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Update on van Oortmerssen's Resistance Prediction

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ABSTRACT
van Oortmerssen in 1971 published the results of a regression analysis of the resistance of ninety-three models of tugs and trawlers which had been tank-tested at the Maritime Research Institute Netherlands. This was in the form of an expression for the residuary resistance of the vessel based on parameters available at an early stage of design. His method remains one of the few suited to such hullforms and quickly found favour with those involved in prediction of their resistance. The method is included in many commercial resistance-prediction packages, and is still widely used.

However, there was a number of errors in the original publication. Depending on how these errors are treated, it is possible to come up with different values of the total resistance, and almost every known implementation gives differing results for the resistance. Many of these errors have been resolved by correspondence with the author and with MARIN, and it is the intention here to record corrections to the known issues.

In addition, it has been found that there are some combinations of parameters which give anomalous results. For these combinations, the resistance does not increase monotonically with speed as might be expected for this type of displacement hullform, but shows a distinct "hump" as might be expected for planing hullforms. The anomalous results have been investigated to determine the combinations of parameters for which they are produced, and a method of dealing with the results is proposed.

1. INTRODUCTION

1.1 General

The prediction of resistance is important in most ship designs for the estimation of either the speed which will be achieved with a given power, or the power which will be required to achieve a given speed. It becomes particularly important if there are penalties in the contract for under-achievement of the required speed.

There have been many fine analyses of resistance data for different hullforms, and the range of hullforms is constantly increasing. However, vessels with hullforms having fine entrances and broad, flat sterns, such as tugs, trawlers and offshore supply vessels, have had less attention paid to their resistance characteristics than most. Designers of these vessels therefore have a harder time of it in predicting their resistance with confidence.

Much of the early resistance data was presented in the form of tables or graphs for use in the design office. One such was the publication of resistance data for trawler hullforms by Ridgeley-Nevitt (1956, 1963 and 1967), whose students tank tested a systematic series of high displacement/length ratio trawler hullforms at the Webb Institute. The results were presented as contour plots of residuary resistance coefficient, C_R, vs displacement-length ratio and prismatic coefficient at each speed-length ratio. Helmore and Swain (2006) published the results of a regression analysis of the Ridgeley-Nevitt data.

However, the determination of the required values for a particular new design from tables or graphs is time-consuming and labour-intensive. The availability of digital computers in the fifties and sixties made regression analysis of large data sets possible, and the availability of personal computers in the eighties made calculations in the design office much quicker. These are things which we now take for granted.

The first application of statistical regression analysis to ship resistance data was made by Doust and O'Brien (1959), who analysed the results for some 130 unrelated trawlers which had been tank tested at the Ship Division of the National Physical Laboratory, UK. Since then there have been many regression analyses of ship resistance data carried out.

One of the early ones to follow was van Oortmerssen (1971), who published the results of a regression analysis of the residuary resistance of a set of 93 unrelated models of tugs and trawlers which had been tank tested at the Maritime Research Institute Netherlands (then the Netherlands Ship Model Basin). He obtained a parametric expression for the residuary resistance in terms of hull characteristics which are usually available at an early stage in the design process. The method has become widely used because of its utility.

The other known publication of resistance data for these hullforms is that of Calisal and McGreer (1993), who published the results of a small systematic series for double-chine, low length/beam ratio hullforms based on the purse seiners on the west coast of Canada. The results were published as a parametric expression for the residuary resistance coefficient obtained by regression analysis. However, the bow shape of the parent hullform was modified to reduce the half-angle of waterline entrance and to remain developable. The low angles of waterline entrance tend to give low resistance at high speeds.

1.2 Issues

van Oortmerssen's method was quickly adopted by tug and trawler designers in the eighties because it could be easily programmed and then gave quick predictions of resistance which were found to be reliable in practice. The method has been subsequently included in many commercial resistance-prediction packages, and is still widely used.

However, there was a number of errors in the original paper. Some of these errors are obvious, and have been known almost since publication, but some are not so obvious. It is in the treatment of the not-so-obvious errors that differences can arise and, depending on how these errors are treated, it is possible to come up with different values of the total resistance. As a result, the known implementations of the method all seem to give differing results for the predicted resistance.

The author has corresponded with Dr van Oortmerssen and with MARIN over a number of years, and has resolved most of the issues, and it is the intention here to record corrections to the known issues.

In addition, Holtrop (2001) noted that MARIN had received a comment some years previously that, for some combinations of parameters, the resistance predicted for the vessel by van Oortmerssen's method did not increase monotonically with speed. For displacement vessels such as these, it would be expected that the resistance *would* increase monotonically with speed. The present author also found such a case, and embarked on an analysis of the extent of the problem.

2. VAN OORTMERSSEN'S METHOD

2.1 Summary of the Method

van Oortmerssen gave the equation for the prediction of the residuary resistance of a vessel as follows:

$$R_R / W = c_1 e^{-m/9F_n^2} + c_2 e^{-m/F_n^2} + c_3 e^{-m/F_n^2} \sin(1/F_n^2) + c_4 e^{-m/F_n^2} \cos(1/F_n^2) \tag{1}$$

where W is the weight of the vessel, F_n is the Froude number, m = $0.14347 C_P^{-2.1976}$, C_P is the prismatic coefficient, and the c_i coeffcients were given by:

$$\begin{aligned} c_i = [&d_{i,0} + d_{i,1} lcb + d_{i,2} lcb^2 + d_{i,3} C_P + d_{i,4} C_P^2 + d_{i,5} L_D / B + d_{i,6} (L_D / B)^2 + d_{i,7} C_{WL} + \\ &d_{i,8} C_{WL}^2 + d_{i,9} B/T + d_{i,10} (B/T)^2 + d_{i,11} C_M]/1000 \end{aligned} \tag{2}$$

where L_D is van Oortmerssen's "displacement length" = $(L_{WL} + L_{BP})/2$, lcb = LCB as a percentage of L_D from midships, B is the beam, T is the draft, $C_{WL} = i_E L_D/B$, i_E is the half-angle of waterline entrance, C_M is the maximum section coefficient, and the $d_{i,j}$ coefficients were given in van Oortmerssen's Table II.

F_n, lcb and C_P are all based on the displacement length, L_D. The ranges of values of the six parameters of the models were:

L_D/B	3.0–6.2	B/T	1.9–4.0	lcb	(–8%)–(+2.8%)
C_P	0.5–0.725	C_M	0.73–0.97	i_E	10^o–46^o

2.2 Errors

In the text, the following errors have been known for many years:

1. In van Ortmerssen's Equation (30), shown as Equation (1) above, the right-hand side should be enclosed in brackets and all should be divided by1000 for consistency with his Table II.
2. In Table II, the sign of the coefficient $d_{3,5}$ should be positive instead of negative.
3. In Equation II-1 in Appendix 2, "…$c_4 + f_4$)" should be replaced by "…$c_4 f_4$)"

In the example calculation in Appendix 2 for a tug of displacement length 29 m at a speed of 13 kn:

4. The values of the c_3 and c_4 coefficients should be interchanged.
5. The values of f_3 and f_4 should be 0.005 and 0.066, based on the given figures.
6. The value of c_3 is –79.33, and f_3 is 0.005so the product $c_3 * f_3$ must be negative, not positive as shown.
7. The value given for C_F is for a length L_D of about 21 metres, not for the 29 metre displacement length of this vessel.
8. The values given for C_P and C_M cannot be obtained simultaneously with the values given for ∇, L_D, B and T. Assuming C_P to be correct, then:
   $C_M = C_B/C_P = \nabla / C_P L_D B T$ = 376/[0.609(29/3.45)(29/3.45/2.85)]= 0.8587

This compares with the value of 0.817 given in the paper. The calculations of the c_i coefficients depend on both C_P and C_M, so the calculated c_i values will vary with both.

9. It is clear from the values given for c_1 to c_4 that van Oortmerssen used $C_P = 0.609$ and $C_M = 0.817$. However, since C_P and C_M are not consistent with the values given for ∇, L_D, B and T, the values of the c_i will be different for a consistent set of values.

Subsequent correspondence (van Oortmerssen 1986 and 2000, and Holtrop 2001) has confirmed these errors. Data for van Oortmerssen's example tug are no longer available, and so the issue of C_P and C_M is not easily decided.

2.3 Resolution

In order to resolve the difficulties, we start with a consistent set of data for the same example vessel, taking only the stated value of C_P and ignoring the stated value of C_M:

$L_D = 29$ m	$L_D/B = 3.45$	$B/T = 2.85$	$lcb = -2.55\%$ of L_D
$C_P = 0.609$	$i_E = 23^o$	$S = 284$ m^2	$\nabla = 376$ m^3
$v = 13$ kn	$\Delta C_F = 0.00051$		

We now calculate the required value of C_M and proceed:

$C_M = C_B/C_P = \nabla/C_P L_D BT = 376/[0.609(29/3.45)(29/3.45/2.85)] = 0.8587$
$m = 0.14347 C_P^{-2.1976} = 0.14347*0.609^{-2.1976} = 0.4267$
$C_{WL} = i_E L_D/B = 23*3.45 = 79.35$

The values of $d_{i,j}$ are taken from van Oortmerssen's Table II, and the c_i are calculated from Equation (2) above, giving:

$c_1 = 2.096\times10^{-3}$ $c_2 = 248.3\times10^{-3}$ $c_3 = -68.87\times10^{-3}$ $c_4 = 42.33\times10^{-3}$

At 13 knots, $Fn = v/\sqrt{(gL_D)} = 13\times0.5144/\sqrt{(9.80665*29)} = 0.3966$

$f_1 = e^{-m/9F_n^2} = 0.7398$ $f_2 = e^{-m/F_n^2} = 0.06634$
$f_3 = e^{-m/F_n^2}\sin(1/F_n^2) = 0.004992$ $f_4 = e^{-m/F_n^2}\cos(1/F_n^2) = 0.06615$

$c_1f_1 = 2.096*10^{-3}\times0.7398 = 1.55*10^{-3}$
$c_2f_2 = 248.3\times10^{-3}\times0.06634 = 16.471\times10^{-3}$
$c_3f_3 = -68.87\times10^{-3}\times0.004992 = -0.344\times10^{-3}$
$c_4f_4 = 42.33\times10^{-3}\times0.06615 = 2.801\times10^{-3}$

$R_R/W = c_1f_1 + c_2f_2 + c_3f_3 + c_4f_4 = 1.55\times10^{-3} + 16.471\times10^{-3} - 0.344\times10^{-3} + 2.801\times10^{-3}$
$= 20.48*10^{-3}$

$R_R = (R_R/W)\rho\nabla = 20.48*10^{-3}*1025*376 = 7893$ kgf
$Rn = vL_D/\nu = (13\times0.5144)\times29/1.18831\times10^6 = 1.632\times10^8$
$C_F = 0.075/(\log Rn - 2)^2 = 0.075/(\log 1.632\times10^8 - 2)^2 = 0.001943$
$C_F + \Delta C_F = 0.001953 + 0.00051 = 0.002453$
$R_F = 0.5\rho Sv^2(C_F + \Delta C_F) = 0.5\times(1025/9.80665)\times284\times(13\times0.5144)^2\times0.002453$
$= 1628$ kgf
$R_T = R_R + R_F = 7893 + 1628 = 9521$ kgf $= 93.37$ kN

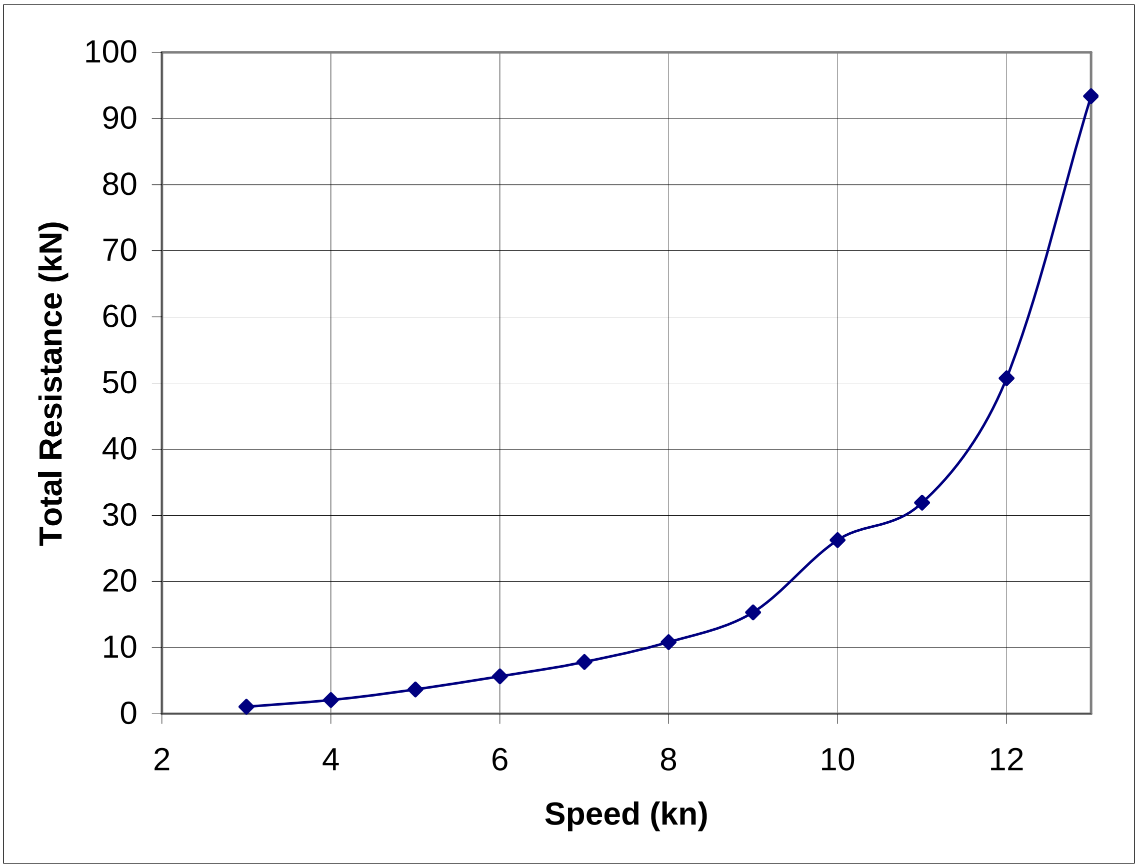

Figure 1 Total resistance vs speed for van Oortmerssen's 29 m example tug

This compares with a total resistance value at 13 kn of 9755 kgf = 95.66 kN in the original calculation. The above calculations are believed to eliminate all of the errors in van Oortmerssen's published example calculation for the 29 m tug. The spreadsheet calculations for a range of speeds up to 13 knots are shown in Appendix 1, and graphed in Figure 1.

3. VARIATIONS OF PARAMETERS

3.1 General

van Oortmerssen did not state a specific range for the variation of Froude number for his method. However, he shows variations of his functions f_3 and f_4 for Froude numbers up to 0.50, and it would seem reasonable to assume that his equation applies up to that limit. The resistance calculation for his example tug was done for a speed of 13 kn, corresponding to $Fn = 0.3966$.

van Oossanen (1979) in his discussion of various resistance prediction methods, says that some extrapolation of van oortmerssen's equation to higher speeds is permissible because of the theoretical nature of the basic expression. van Oortmerssen based his theory on that of Havelock for the waves produced by a travelling two-dimensional pressure disturbance, but simplified so that it could be formulated in terms of the vessel's parameters.

However, MacPherson (1991) sounds a note of caution in his summary of various resistance prediction methods. He says that the basis for the Havelock theory in van Oortmerssen's method is questionable, and a speed-dependent analysis (like Havelock) typically has trouble matching the unusual C_R curve shape at Froude numbers below about 0.3.

The Havelock theory gave rise to the sin and cos terms in van Oortmerssen's equation, and these attempt to account for the humps and hollows in the residuary resistance. Figure 1 shows that, for the example 29 m tug, they do a respectable job.

Inspection of the sin and cos terms shows them to have arguments of $1/F_n^2$. Since F_n is dimensionless, and radians are effectively dimensionless, it is considered that $1/F_n^2$ is already in radians and can be used directly. That this was van Oortmerssen's intention is borne out by taking $1/F_n^2$ in radians for a prismatic coefficient of 0.75 and graphing the functions f_3 and f_4 in Figures 2 and 3, which reproduce his results. However, one known commercial implementation of van Oortmerssen's method considers that $1/F_n^2$ is not dimensionless, and converts $1/F_n^2$ to radians by dividing by 57.296. The effect of so doing on van Oortmnerssen's functions f_3 and f_4 can be seen in Figures 2 and 3.

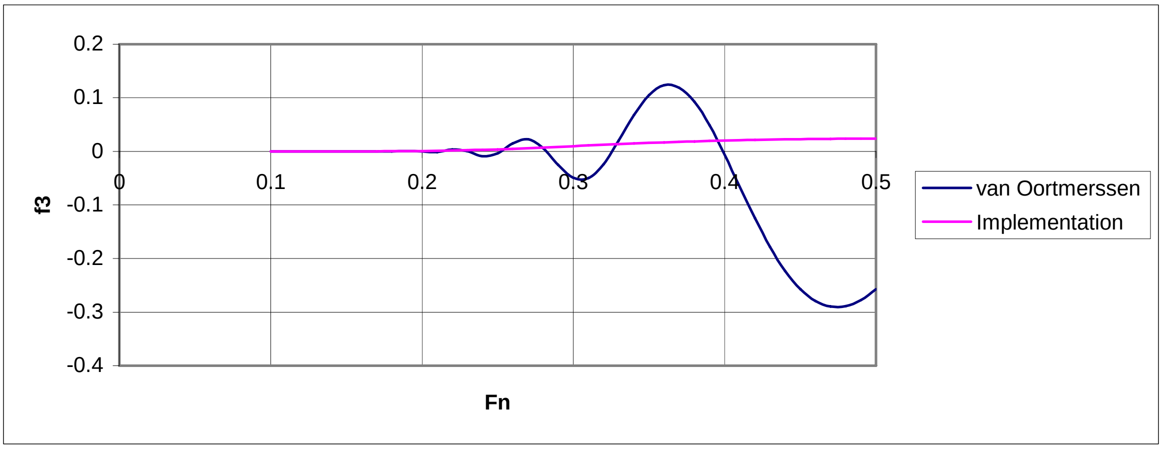

Figure 2 Effect on f_3 of treating the argument $1/F_n^2$ in radians or degrees at C_P = 0.75

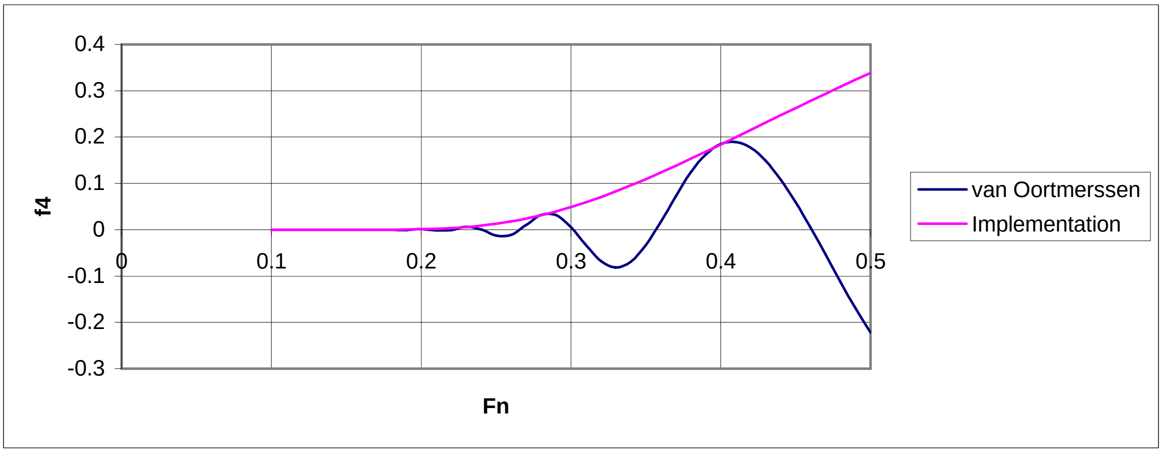

Figure 3 Effect on f_4 of treating the argument $1/F_n^2$ in radians or degrees at C_P = 0.75

Treating the argument $1/F_n^2$ in degrees gives monotonically increasing vaules of f_3 and f_4, and does not introduce any humps and hollows into the residuary resistance as intended by van Oortmerssen.

3.2 Combinations of Parameters

Holtrop (2001) reported that MARIN had received a comment some years previously that, for some combinations of parameters, the resistance predicted for a vessel by van Oortmerssen's method did not increase monotonically with speed, i.e. that the "hollow" of the residuary resistance produced values which reduced as speed increased, before increasing again at higher speeds. For displacement vessels such as tugs and trawlers, it would be expected that the resistance *would* increase monotonically with speed.

This author found such a case while setting an assignment for his students to use van Oortmerssen's method to predict the resistance of a 34 m tug. The six parameters of the tug are as follows:

L_D/B	3.032	B/T	2.643	lcb	–5.1768%
C_P	0.7070	C_M	0.8086	i_E	25°

The parameters for this vessel are all within van Oortmerssen's limits, although L_D/B is close to the lower limit of 3. The calculations are presented in Appendix 2, and the results are graphed in Figure 4.

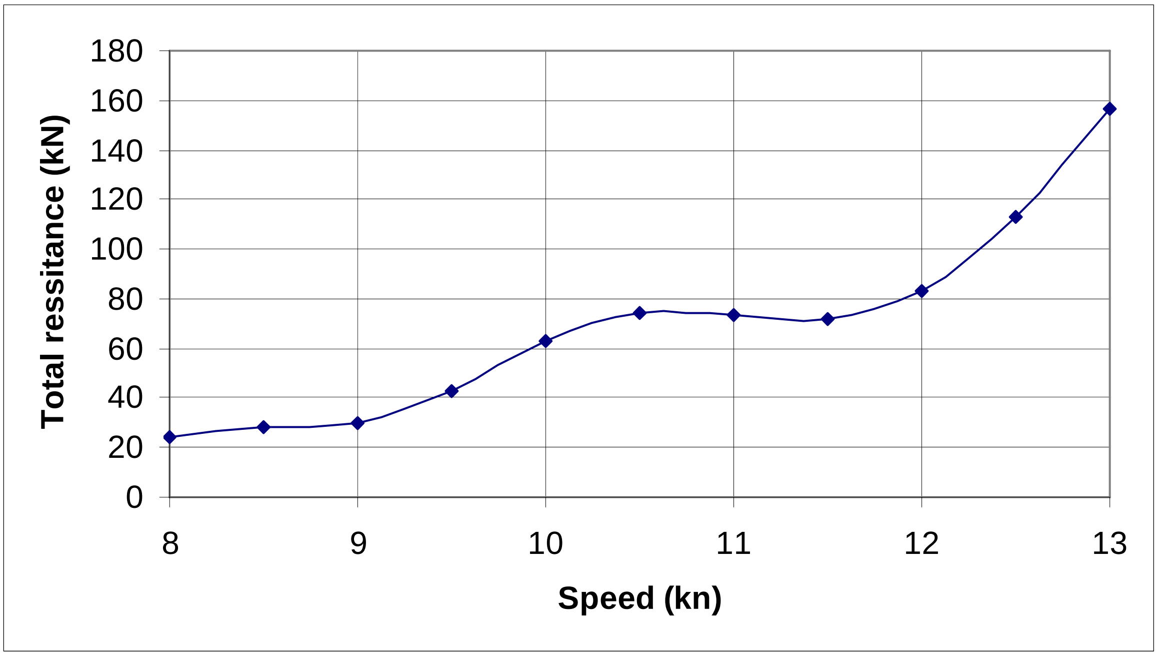

Figure 4 Total resistance vs speed for 34 m tug

As can be seen from Figure 4, the R_T values decrease from about 10.5 kn to 11.5 kn, before increasing at higher speeds. The hollow in the curve can be removed by increasing the beam to give L_D/B = 3.301, resulting in equal values of R_R at 10.5 and 11 kn, but this approach also changes other parameters, (B/T, i_E and, incidentally, the displacement-length ratio), and might not be what is wanted for a particular design. The change in parameters also increases the resistance at the higher speeds.

3.3 The Data Set

In order to investigate the extent of combinations of parameters for which this scenario occurs, it would be useful to examine the original data to see if any particular combinations were not included in the set. However, the original data is no longer available or, at least, not easily accessible (van Oortmerssen 2000, Holtrop 2001).

Inspection of van Oortmerssen's histograms of numbers of vessels with particular parameters shows that some parameters had only one vessel towards the end of the range, while others had several. As an example, the L_D/B ratio had one vessel in the range 3.0–3.4 at the low end, but six vessels in the range 5.8–6.2 at the high end, with at least nine in each range of 0.4 in between. What is not brought out is whether there were particular *combinations* of parameters which were *not* included. For example, it might be expected that vessels with lower values of L_D/B might have higher values of i_E, but the histograms do not show whether there were any vessels with, say, $i_E < 30^o$ for $L_D/B < 4$.

Not having access to the data, we have to start somewhere, and so have included all of each range in the set to be examined here.

One parameter of particular interest is the displacement-length ratio $\Delta/(0.01L)^3$ tons/ft^3 or, in its non-dimensional equivalents, the slenderness ratio $L/\nabla^{1/3}$ or the fatness ratio $\nabla/(L/10)^3$. However, since the author is more familiar with displacement-length ratio, we will work with that. Tugs and trawlers are pushing the boundaries of this ever higher (840 is not unknown for a modern tug), and the author was interested to see if there were any limits placed by the ranges of parameters in van Oortmerssen's data set.

It may be shown that $\Delta/(0.01L)^3 = 28567C_PC_M/[(L_D/B)^2(B/T)]$ tons/ft^3, where the factor 28567 includes a water density of 1.025 t/m^3 and conversion factors from metric SI units to give the result in tons/ft^3.

Substituting maximum values of C_P and C_M, and minimum values of L_D/B and B/T:

$$\Delta/(0.01L)^3{}_{\max} = 28567\times0.725\times0.97/(3^2\times1.9) = 1175 \text{ tons/ft}^3$$

Substituting minimum values of C_P and C_M, and maximum values of L_D/B and B/T:

$$\Delta/(0.01L)^3{}_{\max} = 28567\times0.5\times0.73/(6.2^2\times4) = 68 \text{ tons/ft}^3$$

There are no known tugs or trawlers with such extreme values of $\Delta/(0.01L)^3$, so it is clear that the extreme values of the contributing parameters in the data set did not occur together. However, there appears to be no direct restriction on practical values of $\Delta/(0.01L)^3$ for tugs and trawlers.

3.4 Investigation

The author then set about investigating the data set to find out for which combinations of parameters non-monotonically-increasing values of R_T occurred.

van Oortmerssen's parameter in the equation for residuary resistance, $C_{WL} = i_EL_D/B$, is dependent on i_E and L_D/B, and so i_E was taken as the independent parameter. Combinations of five values of each of the six parameters were tested, as shown in Table 1, giving 5^6 = 15 625 combinations.

Table 1 Combinations of parameters

Value	Lowest	Low	Mean	High	Highest
L_D/B	3.0	3.8	4.6	5.4	6.2
B/T	1.9	2.425	2.95	3.475	4.0
lcb%	–8	–5.3	–2.6	0.1	2.8
C_P	0.5	0.5563	0.6125	0.6688	0.725
C_M	0.73	0.79	0.85	0.91	0.97
i_E	10^o	19^o	28^o	37^o	46^o

The test for monotonic increase of resistance with speed was applied to the residuary resistance from van Oortmerssen's equation; i.e. the calculated R_R was accepted if it increased or remained the same with increasing speed; it was rejected if it decreased with increasing speed. Thus, with the addition of the frictional resistance (which increases monotonically with speed) the total resistance also increases monotonically with speed and the graph visually does the same.

3.5 Results

As might be expected, problems occur for combinations of high length/beam ratios with high angles of waterline entrance, and for low length/beam ratios with low angles of waterline entrance. These combinations were probably not represented in van Oortmerssen's original data set, and are unlikely to be used.

Other results are not easy to summarise. For combinations of L_D/B, B/T and *lcb*%, problems are encountered for some combinations of C_P and C_M at some values of i_E and not at others. No pattern is apparent. Two examples are shown, in Table 2 for L_D/B = 3.8, B/T = 2.95 and *lcb*% = –5.3, and in Table 3 for L_D/B = 5.4, B/T = 4.0 and *lcb*% = 0.1.

Table 2 Monotonic increase in R_R for L_D/B = 3.8, B/T = 2.95 and lcb% = –5.3

L_D/B = 3.8	B/T = 2.95	lcb% = -5.3

$i_E = 10^o$

	Cp				
Cm	0.5	0.5563	0.6125	0.6688	0.725
0.73	✓	✓	x	x	x
0.79	✓	✓	x	x	x
0.85	✓	✓	x	x	x
0.91	✓	✓	x	x	x
0.97	✓	✓	x	x	x

$i_E = 19^o$

	Cp				
Cm	0.5	0.5563	0.6125	0.6688	0.725
0.73	✓	✓	x	x	✓
0.79	✓	✓	✓	x	✓
0.85	✓	✓	✓	✓	✓
0.91	✓	✓	✓	✓	✓
0.97	✓	✓	✓	✓	✓

$i_E = 28^o$

	Cp				
Cm	0.5	0.5563	0.6125	0.6688	0.725
0.73	✓	✓	✓	x	✓
0.79	✓	✓	✓	✓	✓
0.85	✓	✓	✓	✓	✓
0.91	✓	✓	✓	✓	✓
0.97	✓	✓	✓	✓	x

$i_E = 37^o$

	Cp				
Cm	0.5	0.5563	0.6125	0.6688	0.725
0.73	✓	✓	x	x	x
0.79	✓	✓	x	x	✓
0.85	✓	✓	✓	x	✓
0.91	✓	✓	✓	✓	✓
0.97	✓	✓	✓	✓	x

$i_E = 46^o$

	Cp				
Cm	0.5	0.5563	0.6125	0.6688	0.725
0.73	✓	✓	x	x	x
0.79	✓	✓	x	x	x
0.85	✓	✓	x	x	x
0.91	✓	✓	x	x	x
0.97	✓	✓	x	x	x

✓ = R_R ↑ monotonically with speed

x = R_R not ↑ monotonically with speed

Table 3 Monotonic increase in R_R for L_D/B = 3.8, B/T = 2.95 and lcb% = –5.3

L_D/B = 5.4						B/T = 4.0			lcb% = 0.1		
$i_E = 10^o$						$i_E = 19^o$					
	Cp						**Cp**				
Cm	0.5	0.5563	0.6125	0.6688	0.725	**Cm**	0.5	0.5563	0.6125	0.6688	0.725
0.73	✓	✓	✓	x	x	0.73	✓	✓	x	x	x
0.79	✓	✓	✓	x	✓	0.79	✓	✓	✓	x	x
0.85	✓	✓	✓	x	✓	0.85	✓	✓	✓	x	x
0.91	✓	✓	✓	✓	✓	0.91	✓	✓	✓	x	x
0.97	✓	✓	✓	✓	✓	0.97	✓	✓	✓	x	x
$i_E = 28^o$						$i_E = 37^o$					
	Cp						**Cp**				
Cm	0.5	0.5563	0.6125	0.6688	0.725	**Cm**	0.5	0.5563	0.6125	0.6688	0.725
0.73	✓	✓	x	x	x	0.73	✓	✓	x	x	x
0.79	✓	✓	x	x	x	0.79	✓	✓	x	x	x
0.85	✓	✓	✓	x	x	0.85	✓	✓	x	x	x
0.91	✓	✓	✓	x	x	0.91	✓	✓	x	x	x
0.97	✓	✓	✓	x	x	0.97	✓	✓	x	x	x
$i_E = 46^o$											
	Cp										
Cm	0.5	0.5563	0.6125	0.6688	0.725						
0.73	x	x	x	x	x	✓ = R_R ↑ monotonically with speed					
0.79	x	x	x	x	x						
0.85	x	x	x	x	x	x = R_R not ↑ monotonically with speed					
0.91	x	x	x	x	x						
0.97	x	x	x	x	x						

Some resistance curves display a marked deviation from the expected form. An example is shown in Figure 6 for the following combination of parameters (high L_D/B and low i_E):

L_D/B	5.4	B/T	4.0	lcb	0.1%
C_P	0.6688	C_M	0.73	i_E	28^o

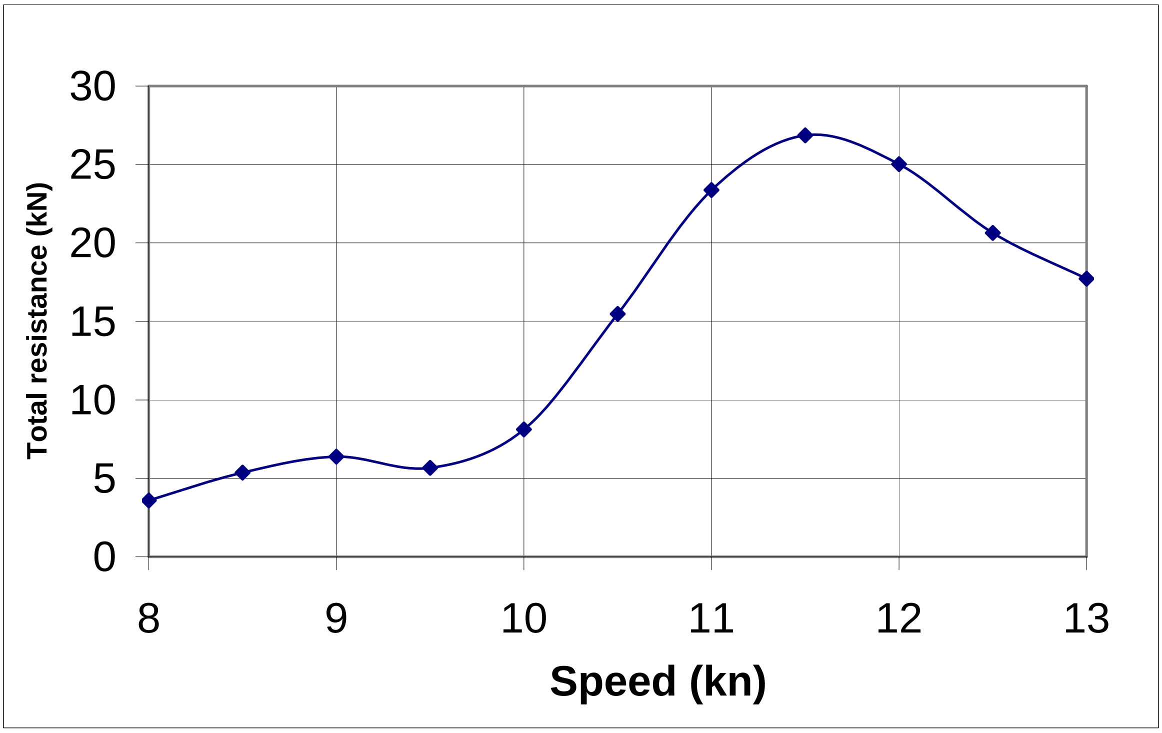

Figure 5 Total resistance vs speed for 34 m tug

The resistance for this vessel is much lower than the previous vessel because of the higher length/beam ratio and, hence, the lower displacement on the same length. The curve is unusual for the location of the resistance hollow at 13 kn (Fn = 0.373).

3.6 Solution

With the overall results being difficult to summarise by way of rules for particular combinations of parameters to avoid, the author proposes a pragmatic approach instead:

(a) If the resistance curves exhibit the characteristics of Figure 5, then the results should not be used, as it is likely that the parameters are outside the range of van Oortmerssen's original data set.

(b) If the resistance curves exhibit the characteristics of Figure 4, then data points on either side of the point of inflexion on the resistance curve should be deleted and the curve faired through the remaining points, as shown in Figure 6.

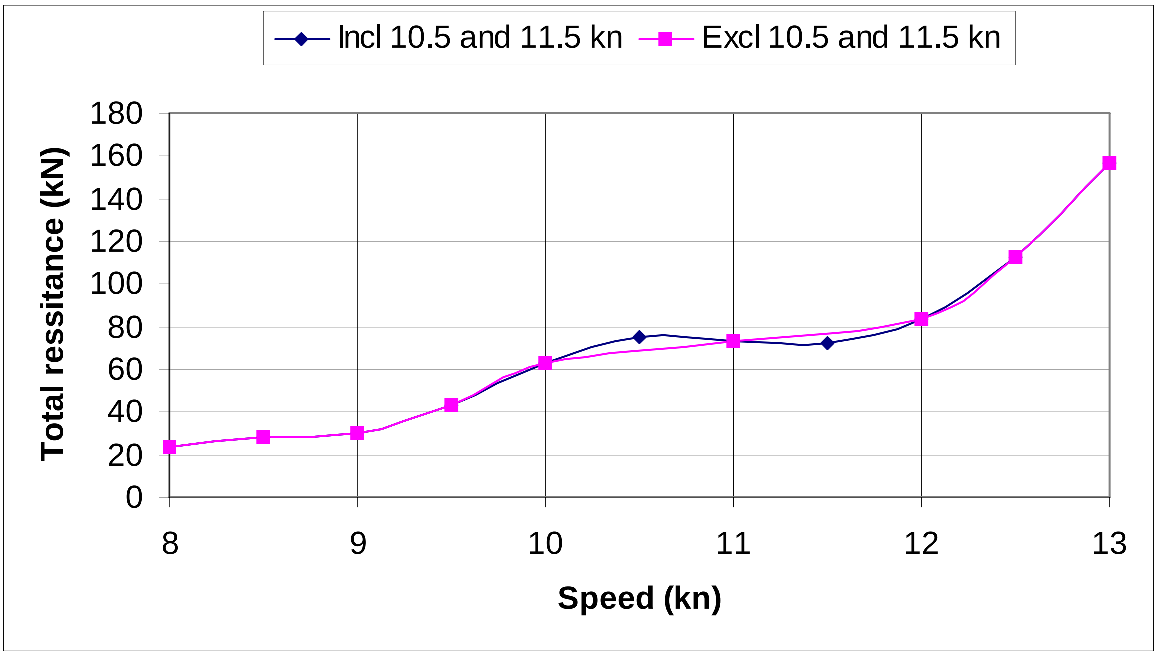

Figure 4 Total resistance vs speed for 34 m tug

4. CONCLUSIONS

Errors in van Oortmerssen's (1971) paper on the prediction of the resistance of tugs and trawlers have been investigated, and a consistent set of results for his example 29 m tug have been generated.

In addition, issues on the combinations of parameters which can be used with the method have been investigated, leading to the conclusion that high length/beam ratios combined with high angles of waterline entrance, or low length/beam ratios combined with low angles of waterline entrance should be avoided. Other combinations which provide non-monotonically-increasing values of resistance are harder to summarise. Rather, a pragmatic approach is proposed, whereby some predicted points are deleted and the curve faired through the remaining points.

In the author's estimation, van Oortmerssen's method is still the best around for these types of vessels, especially for small consultancies which have limited access to high-powered methods of resistance prediction.

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APPENDIX 1

Calculations for van Oortmerssen's Example Tug

Length WL	30.5 m		
Length BP	27.5 m		
Beam WL	8.406 m		
Draft moulded	2.949 m		
LCB fwd of midships L_{WL}	0.0105 m		
Displacement volume	376 m^3	5-3150	
Wetted surface	284 m^2	15-1400	281.0 if unknown
Prismatic co-efficient on L_{WL}	0.5790		
1/2 angle of WL entrance	23 deg	10.0-46.0	
Water density	1.025 t/m^3		
Water viscosity	1.18831 x 10^{-6} m^2/s		
Correlation allowance	0.00051		

Displacement length $L_D = (L_{WL}+L_{BP})/2$	29 m	
Displacement	385.4 t	
L_D/B	3.450	3.0-6.2
B/T	2.850	1.9-4.0
LCB fwd of midships L_D	-0.7395	
LCB% L_D	-2.550	(-8.0)-2.8
Prismatic co-efficient on L_D	0.6090	0.50-0.725
Midsection co-efficient	0.8587	0.73-0.97
C_{WL} entrance	79.35	
1000C1	2.096	
1000C2	248.3	
1000C3	-68.87	
1000C4	42.33	
m	0.4267	

Speed kn	**Fn** on L_D	**Cf+Ca** ITTC'57	**Rf** kN	**Rr/W**	**Rr** kN	**Rt** kN	**Pe** kW
3	0.0915	0.002922	1.01	0.00001	0.03	1.04	1.6
4	0.1220	0.002818	1.74	0.00009	0.33	2.06	4.2
5	0.1525	0.002741	2.64	0.00027	1.03	3.67	9.4
6	0.1830	0.002681	3.72	0.00051	1.93	5.65	17.4
7	0.2135	0.002633	4.97	0.00076	2.87	7.84	28.2
8	0.2440	0.002592	6.39	0.00117	4.42	10.81	44.5
9	0.2746	0.002557	7.98	0.00194	7.33	15.31	70.9
10	0.3051	0.002526	9.73	0.00437	16.51	26.24	135.0
11	0.3356	0.002499	11.65	0.00537	20.28	31.93	180.7
12	0.3661	0.002475	13.73	0.00979	36.99	50.72	313.1
13	0.3966	0.002453	15.97	0.02048	77.40	93.37	624.4

APPENDIX 2

Calculations for 34 m Tug

Length WL	34 m		
Length BP	31.5 m		
Beam WL	10.8 m		
Draft moulded	4.1 m		
LCB fwd of midships L_{WL}	-1.07 m		
Displacement volume	829 m^3	5-3150	
Wetted surface	463 m^2	15-1400	450.6 if unknown
Prismatic co-efficient on L_{WL}	0.681		
1/2 angle of WL entrance	25 deg	10.0-46.0	
Water density	1.025 t/m^3		
Water viscosity	1.07854×10^{-6} m^2/s		
Correlation allowance	0.0005		

Displacement length $L_D = (L_{WL}+L_{BP})/2$	32.75 m	
Displacement	849.7 t	
L_D/B	3.032	3.0-6.2
B/T	2.634	1.9-4.0
LCB fwd of midships L_D	-1.695	
LCB% L_D	-5.176	(-8.0)-2.8
Prismatic co-efficient on L_D	0.7070	0.50-0.725
Midsection co-efficient	0.8086	0.73-0.97
C_{WL} entrance	75.81	
1000C1	2.213	
1000C2	126.4	
1000C3	-32.29	
1000C4	42.43	
m	0.3074	

Speed kn	Fn on L_D	Cf+Ca ITTC57	Rf kN	Rr/W	Rr kN	Rt kN	Pe kW
8	0.2296	0.002518	10.12	0.001644	13.70	23.81	98.0
8.5	0.2440	0.002500	11.34	0.002022	16.85	28.19	123.3
9	0.2584	0.002484	12.64	0.002059	17.16	29.80	138.0
9.5	0.2727	0.002469	13.99	0.003459	28.82	42.82	209.3
10	0.2871	0.002455	15.42	0.005742	47.85	63.27	325.5
10.5	0.3014	0.002442	16.91	0.006921	57.67	74.58	402.8
11	0.3158	0.002429	18.46	0.006606	55.04	73.50	415.9
11.5	0.3301	0.002417	20.08	0.006225	51.87	71.95	425.7
12	0.3445	0.002406	21.76	0.007379	61.49	83.24	513.9
12.5	0.3588	0.002395	23.50	0.010696	89.13	112.63	724.3
13	0.3732	0.002385	25.31	0.015770	131.41	156.73	1048.2