter compared to fuel consumption and hence easier to be measured. On the other hand, the corresponding ship's speed is measured, being the most significant parameter determining both the power and the fuel consumption.

In addition to increases in speed, resistance and fuel consumption increase by any of the following three parameters [2]:

- Increased draft and displacement
- Worsening of weather conditions
- Worsening of hull and propeller roughness

Theories and methods on the estimation of the contribution of each of these parameters on increased resistance and fuel consumption can be found in the literature [3]. However, most are based on experiments obtained from series tests on specific types of ships and hull forms. Therefore, a statistical voyage analysis [16] was carried out for investigating the influence of ship's draft, of the weather and the hull and propeller condition to produce the fuel consumption vs. speed curve, which represents a more realistic and accurate approach for contemporary ships, as required. The approach assumes

that predictions based on a previous year performance are more accurate and reliable than based on sea trials.

The existing power-speed curve has two drawbacks. First, when fuel efficiency and CO_2 emission are of concern, the fuel consumption is more important to be calculated than the engine power.

Secondly, the production of a single curve during sea trials is far from adequate for the entire ship's lifetime, and such a curve is truly theoretical rather than practical. In addition, the operators do not have an analytical and systematic method to come up with a more accurate, updated curve, which is applicable for aged ships, not only for new ones.

By computing a fuel consumption and speed curve, with high degree of preciseness, a more reliable estimation of the fuel needed in a future voyage or even for a sister ship is likely to be obtained.

A simple example for appreciating the importance of establishing such a method can be drawn by taking into account that the main expense of ship owner under voyage charter is fuel cost, and considering 280 yearly running days at a consumption of 50 ton/day in fuel cost of 400 USD/ton, a 5% error in fuel calculations easily accumulates to 280,000 USD/year, meaning about 770 USD/day increase of hire rate. Hence, a small deviation in the fuel calculation immediately is reflected in an operational cost significantly higher or lower than the predicted, which means that operators can respectively decrease their expected revenue, or loose fixtures.

It is therefore essential for decision making, to have better predictions of the fuel consumption, particularly nowadays due to the diminished profit margin of the shipping business and due to the interest in running lower emissions ships.

3. Algorithm and initial corrections

Fig. 1 presents an outline of the process developed in predicting the fuel consumption and speed curve.

For this purpose, four parameters are evaluated:

- Ship's draft in the suggested voyage
- Weather force
- Weather direction
- Date of the fore coming voyage

The draft can be calculated from hydrostatic and stability tables, whereas the input should be the intended cargo weight and arrangement in the cargo holds. Weather forecast is to be used to predict wind force and direction, while the date of the expected voyage is also required for the fuel consumption calculation.

On this basis, Fig. 2 illustrates the algorithm developed for the prediction of fuel consumption and speed curve. By utilizing the final curve obtained through the algorithm described in Fig. 1, it is possible to estimate the fuel consumption in a future voyage, based on predetermined information.

Initially, three corrections are applied before a preliminary curve is plotted:
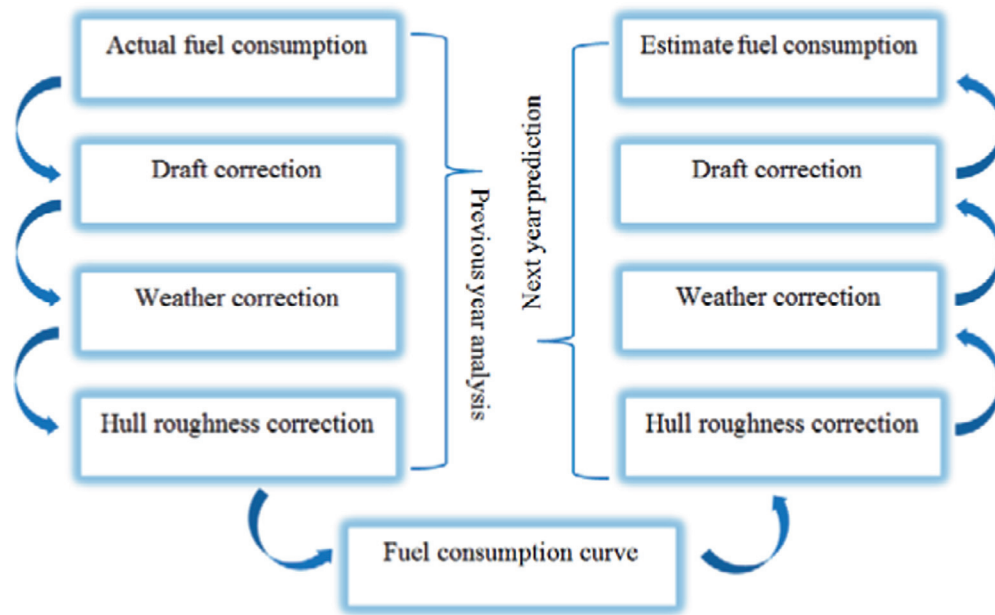
Fig. 1. Outline procedure of fuel consumption curve prediction.

1. The ground speed, item number 9 in Table 1, was calculated by dividing the traveled main distance with the steaming time. More so, the engine fuel consumption is per steaming time. Therefore, fuel consumption is corrected to a common denominator of 24 steaming hours.
2. Departure and arrival drafts for each voyage were also recorded, and intermediate ship's drafts were calculated using interpolation. Thereafter, a correction to the fuel consumption of the actual draft to design draft is carried out using the Admiralty coefficient [10].
3. Ground speed was corrected to take into consideration the current, if occurred. When the current flowed aft wards it was added to the ground speed, while in case that the current flowed forward it was deducted from the ground speed.

The first fuel consumption correction is therefore:

$$\text{Fuel Cons}_{Corr} = 24 \times \frac{\text{Fuel Cons}_{Recorded}}{\text{Steaming Time}} \qquad (1)$$

where *Steaming Time* and *Fuel Cons$_{Recorded}$* are the recorded time and fuel consumption as in Table 1 items 7 and 10, respectively.

The second correction at this initial stage is meant to eliminate the differences in ship's drafts between each of the measuring points. It was done by use of the Admiralty coefficient, which is defined as $Ac = \Delta^{2/3} \times V^3/P$, where Δ is the ship's displacement, V is the ship's speed, and P is the engine break power.

However, it is well known that the Admiralty coefficient is not constant, and can be assumed as changing linearly according to the apparent slip [7]:

$$Ac = C \times S_a + Ac_0 \qquad (2)$$

where C is a constant, S_a is the apparent slip, and Ac_0 is the Admiralty coefficient when slip is 0%. Considering that the apparent slip is kept constant when the ship is at design draft, it was assumed that the Admiralty coefficient did not change as well.

Hence, for the same measured speed and taking into account that the required power is linearly related to the main engine's fuel consumption, a second correction was:

$$\text{Fuel Cons}_L = \text{Fuel Cons}_{Corr} \times \left(\frac{\text{Disp}_{Load}}{\text{Disp}_{Corr}}\right)^{2/3} \qquad (3)$$

where *Fuel Cons$_{Corr}$* is the fuel consumption as corrected in Eq. (1), *Disp$_{Load}$* is the ship's displacement at design draft, and *Disp$_{Corr}$* is the actual displacement, calculated from the ship's hydrostatic tables at the corresponding draft.

Regarding, finally, the third initial correction, and taking into account that in several voyages current was observed, the ship's speed over ground was corrected as following:

IF Current Direction = Aft → Ship's Speed
= Recorded Speed + Current Speed
IF Current Direction = Fwd → Ship's Speed
= Recorded Speed − Current Speed
IF Current Direction = 0 → Ship's Speed = Recorded Speed

4. The weather effect

The weather a ship faces during voyage has significant influence on her fuel consumption, in particular relating to prevailing wind and waves. Normally, a 10–15% weather margin [23] is taken into account in design calculations.

The relative angle of wind to ship's course, α, is another important parameter [12]. Head wind requires more power for
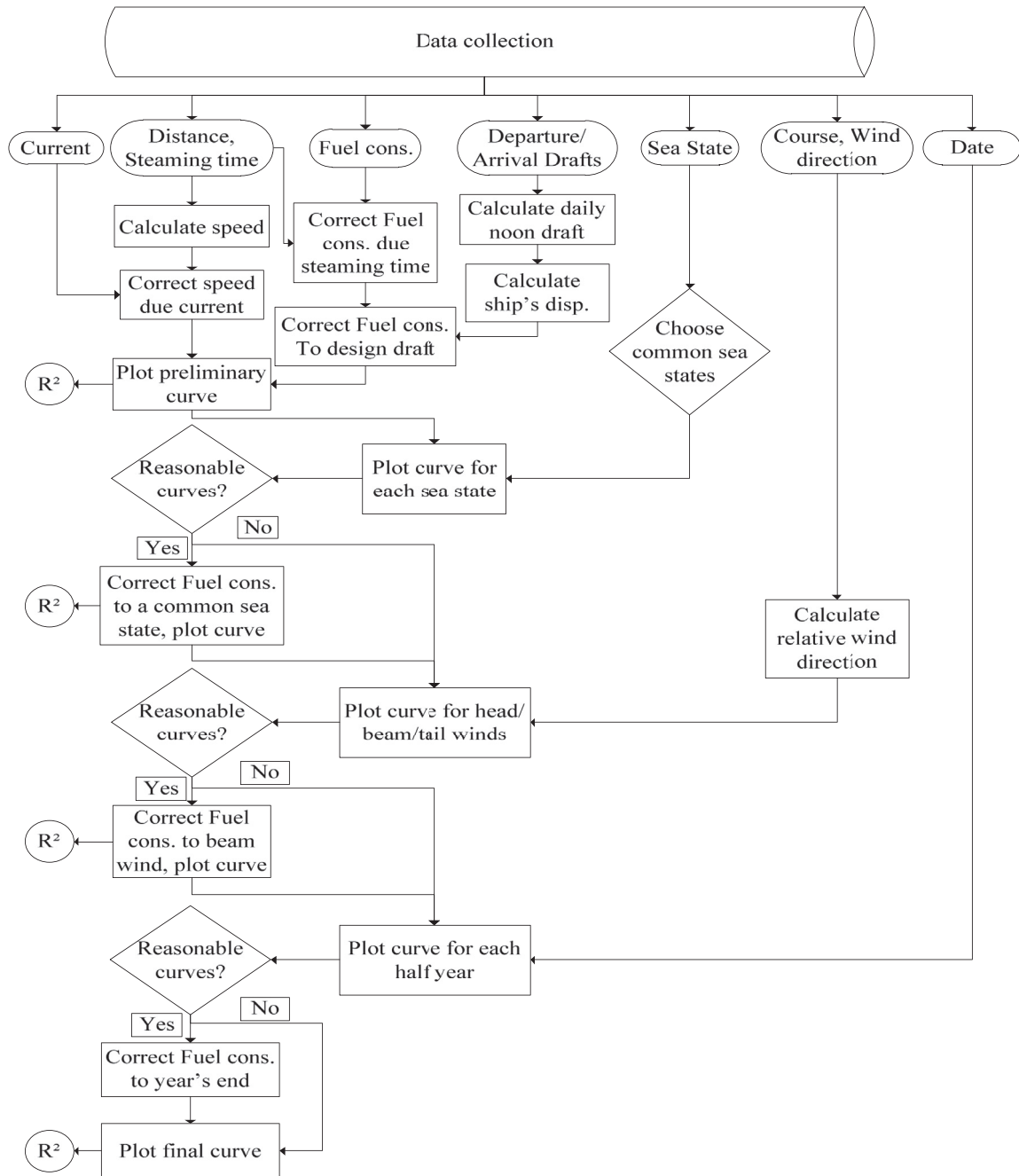
Fig. 2. Outline procedure of fuel consumption curve prediction.

the ship to advance; therefore more fuel is consumed by the main engine. A tail wind, on the other hand, decreases the amount of fuel consumed. In this respect, the relative angle range is 0–180 degrees.

In this respect, the relative angle is calculated according to the following logical statements:

IF Wind Direction − Ship Course $> 180° \rightarrow \alpha$

$= \left|\text{Wind Direction} - \text{Ship Course} - 360°\right|$

IF Wind Direction − Ship Course $< -180° \rightarrow \alpha$

$= \left|\text{Wind Direction} - \text{Ship Course} + 360°\right|$

Otherwise $\rightarrow \alpha = \left|\text{Wind Direction} - \text{Ship Course}\right|$

The weather influences on the curve are analyzed with reference to the following two factors:

- The force of the wind
- The wind direction

In terms of wind force, the Beaufort scale is used [4], in particular sea states 4, 5 and 6, which typically represent more

Table 1
Data recorded in a noon report.

	Data	Instrument of measurement	Unit
1	Date	Master Clock	Day
2	Time	Master Clock	Hour
3	Ship's course	GPS	Degree
4	Weather/Wind direction	Anemometer	Compass card
5	Weather/Wind force (sea state)	Anemometer	Beaufort scale
6	Current	Speed Log	Knot
7	Steaming time	Master Clock	Hour
8	Traveled distance	GPS	N.Mile
9	Ground speed	GPS	Knot
10	Main engine fuel oil consumption	Flow meter	Tons
11	Draft	Draft gauges fore and aft	Meter

than 75% of the time at sea, as determined from operational experience. The collection of data with respect to weather is extremely important for accurate service performance predictions, and even though nowadays all ships are equipped with measuring instruments, an experienced officer usually maintains such records, which is beneficial to the success of the proposed speed and fuel consumption analysis.

On this basis, a fuel consumption correction due to Beaufort seastate was applied by shifting all the points from seastate 4 and 6 to the common denominator of seastate 5:

$$\text{Fuel Cons}_{L,B5} = \text{Fuel Cons}_L \times \frac{\text{Fuel Cons}_{B5}}{\text{Fuel Cons}_{B4/B6}} \qquad (4)$$

where *Fuel Cons$_{L,B5}$* is the fuel consumption corrected to the design loading condition, and corrected to the specific weather condition of seastate 5. The *Fuel Cons$_L$* is the fuel consumption as corrected in Eq. (3), *Fuel Cons$_{B5}$* is the fuel consumption in the average line at seastate 5, and *Fuel Cons$_{B4/B6}$* is the fuel consumption in the average line at either seastate 4 or 6.

It can be noticed from Eq. (5) that the fuel consumption in seastate 5 is being compared to seastates 4 and 6, meaning that a ship at seastate 4 will increase her consumption when she faces seastate 5, and the opposite for seastate 6.

The second weather correction is for wind direction. The fuel consumption vs. speed curve is plotted for three relative angle sections, as these are defined between the wind direction and ship's course.

This is based on research [5] proving that the wind side force on the hull has roughly the same effect for:

- Head wind (0–60 degrees)
- Beam wind (60–120 degrees)
- Tail wind (120–180 degrees)

At this stage each point, *Fuel Cons$_{L,B5}$* is corrected according to the actual weather direction, in order to bring the fuel consumption to the same denominator, chosen to be beam wind. This means that any point at head or tail wind was brought down or up towards the beam wind curve, respectively. The further corrected fuel consumption is therefore:

$$\text{Fuel Cons}_{L,B5,BW} = \text{Fuel Cons}_{L,B5} \times \frac{\text{Fuel Cons}_{Beam}}{\text{Fuel Cons}_{Wind}} \qquad (5)$$

where *Fuel Cons$_{L,B5,BW}$* is the fuel consumption at a designated speed corrected to the design loading condition, corrected to environmental condition of seastate 5, and to a beam wind direction acting as an external force on the ship. The *Fuel Cons$_{L,B5}$* is the fuel consumption as corrected in Eq. (4), *Fuel Cons$_{Beam}$* is the fuel consumption in the average line for beam wind condition, and *Fuel Cons$_{Wind}$* is the fuel consumption in the average line at either head or tail wind.

Eq. (5) compares the beam wind to the head and tail winds, in a way that a ship running with the assistance of a tail wind will increase her fuel consumption when she is facing similar sailing conditions except being at beam wind, whilst the opposite is the case for head wind.

5. Hull and propeller roughness

The last required correction is on the service time, in order to evaluate possible effects of hull and propeller roughness. Since the analysis is based on the information contained in noon reports, it can be logically deducted that the curve points should be divided in a number of groups (periods), according to the dates when they were recorded. The suggested approach would statistically identify the influence of service time on ship's resistance, as could be determined by comparing fuel consumption between the first and subsequent periods of grouped data.

It has been reported that the loss of speed due to fouling after six months is 1.5–2 knot [11], and in another research [13] that 13 months after drydock increased significantly the required power to maintain speed. There are many reasons for increased fuel consumption during service, which are mainly:

- Deteriorated condition of outer hull to marine growth, corrosion, etc.
- Deteriorating propeller due to marine growth, cavitation, etc.
- Regression in the main engine performance.
- Wear of auxiliary machineries driven by the main engine.
- Wear of the shaft line bearings and seals, which reduce their efficiency of power transmission.

Hull roughness is a main factor affecting the total resistance. The surface roughness is built from two separate

Fig. 3. The case ship.

components. These are the permanent roughness and the temporary roughness [7].

The permanent part includes the roughness of the ship as it was built, and it is derived from the steel plate, seam lines, paints being used by the shipyard. The form of the hull and propeller is also affecting the permanent roughness, because fair lines can reduce the friction with water. During the ship's operations this part of the surface roughness is also deteriorating by means of corrosion and hull damages or propeller cavitation.

From the other side, the temporary roughness is named as such, because it can be removed by contemporary hull and propeller polishing, cleaning and painting. This part of the roughness includes mainly the marine fouling accumulating either on the hull or on the propeller.

6. Applications

The prediction algorithm was used to perform a statistical analysis on 418 noon reports of a Pure Car and Truck Carrier (PCTC) case ship in order to calculate the influence of all the factors discussed above.

The principal characteristics and main specifications of the PCTC are the following (Fig. 3):

- Delivery year: 2008
- Car Capacity: 6500 CEU (Car Equivalent Unit)
- Length overall: 199.99 m
- Breadth: 32.26 m
- Draft (design):   9 m
- Displacement: 32,791.6 ton (loaded at design draft)
- Main Engine: MAN B&W 7S60ME-C
- Power: 15,820 kW
- Speed (design):   20 knot

The analyzed data comprise 27 voyages, all above 72 h in duration, in order to have a fully developed ship's speed, which was recorded by the ship's officers, using instruments detailed in Table 1, and then sent to the management company.

Fig. 4 illustrates the scatter diagram of the fuel consumption versus speed corrected to design loading condition and the corrected speed. The data present a wide scatter to the average treadline, $Fuel\ Cons = 0.1727 \times Speed^2 - 0.217 \times Speed$, with fuel consumption in tonnes/day and speed in knots, as can also be deducted from the low starting R-square value of 0.7557, and hence it is difficult to conclude anything from this diagram as it is, unless several more corrections are adopted.

Fig. 5 illustrates the distribution of sea states in operation, as deducted from the 418 noon reports used. It can be seen that seastates 4–6 represent more than 75% of time at sea.

A curve for each state, 4–6, was produced and the results are demonstrated in Fig. 6. As expected, the stronger the weather the ship encountered, the higher the fuel consumption.

The relative wind direction also resulted in a significant effect on the curve, where head wind, as expected, increased the fuel consumption for a specific speed, while tail wind decreased the fuel needed and beam wind curve was found to be in between, as it is illustrated in Fig. 7.

The research herewith supports the influence of weather direction on ship's speed and fuel consumption curve on one hand, but on another hand it opens a window for more detailed analysis by dividing the compass card directions into more sections.

The final correction of the curves is for time in service. As discussed in the foregoing, the suggested approach could statistically identify the influence of service time on the ship's resistance. The data from the noon reports need to be split
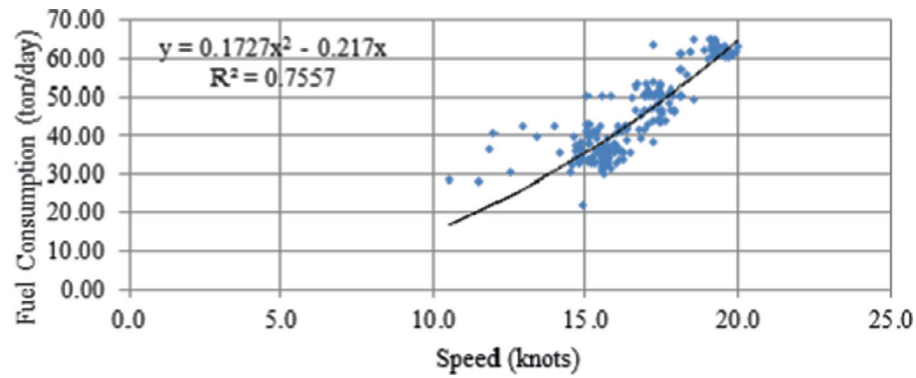
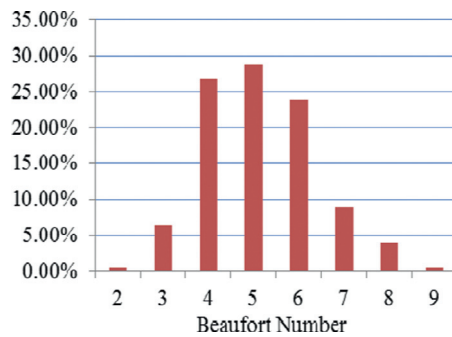Fig. 4. Preliminary fuel consumption and speed curve.

Fig. 5. Distribution of seastates for case ship.

into a number of groups in order possible roughness effects to be evaluated. The data available for the case ship span over a relatively short time period of 14 months, and for this reason, they were divided into two groups only, according to the dates when they were recorded.

Interestingly, for the case ship, the average lines for both groups of points nearly coincide, as seen in Fig. 8; therefore it is safe to say that the influence of service time is negligible.

Accordingly, a further correction due to hull & propeller roughness was unnecessary, and it was concluded that the speed and fuel consumption mean curve, as it is shown in

Fig. 8, describes the most accurate curve obtained by the suggested method for the case ship in accordance to the collected data and for the common denominators of: design draft, no current, sea state 5, beam wind and at any date.

The result for the case ship may be thought as unexpected, however it should be remembered that modern self-polishing paints can prevent fouling to a large extent [20]. Moreover, the outcome may be different for subsequent years because the case ship was only 3 years-old at the time when these data were recorded. On the other hand, this result is very important as it demonstrates that ship behavior may vary and must be investigated separately in order to obtain the correct performance prediction.

On the basis of the analysis above, fuel consumption estimations for the case ship can be based on the following regression formula, as shown in Fig. 8, *Fuel Cons = 0.2525 × Speed² – 1.6307 × Speed*, where *Fuel Cons* is the fuel consumption of the main engine per day, and *Speed* is in knots. It is noted that the starting R-square value for the case ship was 0.7557, according to the data before corrections of Fig. 4, and by applying several additional corrections related to the ship's operations, the improved R-square value of the curve of Fig. 8 is 0.8829, reflecting a significant improvement in the accuracy of the fuel consumption estimation.
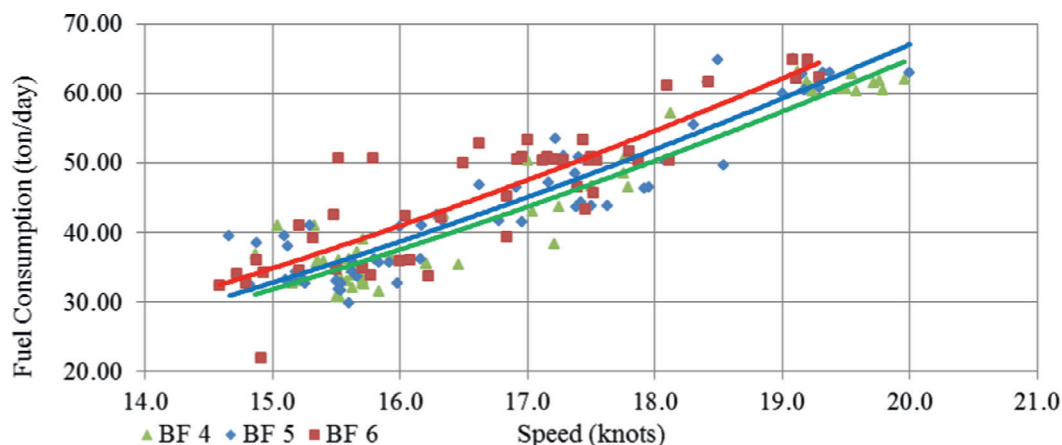

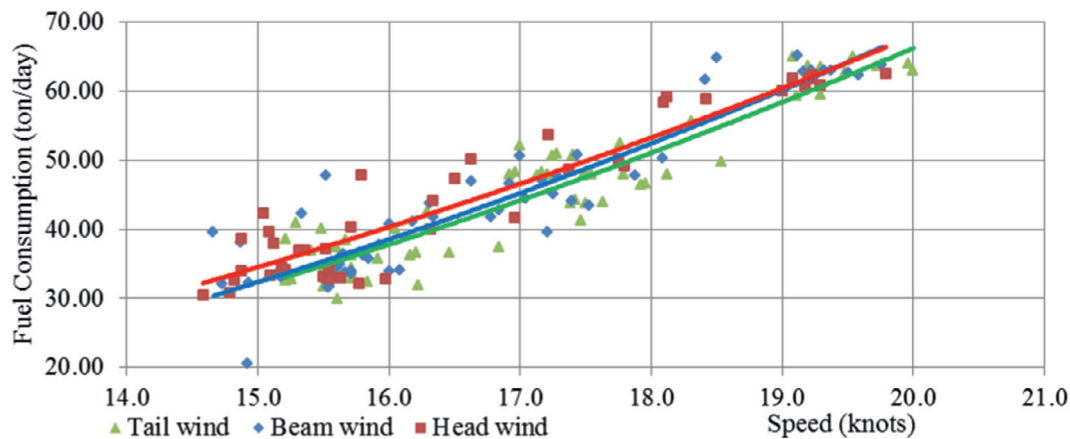Fig. 6. The effect of sea state on the speed and fuel consumption curve.

Fig. 7. The effect of wind direction on the speed and fuel consumption curve.
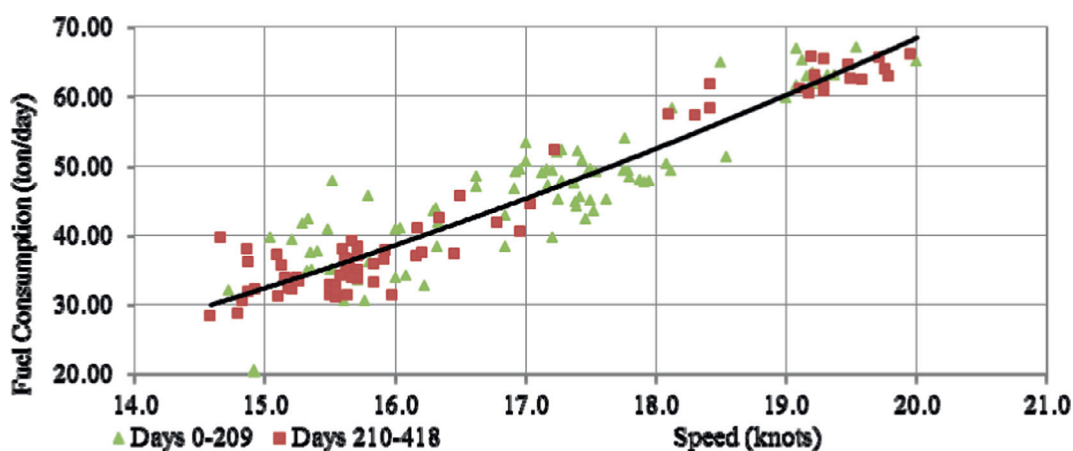

Fig. 8. Influence of service time on the fuel consumption.

6.1. Calculation example

A calculation example for a hypothetical future trip of the case ship is shown in order to demonstrate the applicability of the method. The data for the hypothetical trip are the following:

Port of Departure:	Mizushima
Port of Arrival:	Singapore
Distance:	2711 Nautical Miles
Speed:	18 knot
Voyage time:	6 days and 7 h
Deadweight:	13,246.1 ton
Displacement:	30,274.9 ton
Draft (constant):	8.50 m
Wind forecast:	Beaufort 4, head wind

The estimation could start with the final curve as in Fig. 8, i.e. the daily fuel consumption can be calculated from the regression equation (7). For a speed of 18 knot, the daily fuel consumption obtained is 52.46 ton. Furthermore, based on Figs. 6 and 7, for the proposed speed, wind force Beaufort 4 decreases resistance by 3.1% (compared to wind force 5), and head wind increases the resistance by 1.6% (compared to side wind), resulting in a consumption of 51.63 ton per day. Draft correction using the Admiralty formula as in Eq.

Table 2
Fuel consumption in a proposed voyage at different sea states.

Speed (Knots)	Fuel cons at Beaufort 4 (Tons)	Fuel cons at Beaufort 5 (Tons)	Fuel cons at Beaufort 6 (Tons)
15.0	239.17	246.44	262.00
15.5	250.50	258.21	273.89
16.0	261.84	269.99	285.78
16.5	273.17	281.76	297.68
17.0	284.50	293.54	309.59
17.5	295.84	305.31	321.50
18.0	307.18	317.09	333.41
18.5	318.51	328.86	345.33
19.0	329.85	340.64	357.24
19.5	341.19	352.41	369.16
20.0	352.52	364.19	381.09

(4) further reduces the fuel consumption to 48.95 ton/day. Hence, the fuel consumption for the entire voyage is expected to be 307.18 ton.

Similarly, the voyage fuel consumption can be calculated in various scenarios of speeds and weather force for the case ship, and the results are shown in Table 2 and illustrated in Fig. 9.
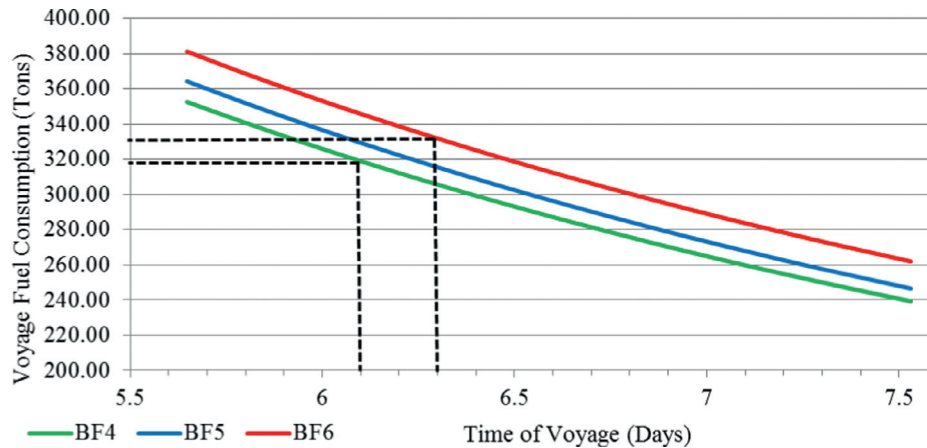
Fig. 9. Fuel consumption dependence on a voyage time and sea states.

Producing such a table is highly important for ship operators in taking decisions regarding the optimum speed and date of voyage [22]. For example an operator may prefer to wait 7.5 h and run in 19.5 knot speed at sea state 4, rather than running in 18.5 knot at sea state 6, and save 4.14 ton for the trip, which is about USD 1700 in current IFO 380 prices. The saving can be accumulated to more than USD 70,000 yearly, which is substantial.

6.2. Application for sister ship

The suggest algorithm can also be applied for sister ships performance prediction, because of hull and machinery similarity to the case ship. As an example an actual voyage of a sister ship had been chosen:

Port of Departure:	Southampton
Port of Arrival:	Cristobal
Distance:	4698 Nautical Miles
Speed:	15.23 knot (average)
Voyage time:	12 days and 20 h
Deadweight:	15,557.8 ton
Displacement:	32,586.6 ton
Draft:	8.96 m (average)
Wind force:	Beaufort 4–5 (most days of the voyage)
Wind direction:	Varies

The actual fuel consumed by the main engine during the trip was 421.9 ton, which is equivalent to a daily consumption of 32.83 ton. Based on the ship's speed, the initial expected daily fuel consumption was 33.73 ton, reflecting a deviation of 2.76% from the actual consumption. By applying a wind force correction of an average between Beaufort 4 and 5, the consumption is reduced to 33.23 ton per day. Higher accuracy was obtained by taking into consideration the actual ship's displacement, which further reduced the consumption to 33.09 ton per day, reflecting 0.81% deviation from reality.

The deviation of the final estimation from the actual, in the example of the sister ship can be explained by:

- The unknown current influence.
- Varying sea states, and wind directions.

- Speed varied between 14.28 and 15.80 knot on daily basis, when 15.23 knot being the mean weighed average.

These accumulate to the method generic error due to the statistical analysis, which from its core may introduce inaccuracies. From both examples, one being an estimation for a case ship and another being a comparison between a sister ship estimation and the actual fuel consumption rate, it is believed that the proposed method is fast, easy and reliable for use, but most importantly has the potential to be very precise, providing powerful means for decision making to ships owners and operators.

Additionally, it is believed that in order to be a practical solution, only the most significant factors should be taken into account. The research is meant to withdraw less significant factors, slightly compromising it accuracy, in order to be increase its applicability.

At the same breadth, the potential errors of sensors such as GPS [9], Flow meter [15], etc., were found to be fraction in comparison to the final error of the curve as reflected in the standard deviation of Fig. 7, and these are also incorporated in the systematic error.

All in all, this is the point to mention that the accuracy of the performance analysis depends more on the crew observation than on the mathematical model [17], and a competent crew has more influence than any of the factors discussed here above.

7. Conclusions

The main concept is that ship operators have much information about the ship's performance from the daily master (noon) reports. Hence, the data can be utilized and updated from year to year instead of estimating the trip's fuel through sea trials plus margin. On the basis of this data, a simple and feasible algorithm was introduced and its two main advantages of simplicity and acceptable accuracy are shown in estimating voyage fuel consumption. This is extremely important for fuel saving by taking the correct decisions where cost efficiency and environmental friendliness are top priorities.

The suggested method as it was shown for a single case ship is believed to be as practical as significant, and it opens the gate for each ship operator to test it on their own fleet.

References

[1] M. Aas-Hansen, Monitoring of Hull Condition of Ships (M.Sc. Thesis), Norwegian University of Science and Technology, Norway, 2011.

[2] P. Andersen, A.S. Borrod, H. Blanchot, Mar. Technol. 42 (4) (2005) 177–183.

[3] V. Bertram, Practical Ship Hydrodynamics, Butterworth-Heinemann, Oxford, 2002.

[4] R. Bhattacharyya, Dynamics of Marine Vehicles, John Wiley & Sons, New York, 1978.

[5] W. Blendermann, J. Wind Eng. Ind. Aerodyn. 51 (3) (1994) 339–351.

[6] H.V.D. Boom, J. Koning, P. Aalbrets, in: Proceedings of the Offshore Technology Conference, Huston, TX, U.S.A., May 2005, pp. 2–5.

[7] J. Carlton, Marine Propellers and Propulsion, second ed., Elsevier, Oxford, 2007.

[8] DNV, "Assessment of measures to reduce future CO2 emission from shipping, research and innovation", Position paper No. 5, Det Norsk Veritas, Hovik, 2010.

[9] Catalogue No. N-847 h FURUNO. http://www.furuno.com, 2015.

[10] SV.AA. Harvald, Resistance and Propulsion of Ships, John Wiley & Sons, New York, 1983.

[11] Hydrex Group, Q. J. Ship Hull Perform. 1 (1) (2011) 22–33.

[12] R.M. Isherwood, Wind Resistance of Merchant Ships, The Royal Institution of Naval Architects, London, 1972.

[13] K.P. Logan, in: Proceedings of the ASNE Intelligent Ships Symposium IX, Philadelphia, PA, U.S.A., 25 May 2011.

[14] Man Diesel & Turbo, Basic Principals of Ship Propulsion, Man Diesel & Turbo, Copenhagen, Denmark, 2011.

[15] Mar-in Controls B.V. http://www.mar-in-controls.com, 2015.

[16] A.F. Molland, S.R. Turnock, D.A. Hudson, Ship Resistance and Propulsion, Practical Estimation of Propulsive Power, Cambridge University Press, New York, 2011.

[17] T. Munk, D. Kane, D.M. Yebra, in: C. Hellio, D. Yebra (Eds.), Advances in Marine Antifouling Coatings and Technologies, Woodhead Publishing, Cambridge, 2009, pp. 148–176.

[18] B.P. Pedersen, J. Larsen, in: Proceedings of the World Maritime Technology Conference, Mumbai, India, WMRC, 21-24 Jan. 2009.

[19] G. Reynolds, in: Proceedings of the World Maritime Technology Conference WMRC, Mumbai, WMRC, 21-24 Jan. 2009.

[20] H. Schneekluth, V. Bertram, Ship Design for Efficiency and Economy, second ed., Elsevier Butterworth-Heinemann, Oxford, 1998, pp. 180–205.

[21] M. Stopford, Maritime Economics, third ed., Routledge, Oxford, 2009.

[22] T. Varelas, S. Archontaki, in: Proceedings of the International Conference on Technologies, Operations, Logistics and Modelling for Low Carbon Shipping, LCS, Glasgow, Scotland, UK, 22-24 June 2011.

[23] D.G.M. Watson, Practical Ship Design, Elsevier, Oxford, 1998.

[24] N. Wijnolst, T. Wergeland, Shipping Innovation, IOS Press, Amsterdam, 2009.