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# ANALYSIS OF RATIOS OF PROPULSION ENERGY DEMAND FOR TRANSPORT BY BULK CARRIERS

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***Abstract***

*The article presents the results of calculations and analysis of the $e_M$ ratio of the propulsion energy consumption per the nautical mile and the $e_{Mt}$ ratio of the propulsion energy demand for the transport of 1-ton cargo per the nautical mile for bulk carriers. The relationship between $e_M$ and $e_{Mt}$ indicators with the EIV (Estimated Index Value) ratio is shown. The output data for the determination of $e_M$ and $e_{Mt}$ indicators was taken from the quoted MAN publication, reading (reproducing) the values of power, velocity v and DWT tonnage from the charts included in this publication. Calculations and analyses were made for velocity v between 11-15 knots and for DWT from 5-400 kt (kilo tonnes). The graphs of $e_M$ and $e_{Mt}$ ratios in the function of speed v and load capacity DWT are presented. Using the stepwise method of least squares, models of statistical dependence of indicators on velocity v and load capacity of bulk carriers were developed. They were based on generalized polynomials with integer exponents. Derivatives $de_M$ / dv and $de_{Mt}$ / dv and derivatives $de_M$ / dDWT and $de_{Mt}$ / dDWT were determined. The main observations resulting from the conducted analyses are observed with the increase of DWT (within the range of 80-100 kt) a significant decrease in the value of the $e_M$ index. For DWT values> 100 kt, the decrease in $e_{Mt}$ is slow − $e_{Mt}$ asymptotically tends to a constant value. The results of the analyses carried out can be used at the stage of designing the transport capacity (tonnage) and nominal speed of the ship as well as selection of ship tonnage and travel speed in a given transport situation.*

***Keywords:*** *bulk carriers, transport, ratio of energy consumption per Nautical Mile, ratio of energy consumption per Nautical Mail and per one ton of DWT*

## 1. Introduction

The energy demand on nautical mile when traveling at speed v can be characterized by means of the ratio $e_M$, which defines the formula:

$$e_M = \frac{N}{v}\ [GJ/M], \tag{1}$$

where:
N – propulsion power [kW],
v – speed [knots],
M – Nautical Mile.

The ratio of unit energy demand for transport of a load unit over a distance of 1 M is defined as follows:

$$e_{Mt} = \frac{N}{v \cdot DWT} = \frac{e_M}{DWT}\ [kJ/(M \cdot t)], \tag{2}$$

where DWT – Deadweight Tonnage [kt].

The ratios defined above (1), (2) are directly linked to the design and operating energy efficiency indicators in an obvious way. To explain this, a simplified form of the EEDI (Energy Efficiency Design Index) can be used in the form of the Estimated Index Value (EIV) [1].

The equation for calculating the estimated index value for each ship (excluding containership) can be as follows [1]:

$$\mathrm{EIV} = 3.1144\,\frac{190\cdot\sum \mathrm{P_{ME}}+215\cdot \mathrm{P_{AE}}}{\mathrm{v}\cdot\mathrm{DWT}}, \tag{3}$$

where:
3.1144 – the $CO_2$ emission factor [g/g],
190 – the specific fuel consumption of main engines [g/kWh],
215 – the specific fuel consumption of auxiliary engines [g/kWh],
$\mathrm{P_{ME}}$ – 75% of the total installed main power [kW],
$\mathrm{P_{AE}}$ – the auxiliary power.

After entering the $\mathrm{e_M}$ ratio, the formula (3) takes the form:

$$\mathrm{EIV} = 3.1144\left(190\,\frac{\mathrm{c_M}\cdot \mathrm{e_M}}{\mathrm{DWT}} + 215\,\frac{\mathrm{P_{AE}}}{\mathrm{v}\cdot\mathrm{DWT}}\right), \tag{4}$$

where $\mathrm{c_M}$ onversion factor of the units used.

After entering the $\mathrm{e_{Mt}}$ ratio, the formula (3) takes the form:

$$\mathrm{EIV} = 3.1144\left(190\cdot \mathrm{c_{Mt}}\cdot \mathrm{e_{Mt}} + 215\,\frac{\mathrm{P_{AE}}}{\mathrm{v}\cdot\mathrm{DWT}}\right), \tag{5}$$

where $\mathrm{c_{Mt}}$ conversion factor of the units used.

## 2. Input data

The input data for the determination of $\mathrm{e_M}$ and $\mathrm{e_{Mt}}$ energy indicators was obtained by reading the values of the power N and velocity v in the DWT function from the graphs available in the MAN publication [2]. MAN gives the following characteristics of the data developed:

Average propulsion power demand Based on the already described average ship particulars and ship speeds for bulk carriers built or contracted in the period of 2000-2013 with due consideration of the latest ones contracted, we have made a power prediction calculation (Holtrop & Mennen's Method) for such bulk carriers in various sizes from 5,000 dwt up to 400,000 dwt. For all cases, we have assumed a sea margin of 15% and an engine margin of 10%, i.e. a service rating of 90% SMCR, including 15% sea margin [2].

Figure 1 shows an example chart taken from the MAN study for the DWT interval 35-80 kt. The DWT interval, which was considered in the MAN study, is 5-400 kt.

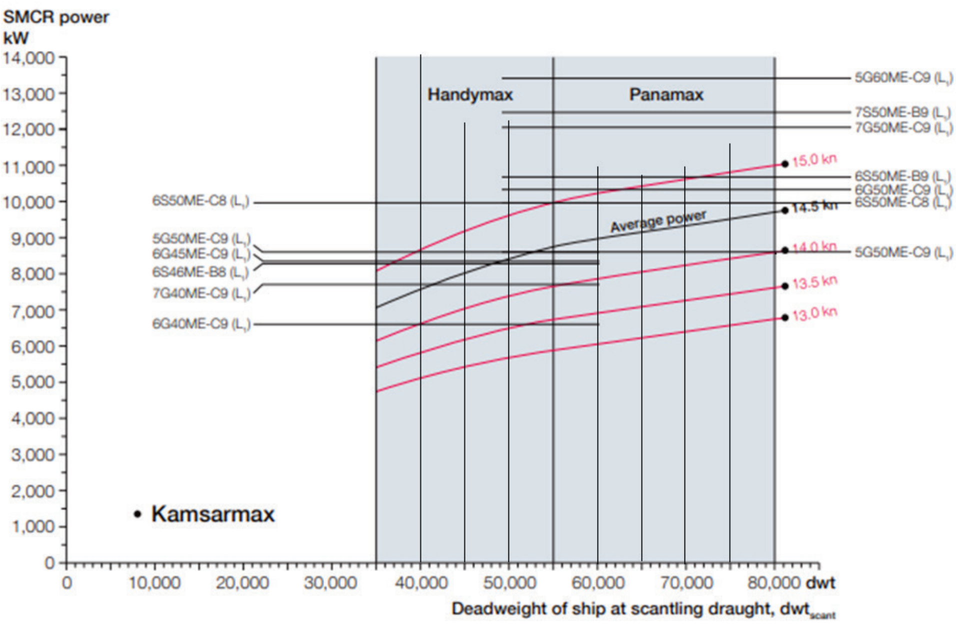


*Fig. 1. Propulsion SMCR power demand of Handymax and Panamax bulk carriers [2]*

In order to determine the N, v and DWT values, the graphs were analyzed using the screen cursor. Fig. 2 illustrates the obtained values of the $e_M$ energy ratio in the v and DWT intervals shown.

The points determined for individual DWT have been combined broken for improved image perception.

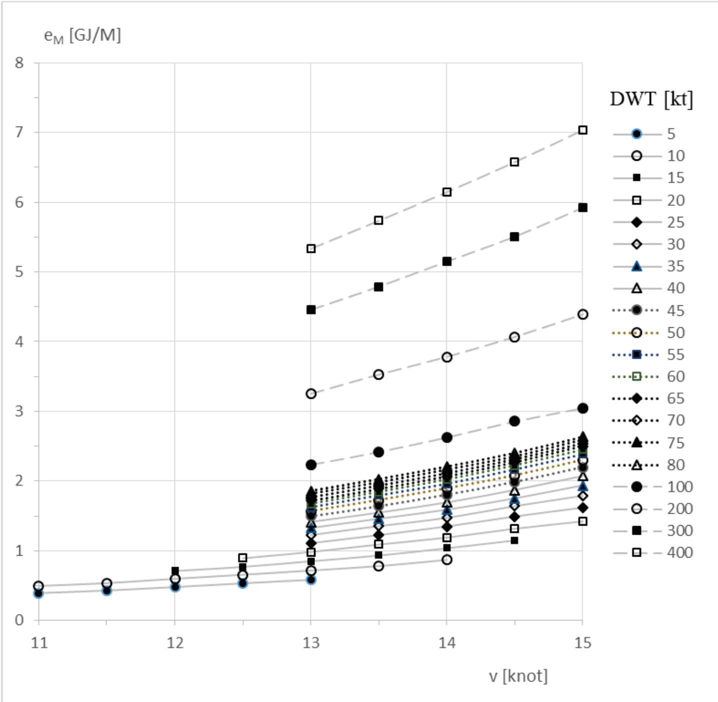


*Fig. 2. The set of ratio points $e_M$ determined based on MAN data [2]*

Figure 3 illustrates the determined values of the $e_{Mt}$ ratio in the indicated intervals v.

In addition, in this case, the determined $e_{Mt}$ points for the given DWT values were connected by broken lines (Fig. 3) in order to improve the perception of the image.

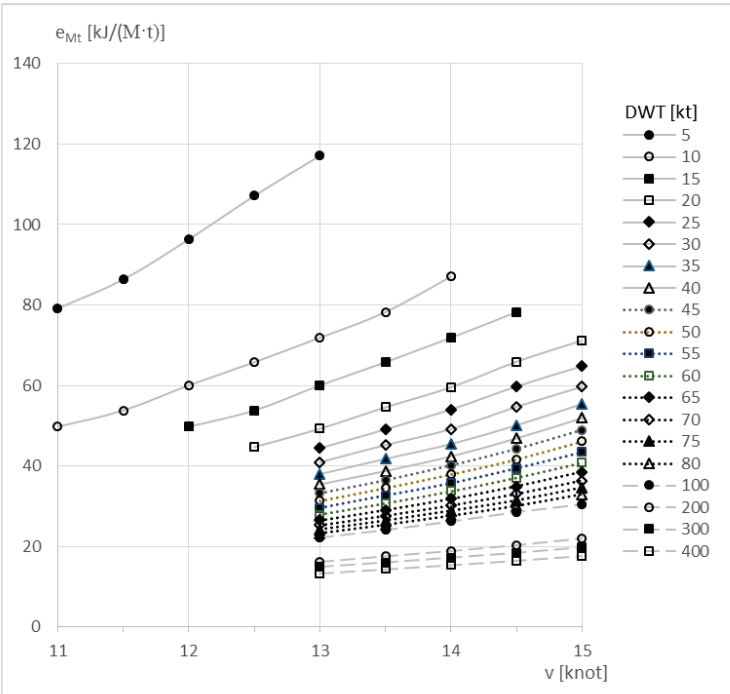


*Fig. 3. The set of ratio points $e_{Mt}$ determined based on MAN data [2]*

## 3. Polynomial models of the $e_M$ ratio

The set of ratios $e_M$ (Fig. 2) was approximated by the least squares stepwise method with generalized polynomials with integer exponents. The model has a form:

$$\begin{gathered} e_{Ma} = 0.01842 \cdot DWT + 0.00000171 \cdot v^5 - 0.0559 \cdot DWT^2 \cdot v^{-3} + \\ +0.000000255 \cdot DWT^3 \cdot v^{-1} \quad [GJ/M], \;\; Ste_{Ma} = 0.087\ GJ/M, \end{gathered} \tag{6}$$

where the $Ste_{Ma}$ standard deviation of the $e_{Ma}$.

Figure 4 compares the $e_M$ input values with the results of their approximation $e_{Ma}$.

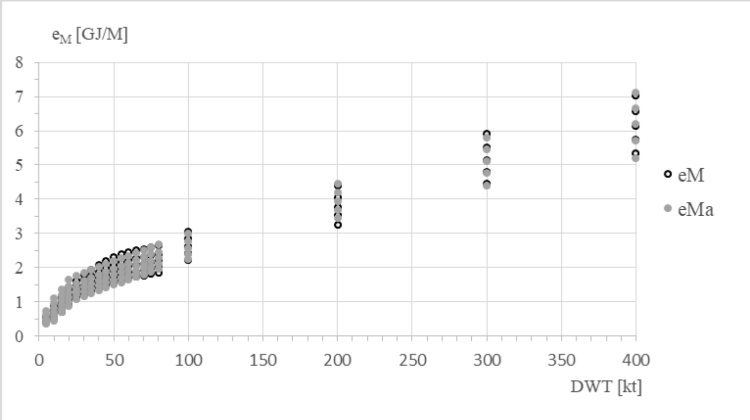


*Fig. 4. Comparison of the results of approximation $e_{Ma}$ with the model (7) with the input data $e_M$*

The obtained model (6) is complex difficult to interpret. For simplification of analysis, approximation was made for three basic speed values: 13, 14, 15 knots. The $e_{Ma}$ models designated for particular v are as follows:

$$\begin{gathered} e_{M13a} = 0.01111 \cdot DWT + 1.025 - 3.06 \cdot DWT^{-1} \quad [GJ/M], \quad Ste_{M13a} = 0.049\ GJ/M, \\ e_{M14a} = 0.01184 \cdot DWT + 1.514 - 13.91 \cdot DWT^{-1} \quad [GJ/M], \quad Ste_{M14a} = 0.064\ GJ/M, \\ e_{M15a} = 0.0132 \cdot DWT + 1.8565 - 13.6 \cdot DWT^{-1} \quad [GJ/M], \quad Ste_{M15a} = 0.064\ GJ/M, \end{gathered} \tag{7}$$

where St − standard deviations of indexed values.

Figure 5 compares the approximated values of the $e_M$ with the approximation results $e_{Ma}$ for the values of the above-selected velocity v.

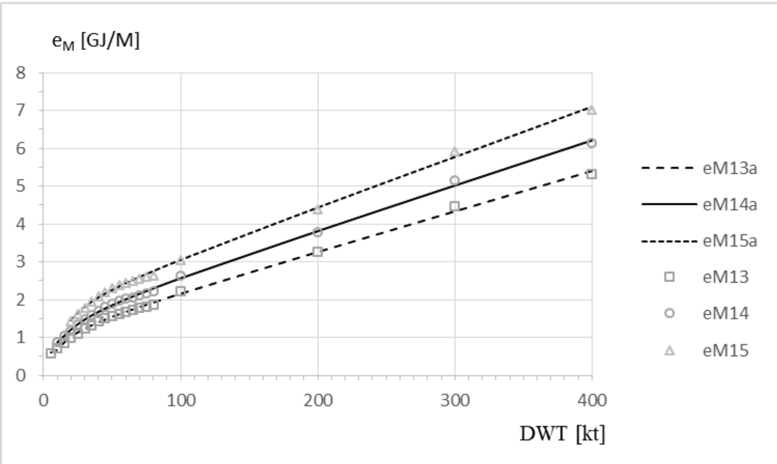


*Fig. 5. Comparison of the results $e_{Ma}$ of approximation with the model (7) with the input data $e_M$ for the next speed of ship: 13, 14, 15 knot*

Derivatives $de_M/dDWT$ determined from the model (7) are shown in Figure 6.

## 4. Polynomial models of the ratio $e_{Mt}$

In order to create an approximation model of the $e_{Mt}$, an identical method was used as in the case of the model of ratio $e_M$. As a result of the above, the following model was obtained:

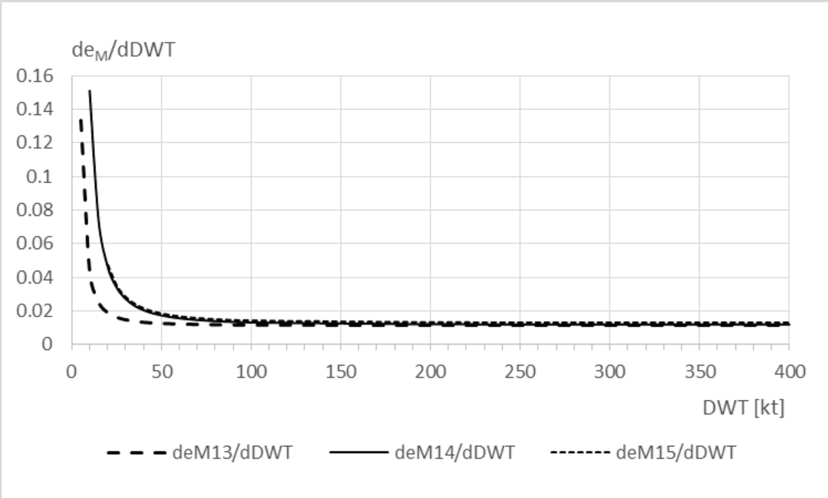


*Fig. 6. Derivatives deM/dDWT obtained based on the model (7)*

$$e_{Mta} = 3516 \cdot v^{-2} + 0.0000951 \cdot DWT^{-1} \cdot v^{6} - 175.4 \cdot DWT \cdot v^{-3} + \\ +0.000000232 \cdot DWT^{3} + 7.61 \quad [kJ/(M \cdot t)], \quad Ste_{Mt} = 2.9\ kJ/(M \cdot t). \tag{8}$$

Figure 7 compares the $e_{Mt}$ input values with the $e_{Mta}$ results of approximation with the model (8).

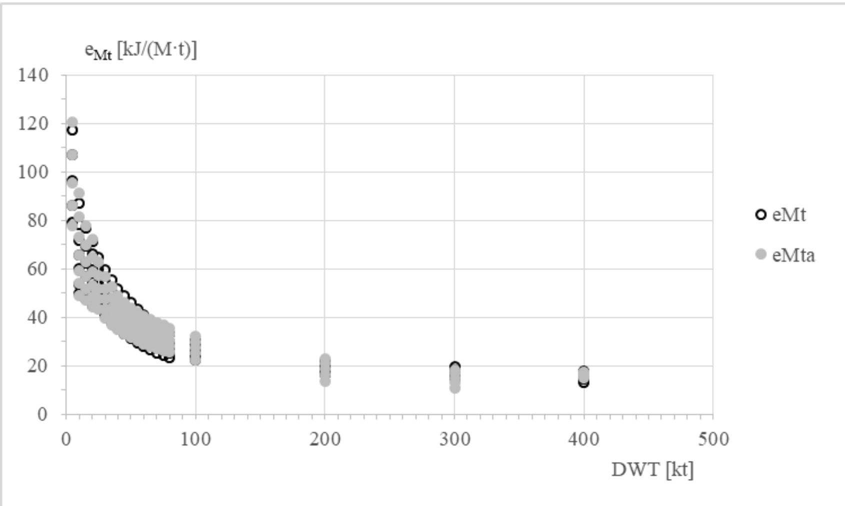


*Fig. 7. Comparison of the input values $e_{Mt}$ with the approximation results $e_{Mta}$ by the model (8)*

In addition, in this case, approximations were made for selected ship speeds: 13, 14 and 15 knot.

Models of ratio $e_{Mt}$ for selected ship speed values, based on stepwise approximation with a generalized polynomial for integer exponents, are as follows:

$$\begin{gathered} e_{Mt13a} = 1100 \cdot DWT^{-1} + 11.25 - 7077 \cdot DWT^{-2} + 21120 \cdot DWT^{-3} \quad [kJ/(M \cdot t)], \\ Ste_{Mt13a} = 0.77\ kJ/(M \cdot t), \\ e_{Mt14a} = 1562 \cdot DWT^{-1} + 11.53 - 15415 \cdot DWT^{-2} + 73580 \cdot DWT^{-3} \quad [kJ/(M \cdot t)], \\ Ste_{Mt14a} = 0.61\ kJ/(M \cdot t), \\ e_{Mt15a} = 1871.8 \cdot DWT^{-1} + 12.94 - 12345 \cdot DWT^{-2} - 38542 \cdot DWT^{-3} \quad [kJ/(M \cdot t)], \\ Ste_{Mt15a} = 0.8\ kJ/(M \cdot t). \end{gathered} \tag{9}$$

Figure 8 compares the input data $e_{Mt}$ with the approximation results $e_{Mta}$ with the model (9) for the values of the above-selected velocity v.

Figure 9 shows the derivatives $de_{Mt}/dDWT$ determined based on the model (9).

## 5. Dynamics of $e_M$ and $e_{Mt}$ ratios in the v domain

The dynamics of ratios $e_M$ and $e_{Mt}$ in the considered variability range can be assessed by analyzing derivatives $de_M/dv$ and $de_{Mt}/dv$.

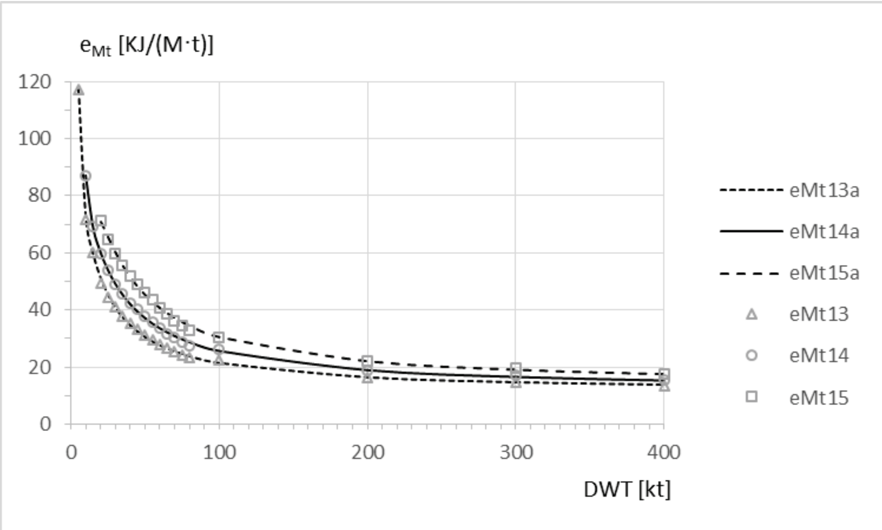


*Fig. 8. Comparison of the results $e_{Mta}$ of approximation with the model (9) with the input data $e_{Mt}$ for the next selected speeds of the ship: 13, 14, 15 knots*

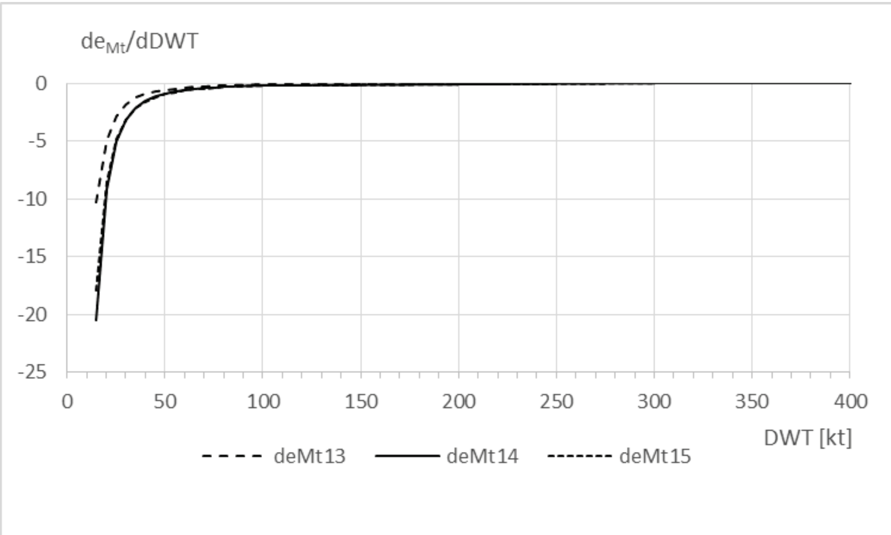


*Fig. 9. Derivatives $de_{Mt}/dDWT$ determined based on the approximation model (9) for the next speeds of the ship 13, 14, 15 knots*

Derivatives of the ratios $e_M$ and $e_{Mt}$ were determined for selected DWT values: 5, 10, 20, 50, 100, 200, 400 kt. The values for each selected DWT were approximated by the following models:

$$e_M = a_M \cdot v^w \ [GJ/M],$$
$$e_{Mt} = a_{Mt} \cdot v^w \ [kJ/(M \cdot t)]. \quad (10)$$

Values of parameters determined for the above models (10) are presented in Tab. 1.

*Tab. 1. Values of parameters determined for models (10)*

| DWT [kt] | $a_M$ | $a_{Mt}$ | w | $St_M$ | $St_{Mt}$ |
|---|---|---|---|---|---|
| 5 | 0.001242 | 0.24231 | 2.41 | 0.0038 | 0.77 |
| 10 | 0.001745 | 0.16161 | 2.35 | 0.0076 | 0.79 |
| 20 | 0.001321 | 0.06603 | 2.58 | 0.0062 | 0.31 |
| 50 | 0.001573 | 0.03147 | 2.69 | 0.0120 | 0.23 |
| 100 | 0.007906 | 0.07906 | 2.20 | 0.0130 | 0.13 |
| 200 | 0.015667 | 0.07833 | 2.08 | 0.0140 | 0.068 |
| 400 | 0.037730 | 0.09432 | 1.93 | 0.0063 | 0.016 |

The curves of the derivatives $de_M/dv$ are shown in Fig. 10; the curves of derivatives $de_{Mt}/dv$ are shown in Fig. 11.

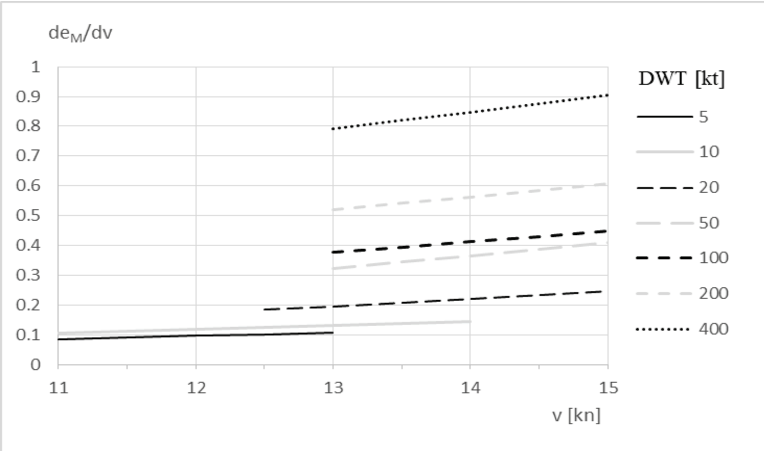


*Fig. 10. The curves of derivatives $de_M/dv$ for selected DWT*

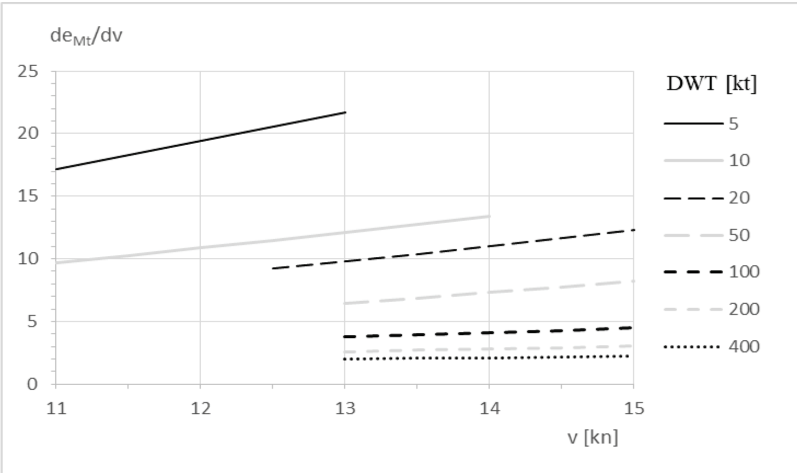


*Fig. 11. The curves of the derivatives $de_{Mt}/dv$ for selected DWT*

## 5. Summary and applications

With the increase of DWT, the value of the $e_M$ ratio increases (Fig. 4, 5). In the DWT range up to 80 kt, the $e_M$ rise rate decreases non-linearly (Fig. 6). Above DWT = 80 kt the rise is linear and quickly tends to a constant value (Fig. 6). Changes in the speed of a vessel with a given DWT have the greatest impact on $e_M$ values for large DWT (Fig. 10).

The value of the $e_{Mt}$ ratio decreases with the increase of DWT (Fig. 8, 9). In the range up to 50 kt, the $e_{Mt}$ drop is nonlinear and fast. For DWT > 100 kt, the decrease in $e_{Mt}$ takes on a linear character. The changes in the speed of the ship have the greatest impact on $e_{Mt}$ values for small DWT values (Fig. 11). With the increase in DWT, the effect of velocity decreases and for DWT > 200 kt the $e_{Mt}$ values are practically constant in the function v (Fig. 11).

The results of the analysis carried out can be used at the stage of designing the transport capacity (tonnage) and nominal speed of the ship as well as selection of ship tonnage and travel speed in a given transport situation.

**References**

[1] Faber, J., Hoen, M., Vergeer, R., Calleya, J., *Historical Trends in Ship Design Efficiency*. Available from: https://www.google.com/search?q=historical+trends+in+ship+design+efficiency&oq=hISTORICAL+TRENDS+IN+SHI&aqs=chrome.1.69i57j0.24169j0j8&sourceid=chrome&ie=UTF-8.

[2] Propultion Trends in Bulk Carriers. MAN Diesel & Turbo. Avaiable from: http://www.deno.oceanica.ufrj.br/deno/prod_academic/relatorios/2011/Matheus%20Pereira%20e%20Marcos%20Dias/relat1/Projectmodels/man%20bw%20technical%20paper.PDF.

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