# An Alternative Approach for Assessment of the Weather Factor in EEDI Formulation Using Statistical Ranking Theory

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**Abstract.** In the IMO procedure for Energy Effectiveness Design Index (EEDI) estimation, a weather factor is being introduced to account for speed loss in real operation conditions, but its calculation is still conditional. In the paper, a balanced alternative solution of the problem is suggested, based on extensive data for speed loss of variety of ships at seas taken by logbook records, experiments or series calculations and using statistical averaging of data over operational range in a form of some generalized rank criterion which match the weather factor. The method is thoroughly validated by available full scale data.

**Keywords.** EEDI, Weather factor, Statistical ranking theory, Regression analysis

## 1. Introduction

Back in 2012, in its attempt to limit excess fuel consumption thus green gas emissions, IMO issued MEPC.212(63) Resolution [1] for calculation of the attained Energy Efficiency Design Index (EEDI) for new ships, which became mandatory since 2013.

The EEDI index is expressed as a relationship of emission's rate (composed by powering factors) and transport effectiveness rate, as shown below:

$$EEDI = \frac{\textbf{Power} \times \textbf{Fuel Consumption} \times \textbf{Fuel} - \textbf{to} - \textbf{CO}_2\ \textbf{Conversion Factor}}{\textbf{Transport Capacity} \times \textbf{Operational Speed} \times f_W} \quad (1)$$

where speed loss coefficient, $f_W$, or so called "weather criterion", has been introduced for account of the added power and consequent speed reduction, occurring at real operational conditions. The interim guidelines for calculating $f_W$ coefficient have been outlined in MEPC.1-Circ.796 [2].

The recommended procedure, however, has some deficiencies, which open wide area for further elaboration, among which:

- The Eq. (1) is composed in "class" fashion by including deterministic (constant) ship parameters, assuming $f_W$ coefficient of the same type of value for the sake of equation consistence, correspondingly taking a single number of percentage speed loss at one only (representative) weather condition of Bf 6. In reality, the weather

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factor is statistical value, depending on ship type, size and geometry, and must be obtained by statistical averaging over environmental conditions on route.

- The speed reduction coefficient $f_W$ is assumed to be linearly proportional to fuel consumption. In reality, speed loss is a function of several parameters, such as available power margin (which predetermines involuntary drop of speed in waves), fuel cost, urgency of cargo delivery and severity of wave loading (which may force a voluntary drop of speed), so it should be considered not just ship system's capability measure, but has also economic impact [3], [4].
- The allowed approaches for estimating the coefficient $f_W$ are varying broadly, including rigorous theoretical methods, linearized methods, model tests utilizing various experimental methodologies, and even simple empirics, thus giving non-commensurable basis for the estimation. Theoretical approaches are mostly dealing with added resistance and speed loss is predicted indirectly, the same is valid for model tests – only a few basins use free-running model technique which gives speed loss directly. In this course of thoughts, statistical data for speed loss collected by full scale observations, calculations and model tests could form a representative sample for creation of relatively simple regression model for weather factor access.

Following above considerations, a practical approach for weather factor assessment is outlined here. Such an approach would operate with statistical hypotheses built on a limited but already representative number of observations about the relationships between a large number of ship design parameters and parameters of external conditions. In particular, the theory of ranking criteria [5] turned to be a handy tool to check the correctness of these hypotheses, known by its successful application in probabilistic theory and in practice [3], [6], [7]. Ranking procedures are performed simply and quickly, when ordered observations with normal statistics are available.

## 2. Description of Ranking Approach

The core of the ranking approach is the assumption for existence of some statistical relationship between a set of certain ship design parameters, **G**, and some generalized operational estimator, **R**:

$$\boldsymbol{R} = f(\boldsymbol{G}) \tag{2}$$

The set of governing ship identity parameters is selected amongst those influencing real operation most. This is done by experience, statistics or sensitivity analysis, considering also scope and resolving abilities of evaluation methods used, as the calculation scheme insists for application of express methods - simplified but fast.

Formulation of the multi-parameter response-based statistically weighted criterion, ***R***, is related to the vessel's type and assignment, and must reflect overall vessel operability or specific operational measure. In our case, it can be simply the non-dimensional speed loss coefficient, $V/V_0$, viz $f_W$, statistical measure of which is expressed as:

$$\boldsymbol{R} = \sum_{j=1}^{M} w_j \, u_j^* \tag{3}$$

where $u^*$ - averaged (statistically weighed ) reaction of the subsystem:

$$u^* = \sum_{p=1}^{P} \sum_{q=1}^{Q} .... \sum_{x=1}^{X} u(p, q...x) \qquad (4)$$

- $u\ (p, q\ ...x)$ - characteristic response as a function of operational conditions
- $w$ – statistical weighting function

Generally, weighting functions take account for the probability of occurrence of certain operational regime, or for contribution of corresponding characteristic in forming the overall ship behavior.

For all weighting functions is valid:

$$\sum_{k=1}^{K} w_k = 1 \qquad (5)$$

## 3. Description of Speed Loss Calculation Method

Modern seakeeping theories provide accurate enough procedures for prediction of added resistance of ships in waves, see i.e. [8], [9], [10], [11] as well as recent comprehensive comparative analysis in [12] and [13]. Then, assuming invariance of propulsive performance in calm water and waves (which is practically observed at moderate seas), the speed loss can be calculated by equating increased demand power with the available one. Performing this kind of analysis however requests application of complex software, application of specific knowledge and availability of detailed information about hull geometry, mass and inertia, which are hardly on disposal at shipping offices. Rather, they are in need of some simplified but accurate enough procedure for express estimation of average speed loss, based either on series calculations, model tests or on comprehensive statistics.

The approach suggested in this study is a mixed one. Generally, regression formulae similar to those of Townsin-Kwon [14], [15] have been utilized, considering their simplicity and involvement of commonly available ship and environment data, as well as the fact, that they had been obtained on the basis of systematic model tests analysis. However, additional data taken from other systematic BSHC studies, both calculation-based and experimental, as well as full scale data taken from 32 ship's logbooks, have been used to expand the original expressions, arriving at a new set of regression coefficients. Altogether, 87 sets of data have been added.

As mentioned above, statistically weighted speed loss in waves has been selected as a generalized operational estimator, ***R***.

Selection of variables in the governing ship parameter's vector, ***G***, has been done by following considerations:

- Principal differences have been observed in reaction of various types of ship forms to wave action and specifically to speed loss as a general criterion (similar assumption has been made by [14] and [15]). This permitted grouping of basic data by ship type and loading, introducing just an integer indicator;

- The ship design parameters influencing speed loss most have been traced from two viewpoints: integrated shape characterization, in order to reduce number of variables, and availability of these parameters at the shipping offices, for easy access to the calculation scheme. After analysis of available data and following some general considerations, i.e. [16], [17], etc., two parameters have been finally selected, namely block coefficient, $Cb$, and volume displacement, $\nabla$ (if needed, volume displacement can be related to deadweight via statistical relationship)

- Parameters describing operation conditions are obviously:

  - Heading angle (it was concluded that, to ease statistics, the 180° sector can be divided into four general directions – head seas, quartering seas from the bow, beam seas and following seas. It is in compliance with [14])
  - Operational speed of advance in calm water, $V_0$, or corresponding Froude number, $Fn$
  - Sea state severity as indicated by Beaufort scale, $Bf$ (this was preferred instead of more rigorous $H_S$ merit, as the wave height observations on-board ships are subjective and can mislead statistics)

Within every group of data, regression analysis has been performed. It has been observed, that the dependence of weather factor on selected set of geometry data can be described by low-order polynomials by using non-linear regressand transforms, thus multiple linear regression approach has been used. Finally, the weather factor has been expressed by:

$$f_W = \alpha.\beta\left(k.Bf + \frac{Bf^{6.5}}{m.\nabla^{0.667}}\right) \tag{6}$$

where:
$k, m$ - coefficients accounting for ship type and loading condition
$Bf$ - Beaufort sea state index
$\nabla$ - Volume displacement
$\beta$ - heading angle coefficient according to [15]

$$\alpha = \sum_{i=1}^{3} \sum_{j=1}^{3} A_{ij}\, Fn^{ij}\, Cb^{ij} \tag{7}$$

$Fn$ - Froude number
$Cb$ - Block coefficient
$Aij$ - regression coefficients

The regression is valid within a wide range of ship parameters, covering:

$Cb$ = [0,55 ÷ 0,85]; $Lpp$ = [120 ÷ 320] m; $L/B$ = [5,4 ÷ 7,6]
$B/T$ = [1,8 ÷ 3,2]; $Fn$ = [0,05 ÷ 0,30]

## 4. Validation

The above outlined approach has been repeatedly tested, always providing good accuracy, including full scale confirmation. It is demonstrated in Figure 1 on the cases of several Bulgarian-built bulk carriers, which have been systematically tested at BSHC and later subjected to full scale observation in real operation conditions [18], [19].

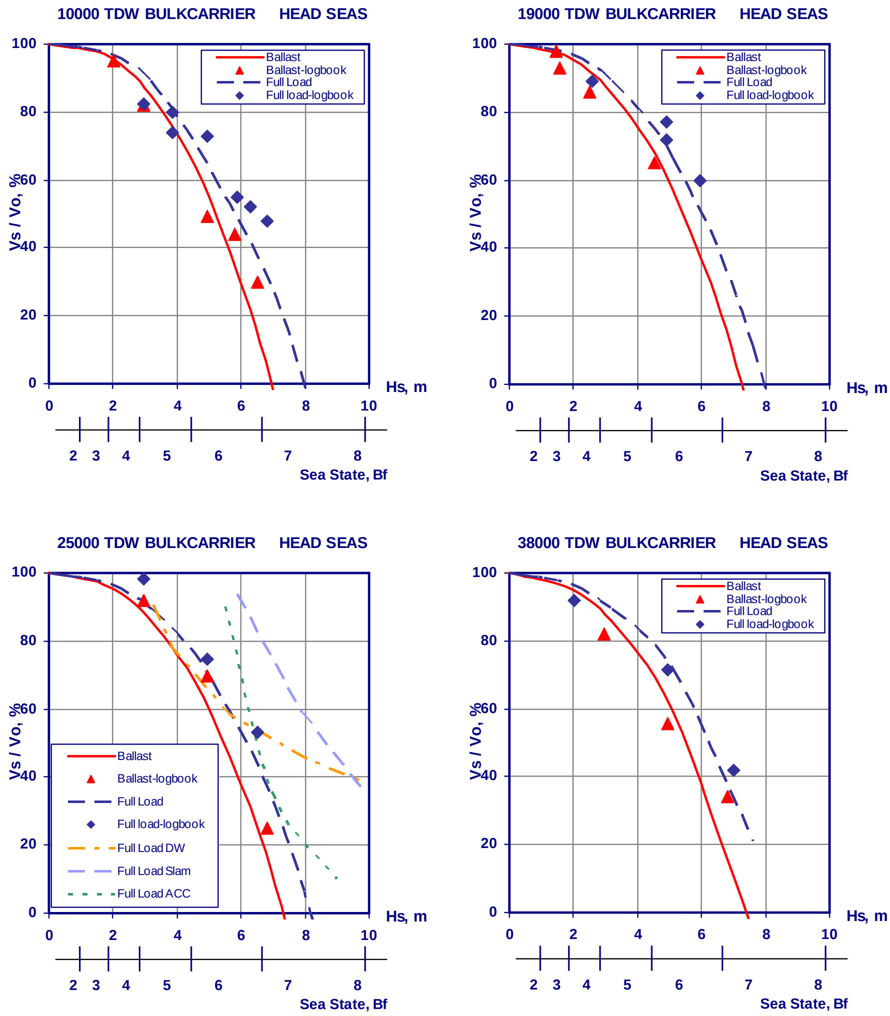


**Figure 1**. Speed loss predictions against logbook data

In the case of 25000 TDW bulk carrier, limiting curves for excess deck wetness, slamming and vertical accelerations are shown as well, proving the suggested method for $f_W$ assessment covers voluntary speed loss as well, as about 1/3 of processed data sample is taken from logbooks in which real operation regimes are recorded.

## 5. Comparative Analysis

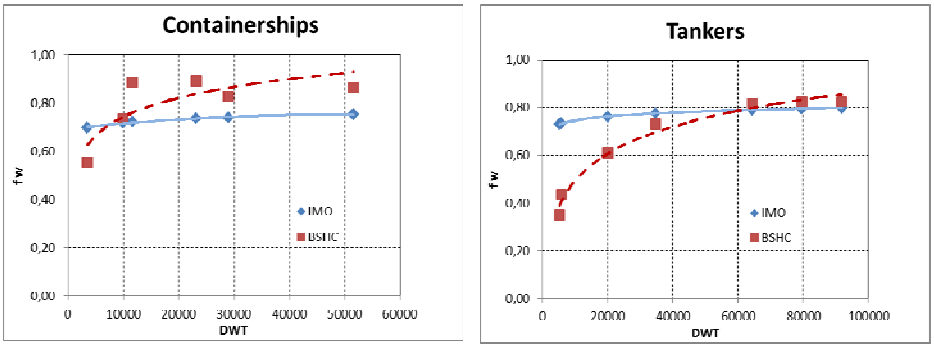


**Figure 2**. Predictions for the weather factor by two methods

In Figure 2, a comparison is made between $f_W$ predictions by simplified IMO 2012 regression formula [2] which is as well addressed by corresponding ITTC RP, versus BSHC database [17], compiled by model tests or calculations with account of wave loading restrictions (voluntary speed loss, observing recommended statistics). Results are given for selected groups of containerships and tankers, 7-10 vessels in every group. The sea conditions correspond to Bf 6, as suggested by [2].

It is well demonstrated, that for smaller ships the voluntary speed loss is significant, as higher sea states are easily bearable by large ships, but for smaller ships problems with excess wave action and consequent need for voluntary speed reduction can occur at lower sea states.

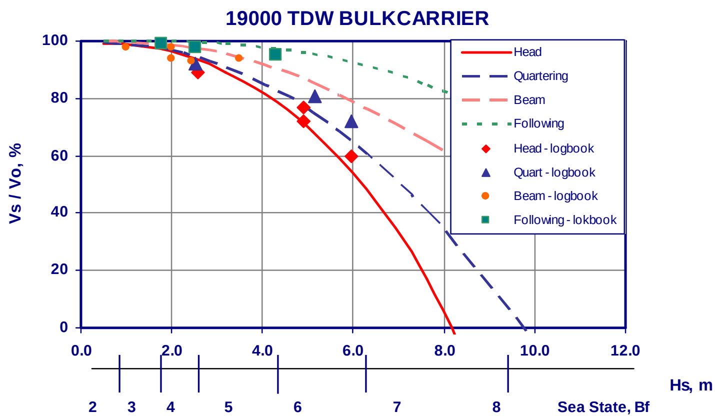


**Figure 3**. Speed loss dependence on wave course angle

In Figure 3, logbook data are compared to BSHC predictions by Eq. (6), showing good conformity, at least up to moderate sea states.

Finally, the weather factors for four bulk carriers considered in Item 4 have been statistically weighted by Eq. (3), using wave height statistics for North Atlantic, and then compared to IMO and BSHC predictions for Bf 6 seas, as illustrated in Figure 4. It is seen, that the values of $f_W$ averaged over probability of wave height occurrence are higher, which leads to reduction in EEDI values.

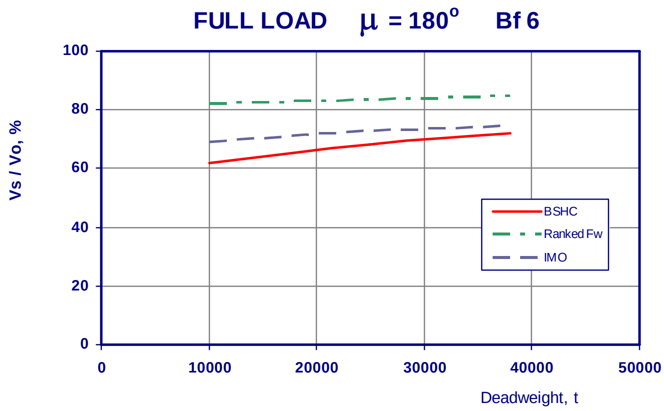


**Figure 4**. Single value $f_W$ predictions versus statistical averaged values

## 6. Conclusions

- In initial compilation of EEDI formula by IMO, the $f_W$ coefficient has been introduced as a mark for some complicated phenomenon, which had to be subjected to more detailed analysis and description on a later stage. It was to some extend covered by the IMO interim guidelines for calculation of weather factor at one fixed sea state, however, it should be perceived, that the ship behavior in real operational conditions depends on too many factors and conditions to be characterized by just a single value. At least, the index should be obtained by statistical averaging over operational regime parameters. It is clearly demonstrated in this paper that "ranked" values of weather factor are explicably higher then single values obtained at high but not frequently occurred sea state, which in result leads to reduction of EEDI.
- More of the existing procedures for $f_W$ estimation deal with involuntary speed loss only. It is explicable, because the speed drop due to added resistance and insufficient power can be assessed more easily either theoretically or experimentally. However, in many cases additional loss is observed due to voluntary master action to keep wave loadings into statistically limited values. This concern mostly deck wetness and motion accelerations, but also slamming and screw racing in some cases, especially for smaller ship sizes. It has been shown, that for smaller ships the voluntary speed loss is significant, as higher sea states are easily bearable by large ships, but for smaller ships problems with excess wave action and consequent need for voluntary speed reduction can occur at lower sea states, which further justifies using of statistically weighted merit.
- In this paper, a very practical approach for account of environmental restrictions on ship operation is suggested, which can be used also by shipping operators for route planning. It must be borne in mind, that speed loss is not always directly related to fuel consumption and green gas emissions, especially at high seas. Considering this, as well as the way of collection of larger part of data sample processed to arrive in here proposed method, the reliability of predictions can be guaranteed until Bf 6. Only small portion of logbook data concerns very high seas. The

process of collection of data should be further continued to cover rarely occurred seas as well as to establish more synonymous relationship with fuel consumption, to benefit EEDI assessment.

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