INVESTIGATION OF SHIP MOTIONS AND FUEL CONSUMPTION WITH RESPECT TO CHARTER PARTY AGREEMENTS

D.A. Hudson and **G.P. Daniels Galle**

Fluid Structure Interactions Group, Faculty of Engineering and the Environment, Boldrewood Innovation Campus, Southampton, SO16 7QF, United Kingdom, dominic@soton.ac.uk.

ABSTRACT

The Charter Party agreement between ship owner and ship charterer inevitably includes a fuel guarantee clause that determines the amount of compensation a charterer is entitled to if the chartered ship consumes more fuel for specified speed and weather conditions. This clause may at times act to prevent both charterer and owner investing in fuel (emissions) reduction measures. In most cases the 'cut off' for a fuel guarantee clause is set at a specific weather condition, expressed through the Beaufort Number and in practice is often set at Beaufort Number 5. The reason for, and choice of, this 'cut off' value is not always immediately apparent.

This paper uses naval architecture software to investigate the prediction of ship added resistance in waves for the major classes of liquid bulk carrying ships. This added resistance in waves is combined with estimates of calm water resistance and added resistance due to wind to provide estimates of ship fuel consumption for a range of weather conditions.

It is found that for the liquid bulk carrying vessels investigated a 'cut off' in the fuel guarantee of a Beaufort 5 is broadly sensible within the current framework, but that the use of a single number, and of the Beaufort number in particular, creates ambiguity. Variations in the wave energy spectrum and addition of wind resistance do not significantly alter added resistance calculations for these vessels. Results indicate that theoretical predictions of ship added resistance in waves can give useful insight into the fuel guarantee 'cut offs' defined by Beaufort number in Charter Party agreements and offer some potential for providing greater transparency in the future.

Keywords: Emissions, Charter Party, Margin, Added Resistance, Fuel Guarantee, Efficiency

1. INTRODUCTION

Container ships, bulk carriers and oil tankers together account for 62% of shipping's CO2 emissions, with the oil and bulk fleets responsible for 36% (IMO, 2014). The commercial structure of the oil tanker and bulk carrier market is such that ships are often chartered from a ship owner under a contract referred to as a Charter Party agreement. Typically, in a time charter the owner is responsible for the purchase of the ship and its equipment (as well as crew and maintenance) and the charterer for port expenses and the fuel consumed. This division of costs has been identified as a potential 'split incentive' for the reduction of fuel consumption and hence CO2 emissions, whereby there is limited incentive for the ship owner to invest in fuel saving measures when the charterer pays for the fuel costs, unless the charter rate reflects improved vessel efficiency. There is evidence that charter rates do partially reflect fuel efficiency, but that how the benefits are split between the owner and charterer depends on market circumstances (Faber et al, 2012).

Charter Party agreements will usually include a performance warranty, defining the fuel consumption of the vessel for a range of speeds. If the ship consumes more fuel than the warranty, then the owner must pay compensation, following a claim by the charterer. The Charter Party agreement defines the periods when fuel consumption is to be measured for the purposes of the performance warranty, usually stipulating that for days when the weather conditions exceed a particular Beaufort Number (typically 5) the fuel consumption is not considered. The owner is also usually permitted to offset over-performance with under-performance to arrive at a net fuel warranty claim. There is some evidence (e.g. Veenstra and Dalen, 2011) that such clauses lead to ship owners being conservative in their performance warranty, most likely in order to avoid excessive claims from charterers. This leads to considerable performance loss in the time charter market as a whole and prevents collective efforts to reduce fuel consumption.

This study investigates the appropriateness of the stipulated Beaufort Number 'cut-off' employed in Charter Party agreements, for a range of typical oil tanker sizes travelling in head seas. By using techniques common in the ship design process to estimate fuel consumption in a range of sea conditions, the efficacy of such methods for providing more transparency in performance warranties may also be assessed.

2. METHODOLOGY

2.1 VESSEL TYPES

In order to investigate the added power and fuel consumption in different sea states, three 'classes' of oil tanker were modelled. These three classes cover different size ranges, in order that the effect of vessel size on added power and fuel consumption may be investigated with respect to the use of a 'cut off' in a Charter Party agreement based on a single Beaufort Number. The three classes of tanker chosen for this initial study are a Panamax-sized LR1, VLCC and a ULCC. Whilst the latter are not currently typically constructed, they represent an interesting extreme of vessel from the perspective of size and its effect on added resistance are summarised in table 1.

Table 1: Principal particulars of vessel classes adopted for added power calculations.

Parameter	LR1	VLCC	ULCC
Waterline length (m)	216.20	312.80	414.03
Beam, maximum at waterline (m)	31.80	59.62	62.48
Draught amidships (m)	13.20	19.90	35.00
Wetted surface area (m^2)	10054.21	24585.12	44224.28

2.2 ESTIMATION OF FUEL CONSUMPTION

2.2 (a) Ship Resistance

The approach adopted in this study follows standard techniques for the estimation of ship resistance, hence required propulsive power, at the preliminary design stage for a vessel and thus requires only limited data for the vessel (e.g. see Molland et al, 2017). Given that the primary interest of the study is the effect of weather conditions and sea-state on the fuel consumption, parameters associated with calm water propulsion are kept constant between vessels and approximate values taken. The intent is that realistic values are used, but the focus is on a comparative study. The total resistance is thus estimated as:

$$R_T = R_c + \bar{R}_{aw} + R_A$$

with,
R_T = total ship resistance
R_c = calm water resistance
$\bar{R}_{aw}$ = added resistance due to waves
R_A = added resistance due to wind

In this study the calm water resistance (R_c) is estimated using the method of Holtrop and Mennen (1982), which is based on regression analysis of 384 models tested at the MARIN tank. The method includes skin friction resistance, wave resistance and resistance due to bulbous bows and appendages. This method is suitable for most conventional merchant vessel hull forms, at least for preliminary design purposes. For a post-Panamax bulk carrier it over-predicted resistance as compared to the model tests by 10-15% in the design speed range (Dedes, 2013). The input quantities required are L, B, T, ∇ and A_w, as well as the coefficients of C_p and C_w, which are available from a geometric description of the vessel.

The resistance due to wind is calculated using,

$$R_A = \frac{1}{2}.C_D.\rho_A.A_f.V_A^2$$

with,
ρ_A= density of air, taken as 1.23 Kg/m^3
V_A = apparent wind speed. This study focuses on head winds and waves and thus is taken as a straight summation of the vessel speed and the true wind speed.
C_D= drag coefficient of above-water hull and superstructure. Given the superstructure geometry for most oil tankers, this was taken as 0.88 for this study.
A_f= vessel frontal area. For simplicity, in this study this was taken as a function of the vessel length.

Added resistance in waves is a subject of ongoing research and there are no completely satisfactory methods available at the present time (Bertram, 2016). There are empirical methods based on full-scale measurements of performance (e.g. Kwon, 2008), towing tank experiments, or computational analyses. At the preliminary design stage the latter are often employed. The most physically complete computational methods available are based on the unsteady Reynold's Averaged Navier-Stokes equations (RANSE), but these remain time-consuming to employ. For this reason a strip theory approach is adopted in this study. The method employed for the estimation of added resistance is that of Gerritsma and Beukelman (1972). This provides reasonable estimates for conventional ships, although as with many strip theories is less accurate for estimating added resistance of large ships in short waves. The added resistance in a sea-state is calculated using spectral methods, by combining the added resistance transfer function calculated using strip theory with a spectral representation of the sea-state.

Thus,

$$\bar{R}_{aw} = 2\int_0^\infty C_{aw}(\omega_e)S_\zeta(\omega_e)d\omega_e$$

where,
$C_{aw}(\omega_e)$ = coefficient of added resistance as a function of wave encounter frequency, calculated using Gerritsma and Beukelman (1972).
$S_\zeta(\omega_e)$ = wave energy spectrum. Two wave energy spectra are adopted in this work, the first being the ITTC two-parameter spectrum, suited to open ocean conditions and defined by the significant wave height ($H_{1/3}$) and modal wave period (*T*) as,

$$S_\zeta(\omega) = \frac{A}{\omega^5}.e^{\frac{-B}{\omega^4}}$$

with,
$A = 172.75\frac{H_{1/3}^2}{T^4}$ and $B = \frac{691}{T^4}$.
The second wave energy spectrum employed is the JONSWAP spectrum, suited to waters with limited fetch. This is expressed as a modification to the ITTC spectrum and is thus also represented by the same two parameters.

All calculations were performed using the Maxsurf suite of ship design software from Bentley Systems (2013).

2.2 (b) Fuel Consumption

With the total resistance in different wave spectra, it is possible to calculate the fuel consumption. This is commonly expressed in metric tonnes per day (mt day^{-1}) and may be estimated as,

$$\text{Fuel consumption} = \frac{R_T.V.SFC}{\eta_D.} \times \frac{24}{10^6}$$

where,
R_T = total ship resistance (kN), calculated as described in 2.2(a).
V = vessel speed (ms^{-1})
η_D= quasi-propulsive coefficient, incorporating the propeller open water efficiency, relative rotative efficiency and hull efficiency. In this study a value of 0.68 was taken for the smaller vessel and 0.52 for the larger vessels.
SFC = specific fuel consumption (g.kWh^{-1}). This is dependent on the installed engine of the ship, the load factor at which it is running and the condition of the engine. In practice, it is thus variable. For this study – in order to compare vessels on a 'like for like' basis - a constant value of 182 g.kWh^{-1} was used. This is higher than many quoted figures for two-stroke marine diesels, but represents the fact that operators will rarely achieve 'shop test' performance.

2.3 SEA STATES

In order to calculate added power and fuel consumption in realistic conditions for the three vessel types, whilst keeping the number of calculations (and hence results) at a manageable level, two sea areas were considered, together with the two sea spectra discussed in section 2.2 (a). The sea areas considered correspond to the mid-Atlantic Ocean and the exit of the Suez canal. The sea spectra are defined in terms of significant wave height and wave zero-crossing period. The combinations and frequency of occurrence of these values are taken from Global Wave Statistics (BMT, 1986) for areas 49 and 50, respectively. For this study, the annual, all directions wave data are used for simplicity. A summary of the most commonly occurring (modal) data are given in table 2.

It is common in Charter Party agreements to refer to a single Beaufort number to describe the weather conditions for a fuel guarantee clause. The Beaufort number is formally a scale based on wind speed, although the probable height of waves and probable maximum height of waves, for fully-developed seas in the open ocean (unlimited fetch) are commonly found in definitions of the Beaufort scale since around 1960. For the purposes of this paper, the scale is reproduced in table 3 from BMT, 1986. This is equivalent to the scale as defined by the World Meteorological Organisation (WMO). It should be noted that the WMO recommend that with modern instrumentation (anemometers and wave buoys) direct measurements should replace use of the Beaufort Scale for wind speed. For sea state recording the Douglas scale is used, although again this is not recommended by the WMO. The Beaufort scale should not be used for recording sea state since, regarding wave height, the scale is 'intended as a guide to show roughly what may be expected in the open sea, remote from land. It should never be used in the reverse way; i.e. for logging or reporting the state of the sea. In enclosed waters, or when near land, with an offshore wind, wave heights will be smaller and the waves steeper' (WMO, 2017).

The reliance on a single number, the Beaufort number, to represent weather conditions in a fuel guarantee clause should thus be questioned in itself. There is much ambiguity about the conditions that this actually represents, never mind in interpreting the conditions and in assigning a fuel consumption to this single number.

Table 2: Summary of most commonly occurring wave data from BMT, 1986 for (a) Atlantic Ocean (area 49) and (b) Suez canal exit (area 50).

(a) Atlantic Ocean (area 49)

Significant wave height (m)	Zero-crossing period (s)	Frequency of occurrence, /1000
0-1	5-6	28
1-2	6-7	133
2-3	7-8	109
3-4	7-8	41
4-5	8-9	11

(b) Suez canal exit (area 50)

Significant wave height (m)	Zero-crossing period (s)	Frequency of occurrence, /1000
0-1	4-5	115
1-2	5-6	133
2-3	5-6	168
3-4	6-7	33
4-5	6-7	16

To use these data as input to the ship motions and added resistance analysis, the median of each data range is taken, i.e. 2-3m significant wave height is interpreted as 2.5m and 7-8s zero-crossing period as 7.5s.

Table 3: The Beaufort scale as defined in BMT, 1986 and by WMO, 2017.

Beaufort Wind Force	Limits of wind speed in knots	Descriptive term	Probable Height of Waves in metres	Probable Maximum Height of Waves in metres
0	Less than 1	Calm	-	-
1	1-3	Light air	0.1	0.1
2	4-6	Light breeze	0.2	0.3
3	7-10	Gentle breeze	0.6	1.0
4	11-16	Moderate breeze	1.0	1.5
5	17-21	Fresh breeze	2.0	2.5
6	22-27	Strong breeze	3.0	4.0
7	28-33	Near gale	4.0	5.5
8	34-40	Gale	5.5	7.5
9	41-47	Strong gale	7.0	10.0
10	48-55	Storm	9.0	12.5
11	56-63	Violent Storm	11.5	16.0

12	64 and over	Hurricane	14 or over	-

3. RESULTS

3.1 EFFECT OF WAVE HEIGHT

The wave added resistance in head seas for the three sizes of tanker is calculated using Maxsurf for the Atlantic (sea area 49), for different ship speeds and significant wave heights. The added resistance is shown in figure 1.

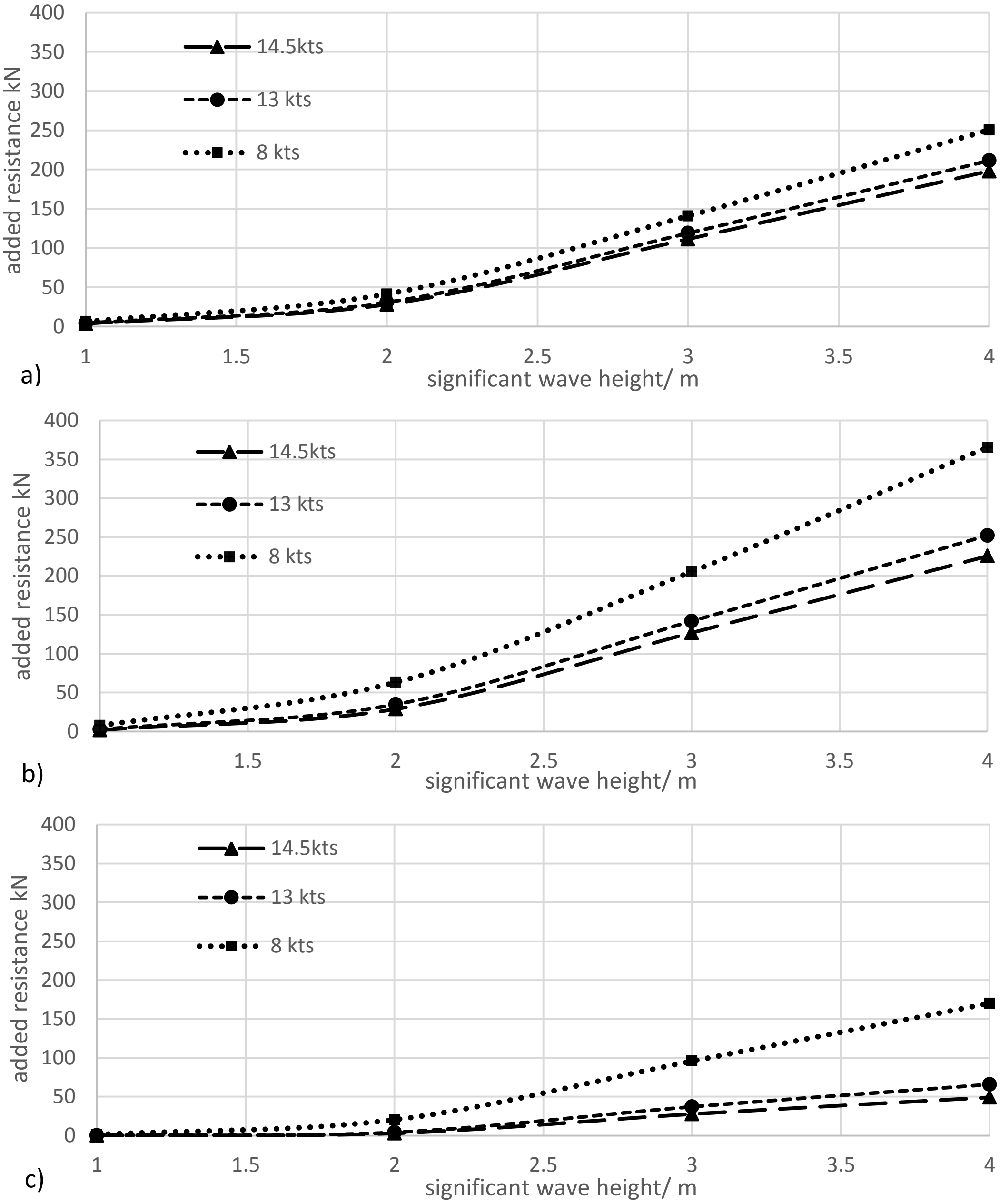

Figure 1: The added resistance of a) LR1 b) VLCC c) ULCC for different significant wave heights in an Atlantic Ocean wave spectra (sea area 49).

As is clear from figure 1, the added resistance due to waves increases as significant wave height increases. There is relatively little added resistance for all vessels up to a significant wave height of around 2m. From 2m the added resistance appears to increase linearly with wave height. This perhaps lends support for using Beaufort force 5 as a cut-off point, since this equates approximately to a significant wave height of 2m and there is thus relatively little added resistance below a Beaufort force 5. For all ship types the added resistance is less for higher ship speeds. This is perhaps not intuitively expected, but maybe explained by the encounter frequency effect. As a vessel travels faster the same length waves will appear shorter and this will, most likely, result in less motion of the vessel and hence less added resistance. The precise degree to which this affects the added resistance changes with speed will depend on the ship length and its resonant motion frequency in relation to the dominant wave period in the spectrum encountered. Also clear in figure 1 is that the *absolute* added resistance is not a straightforward function of ship size. For the two highest speeds the VLCC experiences the most added resistance and the ULCC the least, with the smaller LR1 somewhere between the two. Since the calm water resistance is a function of ship size (largely since the dominant component of resistance is the frictional resistance and this is determined by wetted surface area), the percentage added resistance is inversely related to ship size – the larger the vessel the lower the % added resistance. The larger vessel will have the greatest total resistance and hence power requirement.

To more clearly illustrate the % added resistance and to also include the effects of the added wind resistance, the total hull resistance for the LR1 tanker is presented in figure 2, again for head seas in an Atlantic Ocean sea spectrum and for two vessel speeds. For this calculation the value of wind speed appropriate for particular values of significant wave height was taken from table 3.

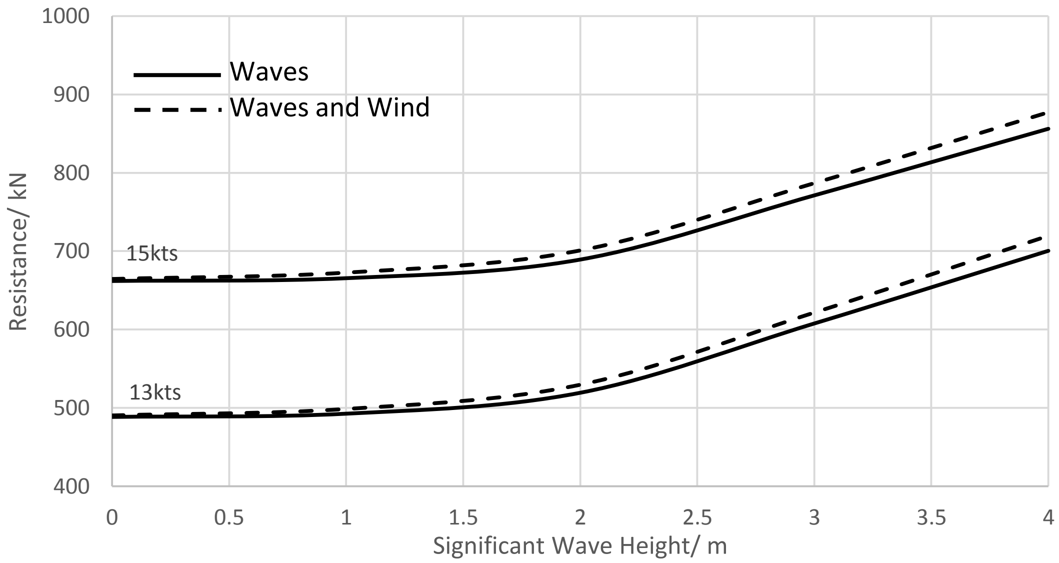

Figure 2: Total resistance of an LR1 tanker in head winds and seas, travelling in an Atlantic Ocean wave spectra.

It may be seen in figure 2 that the added wind resistance is much smaller than the added resistance due to the waves for this vessel. For a vessel with more significant superstructure (e.g. Car Carrier), this may not be the case. It is also clear from figure 2 that the added resistance does not show substantial increase until the significant wave height reaches 1.5m-2m, again perhaps supporting the use of a Beaufort cut-off around Force 5. For this vessel travelling at 13 knots, the added resistance at a significant wave height of 2m is 30.8kN, representing around 6% of the calm water resistance. If a ‘cut-off’ value was specified at this wave height, then there is an effective ‘margin’ on the calm water fuel consumption of around 6%, presuming the fuel consumption in a guarantee clause to be based on the consumption in the 2m wave height and not that in calm water.

3.2 EFFECT OF SEA SPECTRUM

To investigate the effects of using a JONSWAP or ITTC spectra on the added resistance, both spectra were used to calculate added resistance for the LR1 tanker in the vicinity of the Suez canal exit (sea area 50), travelling at 15 knots. These results are shown, for a range of significant wave heights, in table 4.

Table 4: Added resistance for an LR1 tanker travelling in head seas at 15 knots around Suez canal exit (sea area 50), for a range of significant wave heights.

	Added Resistance / kN	

$H_{1/3}$ /m	ITTC	JONSWAP	Difference/ kN
1	2.498	1.717	0.781
1.5	3.56	2.493	1.067
2	9.712	6.869	2.843
2.5	22.694	15.869	6.825

From table 4 it can be seen that the maximum difference between the two sea spectra is 6.83kN. For a wider range of ship speeds and zero-crossing periods, the maximum difference can approach 10kN. From section 2.2, a resistance difference of 10kN for the LR1 travelling at 15 knots equates to a fuel consumption difference of around 0.5 tonnes/day. This therefore suggests that the difference in choice of sea spectra is not particularly significant for these purposes, however if a vessel has a higher added resistance, or travels for the whole of its route in a particular type of wave environment, then clearly the most appropriate spectra should be chosen.

3.3 RELATION TO FUEL CONSUMPTION

The added resistance for the LR1 tanker was calculated for a range of ship speeds and significant wave heights, in an extension to the results presented in figure 2. These results are presented in figure 3, with speed as the independent variable, thus more closely mirroring the presentation typical in a fuel guarantee clause. The total calm water resistance is also illustrated for comparison. The results are summarised in table 5.

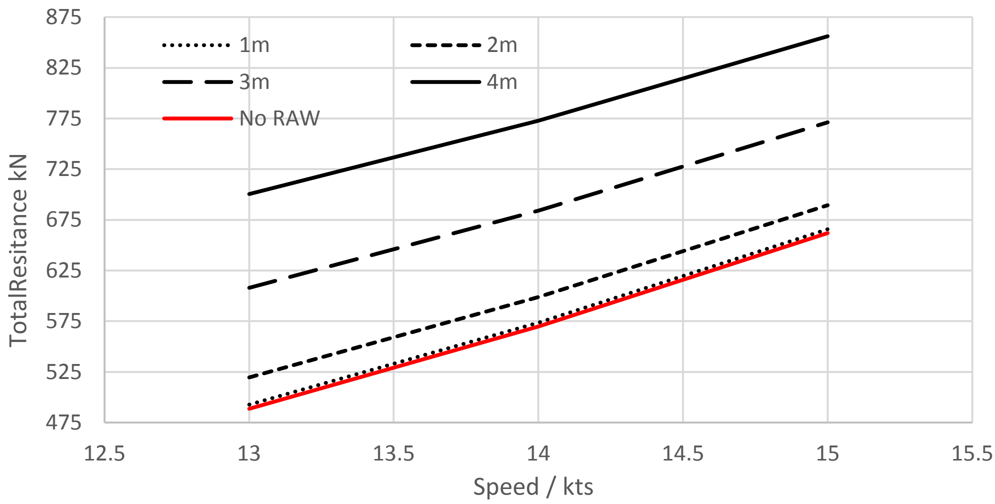

Figure 3: Total resistance for LR1 tanker travelling at different speeds in head waves of different significant wave height, in Atlantic Ocean (sea area 49).

Table 5: Prediction of total and added resistance for a range of speeds and significant wave heights for an LR1 tanker travelling in head waves in Atlantic Ocean sea spectra (sea area 49).

		Sign. Wave h = 1m		Sign. Wave h = 2m		Sign. Wave h = 3m		Sign. Wave h = 4m	
Speed knots	Rc **kN**	Raw kN	Percentage Total %	Raw kN	Percentage Total %	Raw kN	Percentage Total %	Raw kN	Percentage Total %
13	**488.5465**	4.174	0.8471	30.832	5.9363	119.2	19.6137	211.9	30.2536
14	**569.6443**	3.867	0.6742	29.028	5.6084	114.23	16.7034	203.1	26.2807
15	**661.9549**	3.588	0.5391	27.329	5.2975	109.21	14.1616	194.2	22.6783

With the assumptions and method as stated in section 2.2, the daily fuel consumption for the vessel is calculated from these results and presented in figure 4.

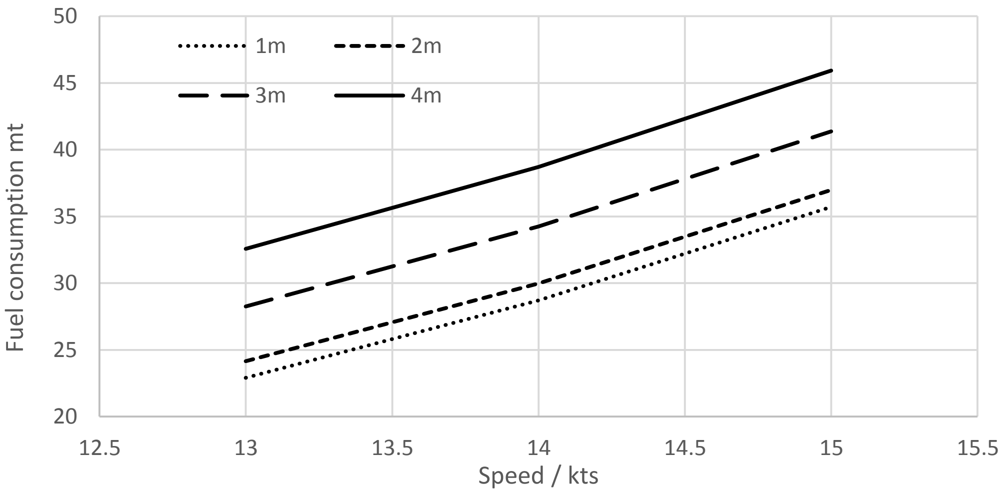

Figure 4: Calculated daily fuel consumption for LR1 tanker travelling at different speeds in head waves of different significant wave height, in Atlantic Ocean (sea area 49).

As previously illustrated with the added resistance (see figures 1a,2), the increase in fuel consumption for significant wave heights less than 2m is rather small. Since a Charter Party usually uses a single value of fuel consumption for speed, it is not clear which value is used. Presumably, the value of fuel consumption appropriate to the Beaufort Force specified as the 'cut off' in the agreement is employed. This would represent a small 'margin' of around 6% on the calm water fuel consumption.

Whilst there is always scope to improve the methods of calculation employed in this study, with agreement from all parties it would be possible to produce results such as those in figure 4 for a specific vessel and route and thus provide greater transparency in fuel guarantee calculations to all parties. A statistical approach to the route(s) sailed would allow a curve for that 'sea state' rather than for individual wave heights.

3.4 STATISTICAL APPROACH TO PREDICT FUEL CONSUMPTION TABLES

In order to better represent the likelihood of encountering different sea states in a typical voyage, similar calculations may be employed in a statistical approach to the calculation of fuel consumption and performance, for a particular route. A simplification of this method could be employed, whereby If it is agreed that it is sensible to disregard fuel consumption in conditions greater than, say a wave height of 3m, then the total likely fuel consumed for sea states less than 3m is estimated. Thus, there is transparency around the 'added fuel' consumed above the calm water and up to the 'cut off' conditions agreed.

By way of example, if the LR1 tanker is taken and the sea area for the Atlantic Ocean (sea area 49) then the probability of the wave height exceeding each eave height can be calculated from the wave statistics. The added resistance is calculated for each wave height. Results are shown for an example calculation in table 6.

Table 6: Calculation of annual added resistance for LR1 tanker travelling in Atlantic Ocean (sea area 49).

Wave height X / m	Probability of exceeding X	Days a year waves lie within X_i and X_{i-1}	Added Resistance when wave Height = X / kN	Resistance per year / kN.year^{-1} (excluding days when X > 3m)
0.5	0.9583	15.1842	1.297	19.6939
1	0.8436	41.8667	7.230	302.6962
1.5	0.6822	58.9421	21.205	1249.8683
2	0.5066	64.0643	53.241	3410.8488
2.5	0.3456	58.7727	122.747	7214.1816
3	0.21660	47.1079	238.880	11253.148
Total		**285.9381**		**23450.4376**

A value of 'average' annual added resistance can be calculated by dividing the total 'annual' added resistance by the number of days per year that waves do not exceed 3m. That is:

$$\text{Average Added Resistance Per Year} = \frac{\text{Resistance per year}}{\text{Total number of days waves do not exceed 3m}} = \frac{23450.4376}{285.9381}$$

$$= \mathbf{82.01}\boldsymbol{kN}$$

This may be either added to the other components of resistance, or used alone. The fuel consumption associated with such an 'average' added resistance may be calculated. The method can be applied for all speeds that are relevant to the vessel. This allows for the transparent calculation of a performance table, tailored to the specific vessel and operating area, whilst still implementing a 'cut off' in the weather conditions to exclude more extreme conditions.

5. CONCLUSIONS

This study has investigated the added resistance in waves for a range of generic tanker forms, particularly with regards to the use of a single 'cut off' Beaufort number in Charter Party agreements. The study implemented methods available to the ship designer to calculate ship resistance, together with motions and added resistance, using minimal detailed vessel characteristics. This suggests the method is reasonably practical for implementation.

The method as implemented focuses on a practical, comparative study. Methods to calculate added resistance for vessels in waves still require validation that is more extensive and greater refinement. In particular, the method employed here is more suited to fast cargo ships. It is likely that for high block coefficient vessels, such as tankers, the added resistance in short waves in particular is underestimated. There is still wide scatter in comparative studies between different methods of estimating added resistance and this suggests a need for ongoing research.

The present study is limited in the range of vessel types considered and in particular is restricted to head seas. Whilst head seas often represent the 'worst case' for added resistance in waves, a more complete analysis would consider the ship route in relation to the sea area traversed as well as the time of year. This work will be extended in these directions in the near future.

Results illustrate that added resistance is small up to a significant wave height of around 2m, reasonably independent of the ship sizes investigated. The added resistance tends to decrease as speed increases. This broadly supports the 'cut off' value of a Beaufort Force 5 frequently employed, however the use of Beaufort number is potentially confusing. The Beaufort Scale is based on wind speed and not wave height. It is shown in this study that the majority of the added resistance experienced by a ship in weather is due to waves. There is no clear relationship between the significant wave height and modal wave period, which characterise the sea conditions experienced, and the Beaufort number at the same location, since fetch and duration of wind from a particular direction influence the waves and hence the vessel added resistance. The limited comparison undertaken here between the ITTC and JONSWAP wave spectra to represent the waves suggests the precise form of the spectra to be less important. However, the present study is limited to head waves and it may be that if different directions are considered, or a combined bi-directional spectrum experienced (i.e. with swell waves from a different direction to wind-generated waves), the spectrum employed in the analysis will make an important difference.

With some assumptions about propulsive efficiency and engine specific fuel consumption, the fuel consumption may be calculated from the combination of the added resistance in waves and calm water resistance. This allows a more transparent method to calculate vessel fuel consumption for a range of encountered sea states, or significant wave heights. If current fuel guarantee calculations are based on the fuel consumption at the point where added wave resistance starts to increase more rapidly (around a significant wave height of 2m), then this represents a fuel margin of around 6% over the calm water fuel consumption, however at present such transparency is lacking. Methods similar to those employed to calculate power margins for selection of installed engine power at the ship design stage may readily be adapted to provide a more transparent means of calculating 'average' fuel consumption in encountered weather conditions.

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