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DETERMINING THE EEDI "MINIMUM PROPULSION POWER"

F. C. Gerhardt, M. Kjellberg, B. Korkmaz, K. Ljungqvist and A. Shiri, SSPA Sweden AB, Sweden

ABSTRACT
The introduction of the EEDI almost a decade ago, slow steaming and the wish to reduce bunkering costs have resulted in a trend to install less powerful engines in ships. To avoid vessels becoming underpowered and unsafe, the International Maritime Organization (IMO) has published an interim guideline regarding the "Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse Conditions".
In this paper we follow the IMO-guideline step by step and work out the minimum engine size for the KVLCC2 tanker. Using a combination of Computational Fluid Dynamics and model tests, the parameters and assumptions behind the guideline are discussed in some detail. Results show, that it is particularly important to determine the added resistance in waves correctly because it dominates the power prediction. It becomes clear, that the selection of the 'propulsive' factors, particularly the thrust deduction factor *t,* has a significant influence on results.

1. INTRODUCTION

In order to measure and reduce greenhouse gas emissions the International Maritime Organization (IMO) has passed a resolution on the Energy Efficiency Design Index (EEDI). The index is a measure of the amount of carbon dioxide a ship emits in relation to its transport work. It is required that most newbuilds have an EEDI smaller than a prescribed value, which in turn is based on statistics and will gradually be lowered over time.
One obvious way to reduce CO_2 emissions is "slow steaming" and the installation of a smaller engine. To avoid vessels becoming underpowered and thus unsafe, the IMO has implemented rules regarding the "Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse Conditions". An IMO "Interim Guideline" first published in 2013 outlines the details of how to determine this "Minimum power".
In 2017, suggestions for modification of the resolutions on minimum power were submitted to IMO as a result of two research projects, SHOPERA (European Union) and JASNAOE (Japan), [1]. These proposals were later criticised, i.a. for limiting the possibilities for hydrodynamic design improvements and for being too conservative.
Subsequent discussions within IMO did not result in consensus and it was therefore recommended that a slightly modified "Interim Guideline" be kept and published as MEPC.1/Circ.850/Rev.2 [2].
By the end of 2019 this guideline was still the only regulatory requirement addressing the safety critical matter of ensuring that ships are provided with sufficient power to safely manoeuvre in adverse conditions [3].

2. THE IMO INTERIM GUIDELINE

The minimum power requirements from IMO interim guideline MEPC.1/Circ.850/Rev.2 (for simplicity called 'The IMO-guideline' here) currently apply to all newbuild ships that need to comply with EEDI rules.
Below follows a short descripting of the guideline and the underlying principles.

2.1 TWO ASSESMENT LEVELS

The IMO-guideline gives two alternative methods to determine minimum propulsion power. Firstly, a "Level 1 assessment" using generic "minimum power lines" and secondly a "Level 2 assessment" that is based on individually calculating ship resistance components which are then used as input to a power prediction.

2.1.1 Level 1 assessment

The "minimum power line" method is simple, conservative and based on installed power of existing ships. It uses deadweight and ship type as the only input. Minimum power is calculated as:

$$P_{D\,min} = a \cdot DWT + b$$

Where *DWT* is the deadweight of the ship in metric tons and *a* and *b* are tabulated in the IMO-guideline

2.1.2 Level 2 assessment

The second method is more advanced and takes main dimensions, rudder size, and windage area into account. It assumes that ships with sufficient power to advance in waves will also be able to keep course. The required advance speed depends on the relative size of the rudder and varies between 4 and 9 knots. The assessment assumes weather conditions equating to Beaufort Force (BF) 7 for ships below 200 m and BF 8 for ships above 250 m, with the condition being linearly interpolated for ships between 200 m and 250 m [2].

The assessment procedure consists of two steps:

1. Definition of the required advance speed in head wind and waves
2. Assessment whether the installed power is sufficient to achieve this required advance speed

Step 2 involves a speed-power prediction in wind and waves and requires detailed knowledge of the various resistance components, namely calm water, wind, and added wave resistance. Figure 1 illustrates the assessment schematically.

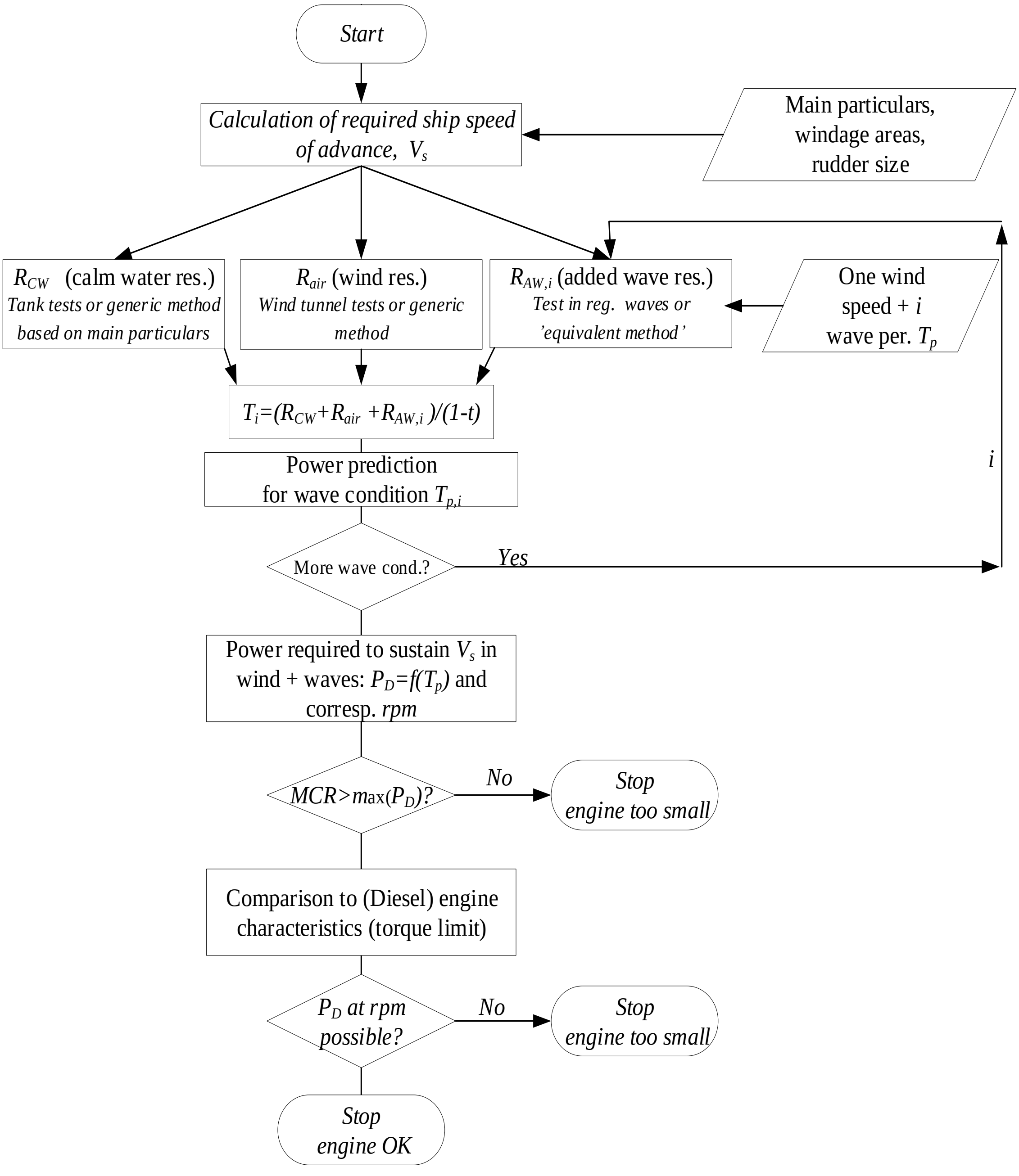

Figure 1: Flow diagram interpreting the Level 2 assessment from MEPC.1/Circ.850/Rev.2 [2]

2.2 EXAMPLE SHIP AND CASE STUDY

In this paper both, Level 1 and Level 2 assessments are discussed. Using the well-known KVLCC2 tanker [4] as a case study, minimum propulsion power is calculated in all the alternative ways described in the IMO-guideline.
The KVLCC2 is the second variant of a generic Very Large Crude Carrier (VLCC) developed at the Korea Research Institute of Ships and Ocean Engineering (KRISO). Although the tanker has never been built, it has been used extensively for CFD and experimental studies. In practice VLCCs are usually unproblematic in terms of minimum power but due to the availability of data and the usefulness as a benchmark case it was decided to use the KVLCC2 for the present case study. On similar note the more common design draft, not scantling as required by EEDI, is used here.
The main particulars of the ship and the two models used for the case study are summarised in Table 1. Photographs of the 1:68 seakeeping model are shown in Figure 2 and further details can be found in [5].

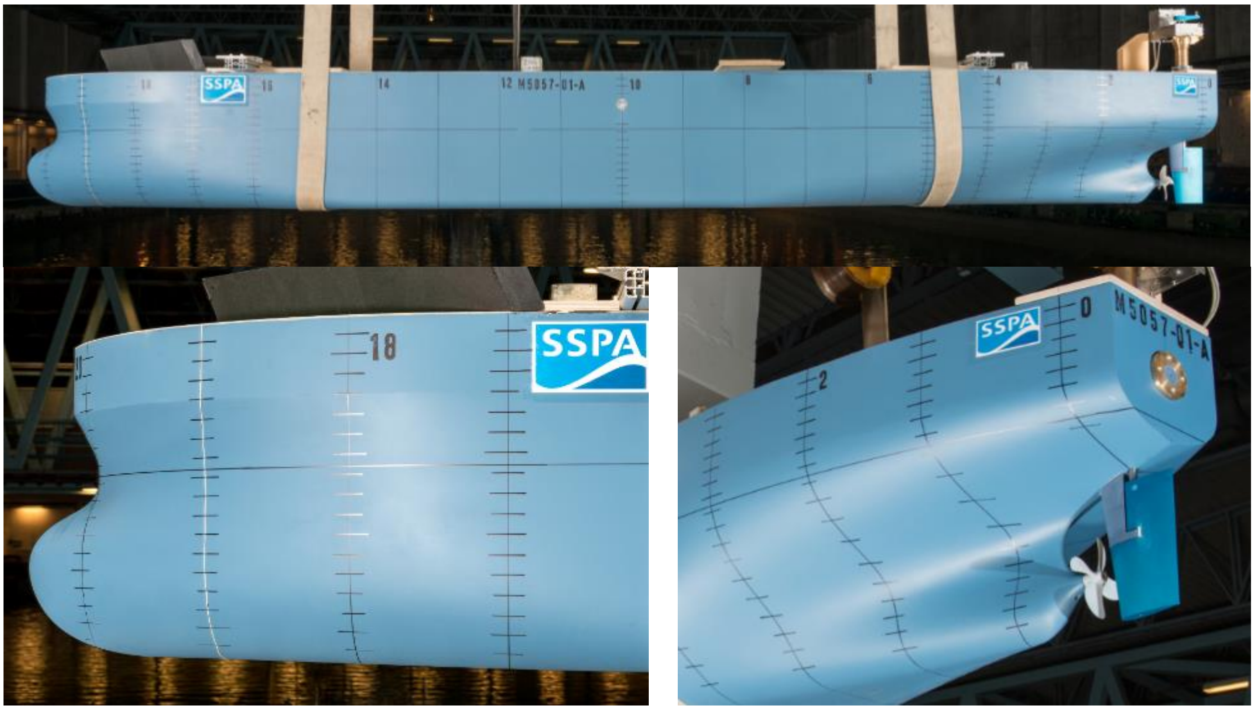

Figure 2: KVLCC2 model used for seakeeping tests

Table 1: Main particular of KVLCC2 [4,6]

	Ship	Resistance model	Seakeeping model
Scale	1	45.714	68
HULL			
Lpp [m]	320	7.0	4.706
Beam, *B* [m]	58	1.269	0.853
Draft, *T* [m]	20.8	0.455	0.306
Displ ∇ [m³]	312 784	3.274	0.995
Wetted surface *S* (hull+rudder) [m²]	27 249+ 275.3 = 27524.3	13.171	5.952
Block coeff., C_B	0.810	0.810	0.810
Deadweight, *DWT* [t]	300 000	NA	NA
Frontal wind area A_{FW} [m²]	1200	NA	NA
Lateral wind area A_{LW} [m²]	3600	NA	NA
Pitch gyradius k_{yy}	NA	NA	0.25*Lpp
PROPELLER KP458 [4]			
No. blades	4	NA, towed models	
D [m]	9.86		
P/D (0.7R)	0.721		
A_e/A_0	0.431		

3. LEVEL 1 ASSESMENT OF KVLCC2

With the “tanker values” of a = 0.0652 kW/t and b = 5960.2 kW [2] and an estimated deadweight of 300 000 t [6] the minimum power according to the Level 1 assessment becomes:

$$P_{D,}min = a \cdot DWT + b$$
$$P_{D,}min = 25.5 \text{ MW}$$

4. LEVEL 2 ASSESMENT OF KVLCC2

The Level 2 assessment procedure is based on the principle that, if the ship has sufficient installed power to move with a certain advance speed, V_s, in head waves and wind, the ship will also be able to keep course in waves and wind from any other direction.

4.1 ADVERSE WEATHER CONDITIONS

The IMO-guideline defines the “adverse conditions”, under which the ship should be able to sustain the advance speed V_s, by means of JONSWAP wave spectra and the mean wind speed V_w. Some of the parameters that define the environmental conditions depend on ship length, see Table 2.

Table 2: Parameters defining “adverse conditions” [2]

Ship length	V_w	H_s	T_p
Lpp < 200m	15.7 m/s	4.0 m	7s-15s
200m≤Lpp≤250m	Linearly interpolated		
Lpp>250m	19 m/s	5.5 m	

It is important to note that the environmental conditions are therefore not defined by one single sea state but by a range of sea states with spectral peak periods varying from 7s to 15s. As a result, not one but several predictions of minimum power need to be carried out, compare Figure 1. The highest power value calculated during this process determines the engine size.

For a large ship like the KVLCC2 (L_{pp}>250m) three example spectra are plotted in Figure 3.

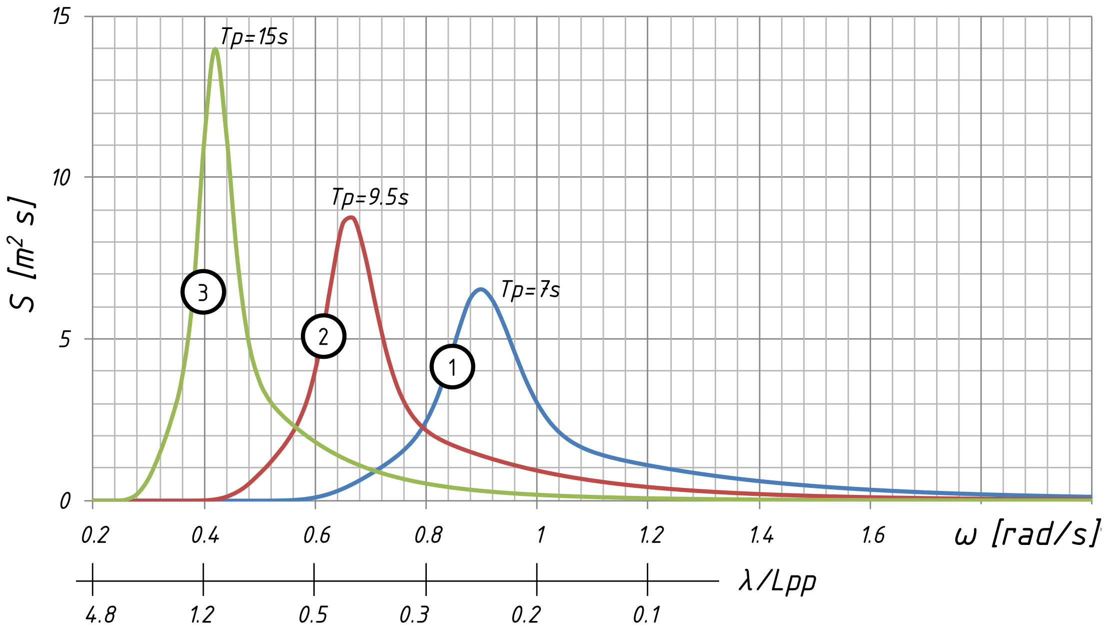

Figure 3: JONSWAP spectra [11] with a significant wave height of H_s=5.5m and three different modal periods T_p

4.2 REQUIRED SHIP SPEED OF ADVANCE

The IMO-guideline determines the minimum ship speed of advance, V_s, depending on ship design. For example, ships with larger rudder areas will be able to keep course with less powerful engines and at lower speeds.

4.2.1 The IMO-guideline

According to the IMO-guideline the required ship advance speed through the water in head wind and waves, V_s, is set to the larger of:

- minimum navigational speed, V_{nav}; or
- minimum course-keeping speed, V_{ck}.

The minimum navigational speed, V_{nav}, facilitates leaving coastal area within a sufficient time before a storm escalates. The minimum navigational speed is set to a fixed value 4.0 knots.

The minimum course-keeping speed, V_{ck}, on the other hand depends on ship and rudder size. It is selected to facilitate course-keeping of the ships in waves and wind from all directions. It is defined on the basis of the reference course-keeping speed $V_{ck,ref}$ related to ships with the rudder area A_R equal to 0.9% of the submerged lateral area corrected for breadth effect, and an adjustment factor that takes the actual rudder area into account:

$$V_{ck} = V_{ck,\,ref} - 10.0\cdot(A_{R\%} - 0.9)$$

where V_{ck} in knots, is the minimum course-keeping speed, $V_{ck,ref}$ in knots, is the reference course-keeping speed, and $A_{R\%}$ is the actual rudder area, A_R, as percentage of the submerged lateral area of the ship corrected for breadth effects, $A_{LS,\,cor}$, calculated as:

$$A_{R\%} = 100\%\ A_R/A_{LS,cor}$$

Where the submerged lateral area corrected for breadth effect is calculated as:

$$A_{LS,cor} = L_{pp}\cdot T_m\,\{(1 + 25\,(B_{wl}/\,L_{pp})^2\}$$

The reference course-keeping speed $V_{ck,ref}$ for bulk carriers, tankers and combination carriers is defined, depending on the ratio of the frontal windage area A_{FW} to the lateral windage area A_{LW}, as follows:

- 9.0 knots for A_{FW}/A_{LW} = 0.1 and below and 4.0 knots for A_{FW}/A_{LW} = 0.40 and above
- Linearly interpolated between 0.1 and 0.4 for intermediate values of A_{FW}/A_{LW}.

4.2.2 Case study KVLCC2

Using the above method and with the values from Table 1 the required ship speed of advance for the KVLCC2 becomes:

$$V_S = 4 \text{ knots}$$

In order to verify that the chosen engine can provide enough power to sustain this speed in wind and waves the total resistance of the KVLCC2 is split into calm water, wind, and added wave components. These are calculated as follows:

4.3 CALM WATER RESISTANCE

4.3.1 The IMO-guideline

Section 3.9 of the IMO-guideline explains how to determine calm water resistance for bulk carriers, tankers and combination carriers. Neglecting the wave-making resistance and also the hull roughness, one obtains:

$$R_{CW} = (1+k)\cdot C_F \cdot \frac{1}{2}\rho S \cdot V_s^2$$

Where k is the form factor, C_F the frictional resistance coefficient, S the wetted surface area of the ship and ρ the density of water.

According to the IMO-guideline C_F should be calculated from the ITTC 1957 correlation line [7] as:

$$C_F = \frac{0.075}{[log_{10}(Re) - 2]^2}$$

Where Re denotes the L_{pp}-based Reynolds number.

The IMO-guideline recommends determining the form factor k from model tests. Where model tests are not available it gives the following empirical formula:

$$k = -0.095 + 25.6 \frac{C_B}{(Lpp/B)^2 \sqrt{B/T}}$$

With C_B block coefficient, *B* beam and *T* draft.

4.3.2 Case study KVLCC2

Based on the generic *k*-equation above and with the C_B, *B,* and *T* values from Table 1 the generic form factor for KVLCC2 becomes

$$k_{generic} = 0.313$$

In order to also experimentally determine *k,* towing tank tests with the large 7-metre model (Table 1) where conducted and analysed using Prohaska's Method [9], resulting in:

$$k_{towing\ tank} = 0.232$$

At a seawater temperature of 15° the frictional resistance coefficient C_F from the above equation is:

$$C_F = \frac{0.075}{[log_{10}(4.19 \cdot 10^8) - 2]^2} = 1.71 \cdot 10^{-3}$$

Based on the experimental results the calm water resistance therefore becomes:

$$R_{CW} = (1 + 0.232) \cdot C_F \cdot \frac{1}{2} \rho S \cdot V_s^2 = 126\ kN$$

The corresponding value based on the generic, rather than the measured, form factor is $R_{CW,generic}$ = 134 *kN*.

4.4 WIND RESISTANCE

4.4.1 The IMO-guideline

Wind resistance is calculated in section 3.11 of the IMO-guideline

$$R_{air} = C_{air} \cdot \frac{1}{2} \rho_{air} \cdot A_{FW} \cdot V_{w,rel}^2$$

where C_{air} is the aerodynamic resistance coefficient, ρ_{air} is the density of air (here 1.2 kg/m^3), A_{FW} is the frontal windage area of the hull and superstructure and $V_{w,rel}$ is the relative or "apparent" wind speed (sum of ship speed and true wind speed from Table 3).

The IMO-guideline recommends finding the coefficient C_{air} by wind tunnel testing, alternatively the generic value of 1.0 can be used.

4.4.2 Case study KVLCC2

Based on the generic aerodynamic resistance coefficient of C_{air} = 1.0, the wind area from Table 1 and the true wind speed of V_w = 19m/s (Table 2) the wind resistance of the KVLCC2 sailing at 4 knots becomes:

$$R_{air,generic} = 319.3\ kN$$

Based on available wind tunnel data for a number of similar VLCCs and the experimentally determined values published by Blendermann [10] a wind resistance coefficient of C_{air} = 0.96 seems to be appropriate for the KVLCC2. This results in a somewhat smaller wind resistance of:

$$R_{air} = 306.6\ kN$$

4.5 ADDED RESISTANCE IN WAVES

4.5.1 The IMO-guideline

The IMO-guideline suggests model testing in regular waves to obtain the quadratic transfer function of the added resistance.

The added resistance under the "adverse conditions" defined by the wave spectra from section 4.1 is then derived based on the hypothesis of linearity and the principle of superposition:

$$R_{AW} = 2\int_0^{\infty} \frac{R_{AW,\,reg.}(Vs,\omega)}{{\zeta_A}^2} S_{\zeta}(\omega)d\omega \quad (1)$$

Where $R_{AW,reg}$ *(Vs,ω)* denotes the added resistance values from the model tests in regular waves at discrete different wave frequencies ω , $S_\zeta(\omega)$ is the wave energy density spectrum and ζ_A is the wave amplitude, compare section 4.1 of this paper and also [11].

4.5.2 Case study KVLCC2

In order to determine the quadratic transfer function of the added resistance, tests in regular (i.e. harmonic) waves were conducted. Because of the low speeds involved (ca. 4 knots) such tests cannot be carried out in ordinary towing tanks. In order to "outrun" wave reflections from the walls the facility needs to be about 30 m wide [11]. Consequently, tests with the smaller of the two KVLCC2 models were conducted in SSPA's 40 m wide seakeeping basin.

All experiments were carried out using the technique of "towing in waves". Several commercial model-testing basins, including SSPA, have recently investigated the idea of towing a model in waves using a modified soft-mooring arrangement consisting of long lines and springs, compare [5]. The setup consists of plywood "wings" at deck level either side of the model. Stiff tow wires are attached to these wings and meet forward of the bow and aft of the transom. These lines are let through blocks and connect to soft vertical springs that allow the model to surge in a more or less unrestricted way and at the same time dampen out violent wave induced jerks. Ring-type strain gauges measure the forces in all four lines. The total towing force (= resistance) is determined from the measured signals and the geometry of the setup. The stiffness of the springs was chosen in such a way that the natural frequency of the whole system was far away from the encountered wave frequencies.

Figure 4 summarises the results from the added resistance tests with this setup. When analysing the experiments added resistance due to waves $R_{AW,reg}$ was determined by subtracting the mean resistance in calm water from the mean resistance in regular waves.

The coefficient of added resistance due to waves plotted in the figure is defined as:

$$C_{AW}(Vs,\omega) = \frac{R_{AW,\,reg.}(Vs,\omega)}{\rho g B 2{\zeta_A}^2/L_{pp}}$$

For the design speed of 15.5 knots Figure 4 (top) also shows C_{AW} values from various other sources. It can be noticed that a) for waves shorter than 0.7 ship length the experimental scatter is very large. The most likely reason for this is decreasing experimental accuracy with decreasing wave height, compare also [12] and b) the STAWAVE-2 method, which was developed for correcting sea-trials and uses main particulars as the only input [13], seems to predict the 'peak height' of the C_{AW} function fairly well. The peak position is however off.

The bottom plot in Figure 4 shows results from seakeeping tests with the KVLCC2 and also an Aframax at 4 knots. It is somewhat surprising to see, that the STAWAVE-2 method, which was developed for something completely different, captures the level of the added resistance transfer function fairly well, albeit not in the conservative way that would be expected from a generic method. To be conservative in the context of minimum power predictions it would have to overpredict C_{AW} compared to the experiments.

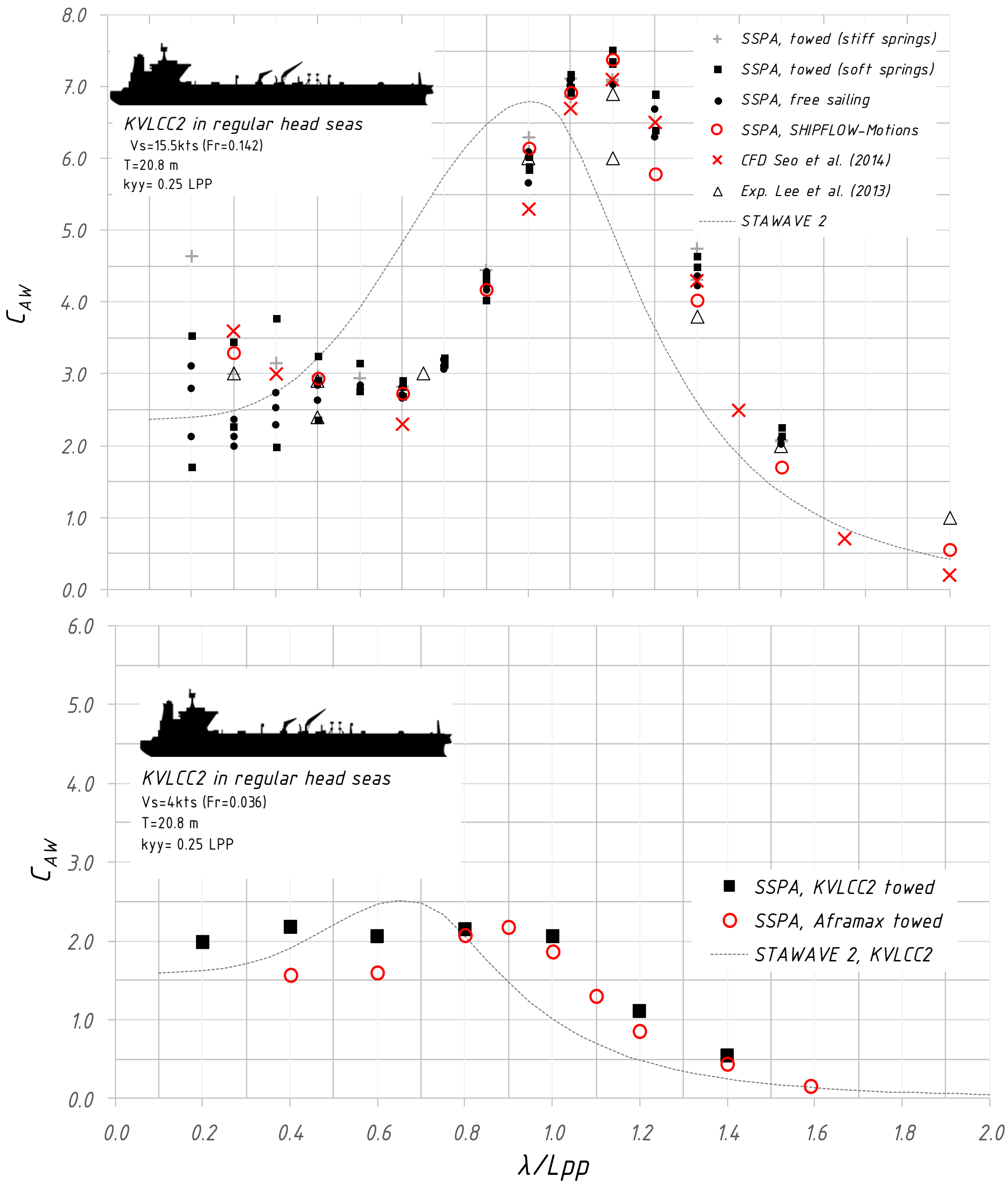

Figure 4: Transfer functions for added resistance of KVLCC2. 15.5 knots (top) and 4 knots (bottom)

Using the measured C_{AW} function (square symbols, bottom of Figure 4) as input to Equation 1 and integrating with the spectra defined in section 4.1 yields one unique R_{AW} value for each spectral peak period. Focusing on the three example spectra from Figure 3 one obtains the following added resistance forces:

$$R_{AW}\textcircled{1} = 810.0\ kN$$
$$R_{AW}\textcircled{2} = 840.1\ kN$$
$$R_{AW}\textcircled{3} = 657.2\ kN$$

4.6 TOTAL RESISTANCE

Once calm water, air, and added wave resistance are known, the total resistance can be calculated as the sum of these components, compare section 3.8 of the IMO-guideline. In the present paper the calm water resistance already includes the resistance of the appendages and the total resistance for the three example spectra becomes:

$$R(1) = 1220kN$$
$$R(2) = 1250kN$$
$$R(3) = 1067kN$$

see also Figure 5. The IMO-guideline does not give a generic method to determine added resistance in waves, the corresponding 'staple' in the figure is therefore left blank.

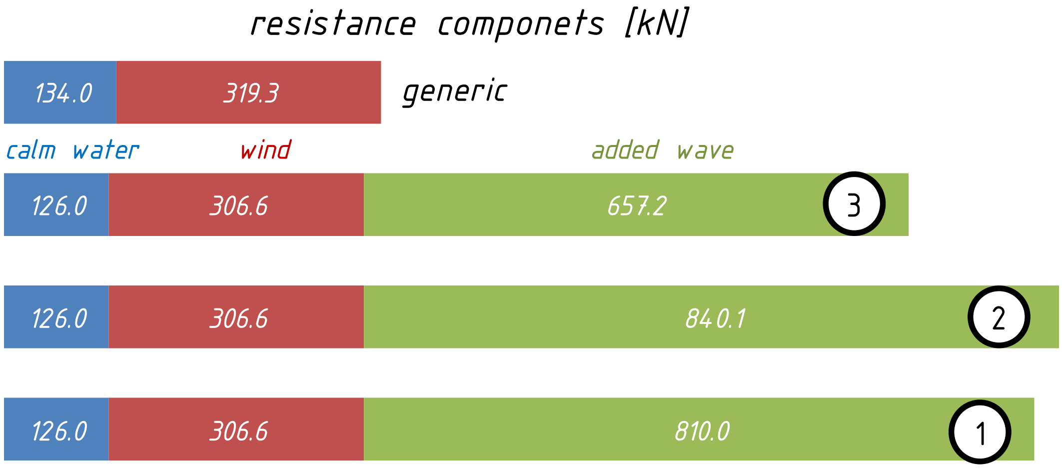

Figure 5: Comparison of resistance components for KVLCC2 at 4 knots

4.7 POWER PREDICTION

Now that the total resistance has been calculated a power prediction can be made, compare flow diagram in Figure 1.

4.7.1 The IMO-guideline

As described in sections 3.14 to 3.16 of the IMO-guideline such a power prediction is based on the "K_T/J^2 method" from the "1978 ITTC Performance Prediction Method" [7]. The required advance ratio *J* of the propeller is found from the propeller loading K_T/J^2:

$$\frac{K_T}{J^2} = \frac{T_S}{\rho D^2 (1-w)^2 V_S^2}$$

Where D is the propeller diameter. From the definition of the advance ratio the rate of revolution of the propeller becomes:

$$n_S = \frac{(1-w)\ \ V_S}{J\ \cdot D}$$

Where *w* is the (full-scale) wake fraction coefficient.

Finally, the shaft power to propel the ship at V_S in "adverse conditions" becomes:

$$P_{DS} = 2\pi\rho \cdot K_Q(J) \cdot D^5 n_S^3$$

Where K_Q denotes the torque coefficient of the full-scale propeller at the advance ratio *J*. This is calculated from the full-scale propeller open water curves [7].

4.7.2 Case study KVLCC2

Section 3.13 of the IMO-guideline gives generic values for wake fraction *w* and thrust deduction factor *t*. For the KVLCC2 these generic values are:

$$t_{generic} = 0.245$$
$$w_{generic} = 0.350$$

Figure 6 compares these numbers to measured and calculated values from different sources.

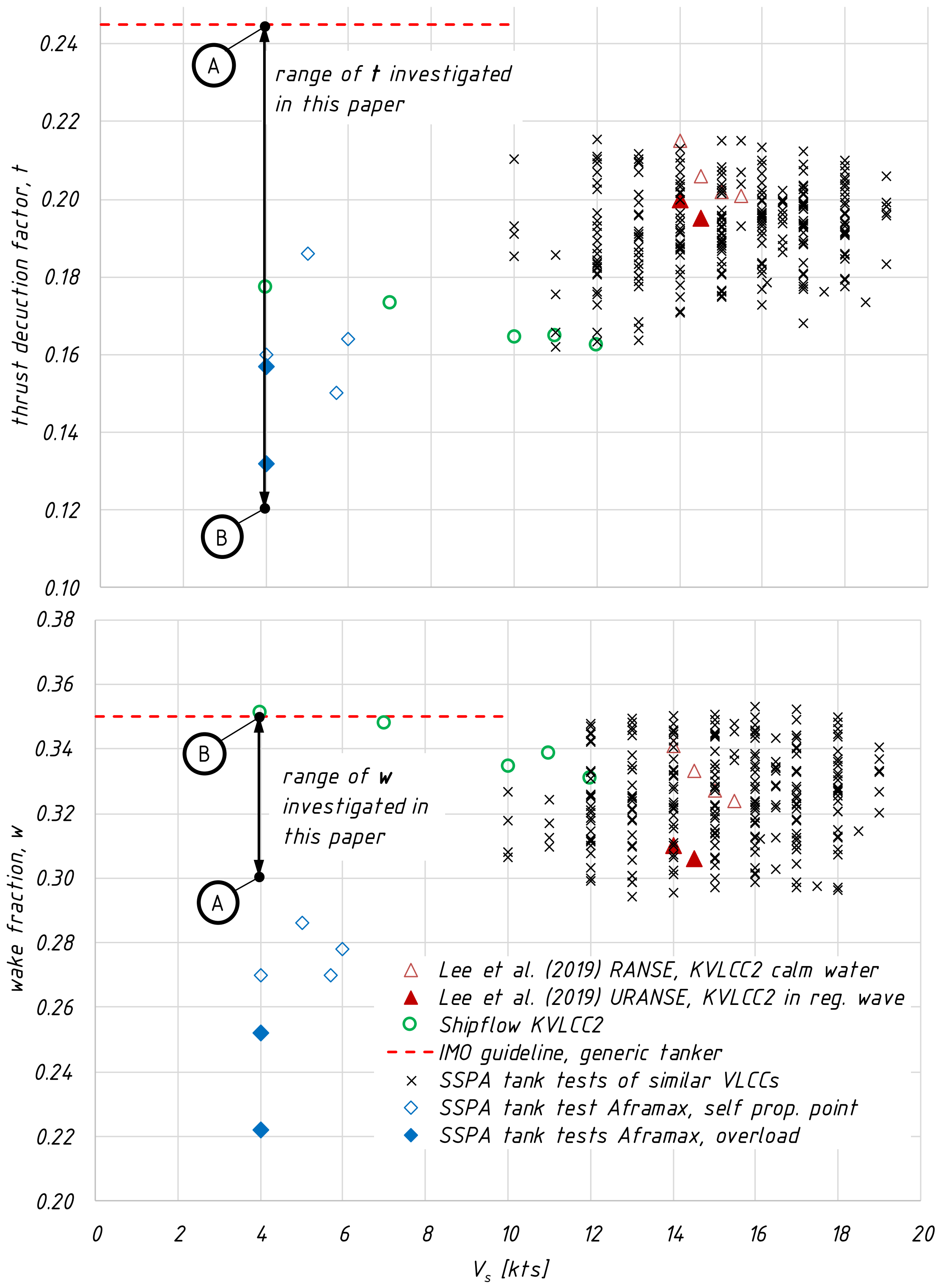

Figure 6: Wake fraction and thrust deduction for tankers

As can be noticed:

- The generic values (dashed lines) are higher than most of the experimental and CFD values
- SHIPFLOW simulations (combined potential flow, thin boundary layer and RANSE code) seem to plausibly extend the experimental trend at lower speeds
- Wake values from the RANSE simulations by Lee et al. [6] are similar to the SHIPFLOW simulations. *t*-values from the two sources, however, differ by some 20%.
- As illustrated by the URANSE results (solid vs. light triangles) and 'SSPA Aframax' tests (diamonds) the effect of overloading the propeller e.g. due to waves is to reduce *w* and *t* compared to the calm water case or the self-propulsion point values.

For the present case study of the KVLCC2 values of *t* and *w* are taken from the SHIPFLOW calculations at 4 knots (circular green symbols):

$$t = 0.177$$
$$w = 0.351$$

Additionally, the influence of *t* and *w* on the minimum propulsion power was investigated by varying the two factors within the range illustrated by the circular **A** and **B** symbols in Figure 6.

Scenario A (conservative): t=0.245; w=0.300
Scenario B (optimistic): t=0.120; w=0.351

Based on these assumptions and with the resistance values calculated above, power predictions were made. The results are illustrated in Figure 7.

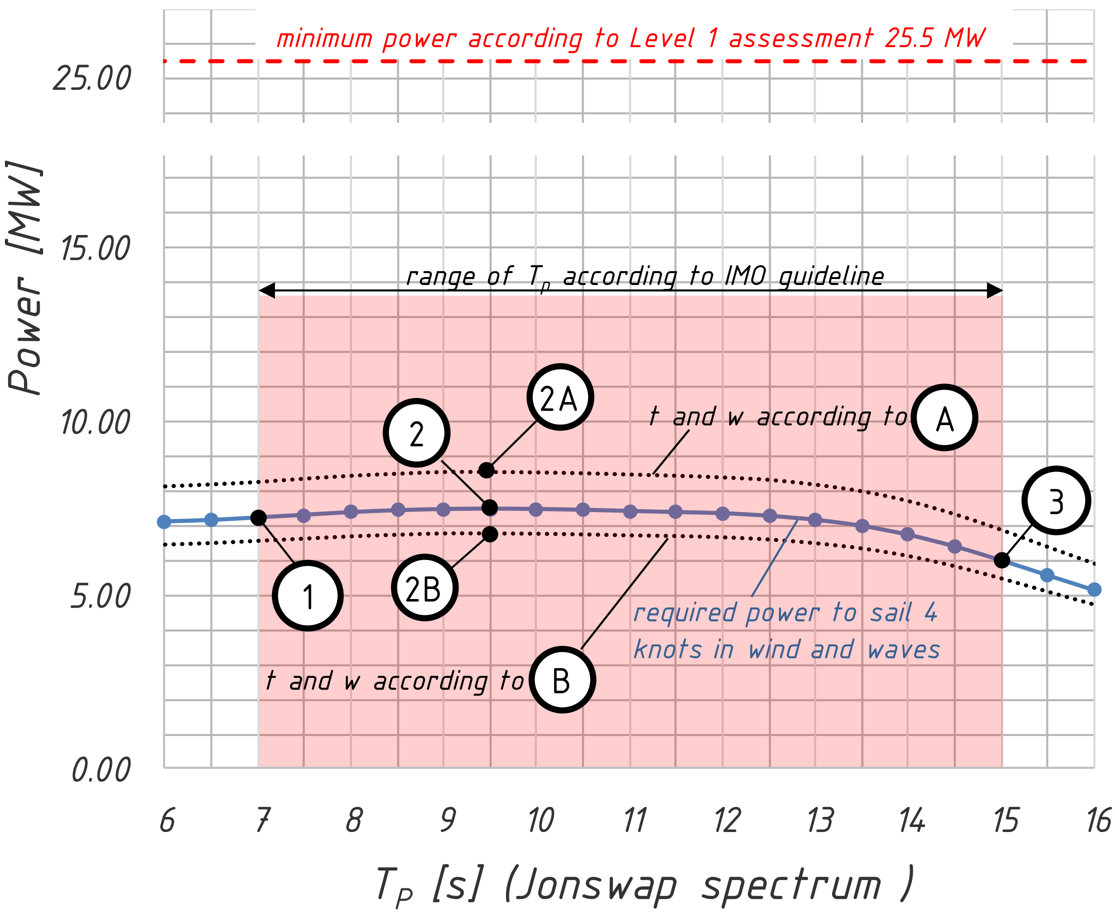

Figure 7: Required power to maintain a speed of 4 knots in wind and waves as function of modal period T_p

As expected, point 2 –having the largest total resistance– requires the highest power, P_D=7.5 MW. This corresponds to 'Spectrum 2' with a T_p of 9.5s, see also Figure 3. To maintain a speed of 4 knots in the other spectra requires less power. The Level 2 minimum propulsion power and the corresponding *rpm* for the KVLCC2 therefore correspond to point 2:

P_{DS}=7.5 MW $n_{Level\ 2}$ = 47 rpm

It can also be seen from Figure 7, that varying thrust deduction factor and wake fraction within the A-B range from Figure 6 significantly influence the results of the power prediction. This is illustrated by the corridor between the dotted lines. Depending on the choice of *w* and *t* the power demand can differ by about ± 1 MW.

4.8 TORQUE LIMITATION

Finally, it remains to be checked, that the chosen Diesel engine can actually provide the required power at the calculated *rpm* values

4.8.1 The IMO-guideline

As described in section 3.17 of the IMO-guideline the required minimum MCR for Diesel engines is calculated considering the torque limitation line.

4.8.2 Case study KVLCC2

Figure 8 plots the operational points 1-3 (i.e. power/*rpm* combinations corresponding to wave spectra 1-3) into load diagrams for two Diesel engines.
Engine 1, with an MCR of 24 MW at a rate of revolution of 75 1/min, is a typical VLCC-engine (green solid line). It can bring the KVLCC2 up to a design speed of 15.5 knots in calm water with a sea margin of 15%.
Engine 2 (red dash-dotted line) is much smaller (12 MW @ 69 rpm) and can be considered a “slow steaming” option. It will propel the ship at about 12.2 knots in calm water with the same sea margin as the larger engine.

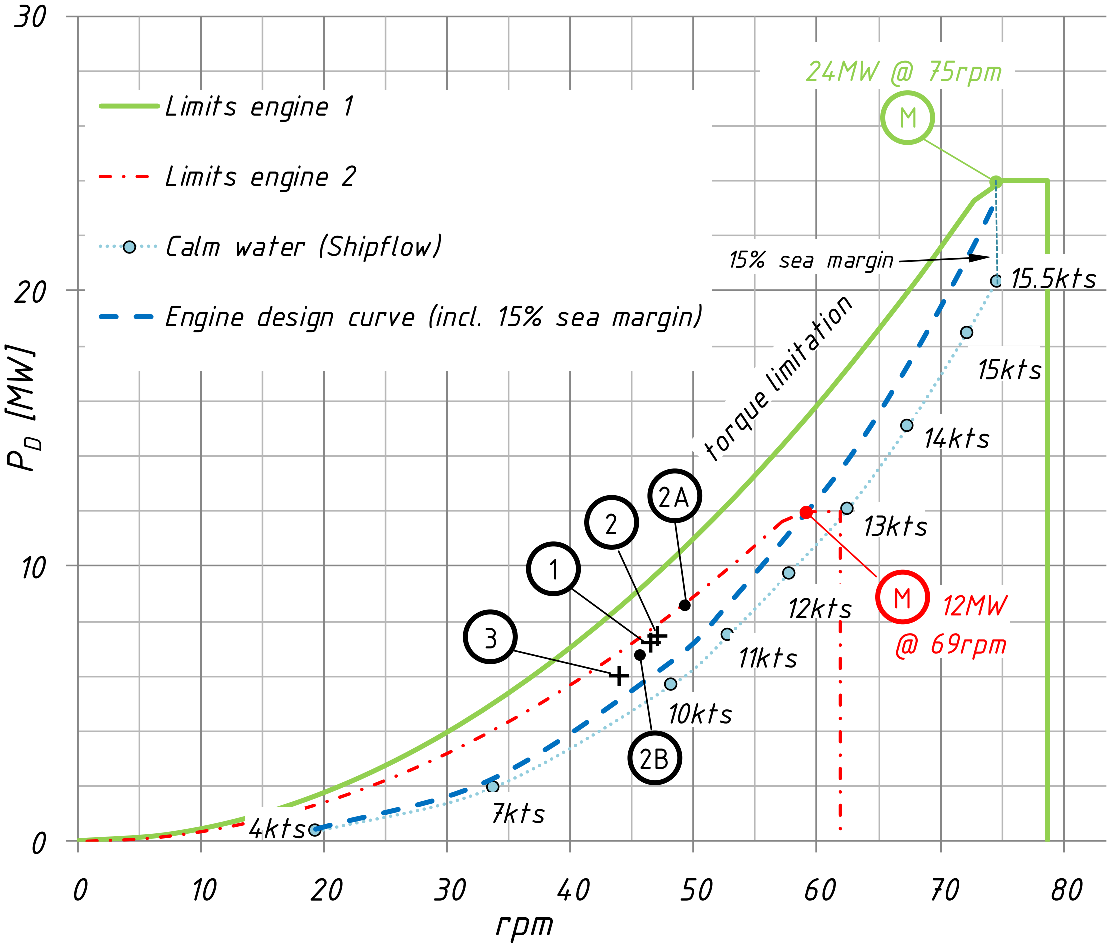

Figure 8: Load diagram for two Diesel engines

It can be seen from the figure, that the larger engine will deal effortlessly with all the situations the KVLCC2 might encounter under the “IMO adverse conditions”. This is because all the operational points (1,2,3, 2A and 2B) end up below

the torque limit line (solid, green curved line). Here the latter two points correspond to variations of point 2 with a conservative (2A) and an optimistic (2B) choice of *t* and *w*.
Things are different for the smaller engine. Here an optimistic choice of thrust deduction factor (2B) can prove that the ship complies with the IMO regulation while the “best guess” (point 2) shows that the engine will just be able to provide the required torque for V_s = 4 knots. Point 2A even ends up outside the operational range for Engine 2.

5. RESULTS AND CONCLUSIONS

Using the KVLCC2 tanker as a case study the “IMO interim guideline regarding the Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse Conditions” was studied in some detail. Results of model tests and CFD-simulations show:

- The simple Level 1 assessment from the IMO-guideline yields, that the minimum installed power to sustain the required ship speed of advance of 4 knots in wind and waves is 25.5 MW.
- According to the more advanced Level 2 assessment this power reduces to 12 MW.
- It is important to consider the torque limitations of Diesel engines
- An analysis of the individual resistance components shows, that, under the wind and wave conditions from the IMO-guideline, the total resistance consists of about 10% calm water resistance, 24% wind resistance and 66% added resistance.
- The fact that added resistance dominates the power prediction leads to the conclusion, that it is particularly important to predict this force component correctly. Because of the low tests speed (4 knots) and the issue of tank wall reflection it is important to carry out added resistance tests in a wide basin, not a narrow tank.
- The IMO-guideline neither specifies the details of how exactly added resistance should be determined experimentally, nor does it give a generic way to determine it. This is different from the calm water and wind resistance components where generic and conservative alternatives to model tests are listed.
- Such a generic/main-particular-based method could possibly be developed along the lines of the STAWAVE-2 or similar methods [13, 14]. Any such method should however be adopted to the special case of predicting minimum power at low ship speeds in a conservative way. The existing STAWAVE method was developed for correcting sea trials and will be too optimistic in the context of minimum power predictions.
- During the Level 2 assessment of the KVLCC2 it became obvious, that the choice of the thrust deduction factor *t* is not well defined in the guideline but has a huge influence on the outcome.
- To plug this potential “loophole” in the regulations further research and a fresh approach are required.

6. NOMENCLATURE

A_R	Rudder Area (m^2)
A_{FW}	Frontal wind area (m^2)
A_{LW}	Lateral wind area (m^2)
B	Beam of hull (m)
C_{AW}	Added resistance coefficient (-)
C_F	Frictional resistance coefficient (-)
D	Propeller diameter (m)
DWT	Deadweight (t)
H_s	Significant wave height (m)
IMO	International Maritime Organisation
J	Advance ratio of propeller (-)
K_T	Thrust coefficient of propeller (-)
K_Q	Torque coefficient of propeller (-)
k	Form factor (-)
k_{yy}	Pitch gyradius (m)
Lpp	Length between perpendiculars (m)
n	Rate of revolution (1/s)
$P_{D\ min}$	Minimum Propulsion Power (W)
RANSE	Reynolds Averaged Navier Stokes Eq.
R_{AW}	Added resistance in waves (N)
R_{CW}	Calm water resistance (N)
R_{air}	Air/wind resistance (N)
rpm	Rate of revolution (1/min)
S	Wetted surface area (m^2)
MCR	Maximum continuous rating (W)
T	Draft (m)
T_p	Spectral peak (modal) period (s)
t	Thrust deduction factor (-)
V_s	Required ship speed (m/s or knots)
V_w	Mean wind speed (m/s)
w	Wake fraction coefficient
ζ_A	Wave amplitude (m)
∇	Volume displacement (m^3)
ρ	Density of sea water (kg/ m^3)

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