ESTIMATION OF GREAT LAKES BULK CARRIER RESISTANCE BASED ON MODEL TEST DATA REGRESSION

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ERRATA in "Estimation of Great Lakes Bulk Carrier Resistance Based on Model Test Data Regression".

Page ii: C should read "C_v"

Page 10, line 17: multiple correlative coefficient should read "multiple correlation coefficient"

Page 12, line 7 of table should read:

\[(C_B)^2(L/B) \quad (C_B)^2(B/T) \quad (C_B)^2(C_n) \quad (C_B)^2(C_v)\]

Page 36: add to term \(F_3\):

\[+ A_9(B/T)^2(L/B) + A_{11}(C_v)^2(L/B)\]

Page I-1, line 14: add after \(C_v\): \(x 10^3\)

Page I-5: line 3: add after \(C_v\): \(x 10^3\)

Fig. 27: \(C_v\) should read "\(C_v=3.5\)"

Fig. 28: insert \(B/T=3.0\)
SYNOPSIS

Tank data have been collected, analyzed and standardized for 50 tests of Great Lakes Bulk Carriers. Regression analysis has been applied in order to estimate the coefficient of residuary resistance of such vessels in terms of their nondimensional form parameters. The results are presented for eight Froude numbers from 0.11 to 0.18 in the form of coefficients obtained by different regressions, and in the form of charts at Froude numbers 0.14 and 0.16. Examples illustrate the use of the regression formulas in estimating the full scale resistance.
NOMENCLATURE

B  beam (ft.)

C_A  model-ship correlation allowance

C_B  block coefficient, $V/(LB \cdot T)$

C_F  frictional resistance coefficient, $R_F/(0.5\rho V^2S)$

C_R  residuary resistance coefficient, $R_R/(0.5\rho V^2S)$

C_T  total resistance coefficient, $R_T/(0.5\rho V^2S)$

C  volumetric coefficient, $V/L^3$

C_WS  wetted surface coefficient, $S/V^{2/3}$

EHP  effective horsepower (without appendages)

F_n  Froude number, $V/\sqrt{gL}$

g  acceleration of gravity (ft./sec.$^2$)

i_E  half angle of entrance

L  length of the waterline (ft.)

LCB  longitudinal center of buoyancy

R_F  frictional resistance (lbs.)

R_R  residuary resistance (lbs.)
\( R_t \) total resistance (lbs.)

\( S \) wetted surface area (ft.\(^2\)), without appendages

\( T \) draft (ft.)

\( V \) speed (ft./sec.)

\( V \) displacement volume (ft.\(^3\))

\( \rho \) water density (lb. sec.\(^2\) ft.\(^{-4}\))

The quantities defined in the foregoing are used in the paper only in such dimensionless context that, instead of the British units suggested here, any other consistent set of units may be used.
1. **Introduction**

This paper describes a series of methods to estimate the residuary resistance coefficient of Great Lakes bulk carriers based on model test data regression. The results of this work are intended to assist the designer in estimating the effective horsepower of such ships in the initial design stage.

A sample of 70 model tests of such vessels was collected from various sources. After some initial screening 50 test data sets, which formed a sufficiently coherent sample, were selected for further analysis. All data sets were converted to the ITTC line test evaluation as a uniform reference base. Then, a series of regression analyses was performed for different sets of independent variables at each of eight Froude numbers. The results of two of these analyses are presented in this paper, one aiming at a high level of accuracy, and another representing a simplified, design-oriented version.

The format of the paper is as follows: Section 2 describes the sample of model tests; Section 3 explains the regression analysis techniques, Section 4 presents the results of the regressions, and Appendix I contains some examples of the procedure for estimating Great Lakes bulk carrier resistance from the regression formulas.
2. The Sample

Model test data were assembled for 70 tank tests of Great Lakes bulk carriers. These tests were conducted during the last 30 years at the following establishments:

Naval Ship Research and Development Center, Carderock (formerly David Taylor Model Basin)

Netherlands Ship Model Basin, Wageningen

Ship Hydrodynamics Laboratory, University of Michigan, Ann Arbor

Ship Laboratory, National Research Council, Ottawa

The data were made available by the tanks, Ref. 1, the sponsors, from published reports and SNAME Data Sheets, Ref. 2.

Since some of the organizations that released their data did not want the identity of their ships to be revealed, we have to refrain from a detailed reference to the characteristics of each model in the sample.

For each model, the length of the waterline, \( L \), beam, \( B \), draft, \( T \), wetted surface (without appendages), \( S \), block coefficient, \( C_B \), and load condition were noted together with the resistance measurements at each speed tested. Whenever available, the longitudinal center of buoyancy, \( LCB \), and half - angle of entrance, \( \theta_E \), were also recorded.

The data obtained from the various sources originally were not presented in accordance with any uniform standard but differed in the friction line, the tank water reference temperature, the roughness allowance when full scale data were given, and other minor details of the test evaluation procedure. It was, therefore,
necessary to standardize all input data to the regression analysis: The residuary resistance coefficient $C_R$, at each speed was converted to the ITTC friction line for the model as a reference base, assuming a fresh water temperature of 59° F. The dimensionless hull form parameters were corrected to conform with the standard set given in the nomenclature of the paper.

The Froude number $F_n$, was calculated at each speed and $C_R$ values were obtained by interpolation at $F_n$ values, 0.11, 0.12, 0.13, 0.14, 0.15, 0.16, 0.17 and 0.18. The regression variables, $C_B$, $L/B$, $B/T$, $C_{WS}$, $C_T$, $i_E$ and LCB were determined for each model.

Values of $i_E$ and LCB were only available for about 60% of the sample and initially it was decided that the mean value of the distributions of $i_E$ and LCB should be used when data were lacking in the sample. However, early regression analyses indicated that, because of the consequent large clusters at the mean values, artificial emphasis was placed on the deviation from the mean. It was decided, therefore, to remove $i_E$ and LCB from the list of regression variables.

These early regression analyses also suggested that tests in the ballast condition in 11 cases were not suitable for consideration with those in the full load and intermediate load (cubic load) condition, probably due to the nature of the trim effect. The ballast tests were, therefore, removed from the sample. Regrettably, this ballast sample was not of sufficient magnitude to permit separate study.

In three cases, the accuracy of the original input data was severely questioned and it was decided to discard these three sets.

In six of the tests, the data were only available over a small speed range, and rather than risk the error
of extrapolation, these tests were also removed, thus providing a uniform size of sample over the whole speed range.

This left 50 sets of data, in the full load and intermediate load (near even keel) condition, in the sample.

Figs. 1 - 5 show the distribution of each of the five regression variables, $C_B$, $L/B$, $B/T$, $C_{WS}$, $C_V$, within the sample of these 50 tests. The great majority of the ships in the sample vary within only small limits in accordance with standard Great Lakes ship design practice. In a few cases where larger deviations do occur, these can for the most part be traced to intermediate draft conditions or jumboized designs.
Fig. 1

DISTRIBUTION OF $C_B$ IN REGRESSION SAMPLE
Fig. 2

DISTRIBUTION OF L/B IN REGRESSION SAMPLE
Fig. 3

DISTRIBUTION OF B/T IN REGRESSION SAMPLE
Fig. 4

DISTRIBUTION OF $C_{ws}$ IN REGRESSION SAMPLE
Fig. 5

DISTRIBUTION OF $C_v$ IN REGRESSION SAMPLE
3. **Regression Analysis**

3.1 **Terminology**

*Polynomial regression* is the fitting of a dependent variable by a polynomial function of one independent variable with the degree of the polynomial specified.

*Linear regression* is the fitting of a dependent variable by a linear function of a specified independent variable. When more than one independent variable are specified, this is known as *multiple linear regression*.

In *stepwise multiple linear regression* a dependent variable is fitted in terms of specified independent variables in a stepwise manner.

In this procedure the regression equation is gradually built up, adding in each step one further term - out of a set initially specified - which is selected so that it improves the fit more than any other term still in contention for being included. (The quality of the fit is measured in terms of the multiple correlative coefficient.) This stepwise procedure continues until any further improvement to be expected by including another term does not exceed a specified tolerance. The stepwise regression offers the advantage that it establishes the relative significance of the terms within a preselected set.

3.2 **Regression Programs**

The regression programs used in these analyses were made available by The Statistical Research Laboratory of The University of Michigan and were run on the University of Michigan's IBM 360/67 computer.

In all programs, the option of zero intercept was available.
4. Results

4.1 Regression with 45 Variables at Each Speed

At Froude numbers 0.11, 0.12, 0.13, 0.14, 0.15, 0.16, 0.17, 0.18, a stepwise multiple linear regression with zero intercept was performed using as the independent variables the five original regression variables, the same regression variables squared and cross-products of these ten terms. This results in a total of 45 independent variables, Table I. From this set the regression at each speed extracted the 12-16 most significant variables for inclusion. (In accordance with the F-values and tolerance level specified.)

The results of the regressions are given in Tables II - IX,
Table I: List of independent variables in 45 term regression

<table>
<thead>
<tr>
<th>$C_B$</th>
<th>$L/B$</th>
<th>$B/T$</th>
<th>$C_{WS}$</th>
<th>$C_V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(C_B)^2$</td>
<td>$(L/B)^2$</td>
<td>$(B/T)^2$</td>
<td>$(C_{WS})^2$</td>
<td>$(C_V)^2$</td>
</tr>
<tr>
<td>$(C_B)^2 (L/B)$</td>
<td>$(C_B)^2 (B/T)$</td>
<td>$(C_B) (C_{WS})$</td>
<td>$(C_B) (C_V)$</td>
<td></td>
</tr>
<tr>
<td>$(L/B) (B/T)$</td>
<td>$(L/B) (C_{WS})$</td>
<td>$(L/B) (C_V)$</td>
<td>$(B/T) (C_{WS})$</td>
<td></td>
</tr>
<tr>
<td>$(B/T) (C_V)$</td>
<td>$(C_{WS}) (C_V)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(C_B)^3$</td>
<td>$(L/B)^3$</td>
<td>$(B/T)^3$</td>
<td>$(C_{WS})^3$</td>
<td>$(C_V)^3$</td>
</tr>
<tr>
<td>$(C_B)^2 (L/B)$</td>
<td>$(C/B)^2 (B/T)$</td>
<td>$(C/B)^2 (C_{WS})$</td>
<td>$(C_B)^2 (C_V)$</td>
<td></td>
</tr>
<tr>
<td>$(L/B)^2 (C_B)$</td>
<td>$(L/B)^2 (B/T)$</td>
<td>$(L/B)^2 (C_{WS})$</td>
<td>$(L/B)^2 (C_V)$</td>
<td></td>
</tr>
<tr>
<td>$(B/T)^2 (C_B)$</td>
<td>$(B/T)^2 (L/B)$</td>
<td>$(B/T)^2 (C_{WS})$</td>
<td>$(B/T)^2 (C_V)$</td>
<td></td>
</tr>
<tr>
<td>$(C_{WS})^2 (C_B)$</td>
<td>$(C_{WS})^2 (L/B)$</td>
<td>$(C_{WS})^2 (B/T)$</td>
<td>$(C_V)^2 (C_{WS})$</td>
<td></td>
</tr>
<tr>
<td>$(C_V)^2 (C_B)$</td>
<td>$(C_V)^2 (L/B)$</td>
<td>$(C_V)^2 (B/T)$</td>
<td>$(C_V)^2 (C_{WS})$</td>
<td></td>
</tr>
</tbody>
</table>
Table II: Regression equation with 45 independent variables at Froude number = 0.11

\[ c_R = \]
\[ 0.39093E-03 \quad (B/T) \]
\[ + 0.44806E 01 \quad (C_\vartheta) \]
\[ + 0.83000E 03 \quad (C_\vartheta)^2 \]
\[ + 0.72338E-05 \quad (B/T) (C_{WS}) \]
\[ -0.26627E 01 \quad (E/T) (C_\vartheta) \]
\[ -0.70351E-02 \quad (C_B)^3 \]
\[ + 0.12980E-04 \quad (C_{WS})^3 \]
\[ -0.53032E-05 \quad (C_\vartheta)^3 \]
\[ + 0.51622E-02 \quad (C_B)^2 (B/T) \]
\[ + 0.17866E 01 \quad (C_B)^2 (C_\vartheta) \]
\[ -0.70676E-03 \quad (E/T)^2 (C_B) \]
\[ + 0.30530E 00 \quad (E/T)^2 (C_\vartheta) \]
\[ -0.11269E-03 \quad (C_{WS})^2 (C_B) \]
\[ -0.19202E-01 \quad (C_{WS})^2 (C_\vartheta) \]
\[ -0.97511E 02 \quad (C_\vartheta)^2 (L/B) \]
\[ + 0.59050E 02 \quad (C_\vartheta)^2 (B/T) \]

Statistical measures:

Multiple correlation coefficient = 0.9857

Standard error of estimate = 0.5757 E-4

F-values for inclusion and deletion = 0.00001

Tolerance level = 0.00001
Table III: Regression equation with 45 independent variables at Froude number = 0.12

\[ C_R = \]
\[ 0.19077E-02 \ (B/T) + 0.20311E \ 03 \ (C_V)^2 - 0.89316E-03 \ (B/T) \ (C_{WS}) - 0.60310E \ 00 \ (B/T) \ (C_V) - 0.13943E-01 \ (C_B)^3 + 0.11453E-03 \ (B/T)^3 - 0.26071E \ 05 \ (C_V)^3 + 0.11915E-01 \ (C_B)^2 \ (B/T) - 0.21997E-02 \ (B/T)^2 \ (C_B) - 0.45059E-05 \ (B/T)^2 \ (C_{WS}) + 0.17105E \ 00 \ (B/T)^2 \ (C_V) - 0.21553E-03 \ (C_{WS})^2 \ (C_B) + 0.12299E-04 \ (C_{WS})^2 \ (L/B) + 0.80595E-04 \ (C_{WS})^2 \ (B/T) + 0.13902E \ 02 \ (C_V)^2 \ (L/B) \]

Statistical measures:

Multiple correlation coefficient = 0.9905

Standard error of estimate = 0.4848 E-4

F-values for inclusion and deletion = 0.00001

Tolerance level = 0.00001

14
Table IV: Regression equation with 45 independent variables at Froude number = 0.13

\[
C_R = 0.79997E-02 \quad (B/T) \\
-0.72573E 03 \quad (C_v)^2 \\
-0.24164E-01 \quad (C_B)(B/T) \\
+ 0.34961E 00 \quad (B/T)(C_v) \\
-0.10479E-01 \quad (C_B)^3 \\
+ 0.20239E-03 \quad (B/T)^3 \\
-0.25212E 05 \quad (C_v)^3 \\
+ 0.28514E-01 \quad (C_B)^2(B/T) \\
-0.59229E 01 \quad (C_B)^2(C_v) \\
-0.33756E-02 \quad (B/T)^2(C_B) \\
+ 0.41254E-04 \quad (B/T)^2(L/B) \\
+ 0.11644E 00 \quad (B/T)^2(C_v) \\
+ 0.10623E 04 \quad (C_v)^2(C_B) \\
+ 0.74931E 02 \quad (C_v)^2(L/B) \\
-0.22780E 02 \quad (C_v)^2(C_{WS})
\]

Statistical measures:

Multiple correlation coefficient = 0.9926
Standard error of estimate = 0.4513 E-4
F-values for inclusion and deletion = 0.00001
Tolerance level = 0.00001
Table V: Regression equation with 45 independent variables at Froude number = 0.14

\[ C_R = 0.27304 \times 10^{-03} (C_{WS}) + 0.22876 \times 10^{03} (C_V)^2 - 0.11519 \times 10^{-01} (C_B)(C_{WS}) + 0.56176 \times 10^{-03} (L/B)(C_{WS}) + 0.85505 \times 10^{00} (B/T)(C_V) + 0.40181 \times 10^{05} (L/B)^3 - 0.12906 \times 10^{05} (C_V)^3 + 0.82250 \times 10^{02} (C_B)^2(C_{WS}) - 0.49417 \times 10^{00} (C_B)^2(C_V) - 0.20037 \times 10^{-03} (L/B)^2(C_B) - 0.13293 \times 10^{-04} (C_{WS})^2(L/B) - 0.83026 \times 10^{-02} (C_V)^2(B/T) \]

Statistical measures:
Multiple correlation coefficient = 0.9943
Standard error of estimate = 0.4529 E-4
F-values for inclusion and deletion = 0.00001
Tolerance level = 0.00001
Table VI: Regression equation with 45 independent variables at Froude number = 0.15

\[ C_R = \]

\[
0.27252E-01 \quad (C_B) \\
-0.57810E-03 \quad (C_B^2) (L/B) \\
-0.18397E-02 \quad (L/B) (B/T) \\
-0.65332E-05 \quad (L/B)^3 \\
-0.53638E-04 \quad (B/T)^3 \\
+ 0.10299E-04 \quad (C_{WS})^3 \\
+ 0.17691E-04 \quad (C_V)^3 \\
-0.22049E-02 \quad (C_B)^2 (C_{WS}) \\
+ 0.15197E-03 \quad (L/B)^2 (B/T) \\
-0.25054E-05 \quad (L/B)^2 (C_{WS}) \\
+ 0.19035E-02 \quad (L/B)^2 (C_V) \\
+ 0.68141E-03 \quad (B/T)^2 (C_B) \\
-0.24471E-05 \quad (B/T)^2 (L/B) \\
+ 0.18555E-00 \quad (B/T)^2 (C_V) \\
+ 0.61236E-02 \quad (C_{WS})^2 (C_V) \\
-0.71073E-02 \quad (C_V)^2 (B/T)
\]

Statistical measures:

Multiple correlation coefficient = 0.9954

Standard error of estimate = 0.4688 E-4

F-values for inclusion and deletion = 0.00001

Tolerance level = 0.00001
Table VII: Regression equation with 45 independent variables at Froude number = 0.16

\[ C_R = \]

\[-0.34769E-03 \text{ (L/B)} + 0.36576E-03 \text{ (L/B)}^2 -0.15297E-01 \text{ (C}_B\text{) (B/T)} -0.33813E-01 \text{ (C}_B\text{) (C}_V\text{)} -0.18196E-04 \text{ (L/B)}^3 + 0.26462E-05 \text{ (B/T)}^3 -0.45552E-05 \text{ (C}_V\text{)}^3 + 0.14342E-01 \text{ (C}_B\text{)}^2 \text{ (B/T)} -0.84322E-03 \text{ (C}_B\text{)}^2 \text{ (C}_WS\text{)} -0.24405E-01 \text{ (L/B)}^2 \text{ (C}_V\text{)} -0.91883E-03 \text{ (B/T)}^2 \text{ (C}_B\text{)} + 0.74922E-04 \text{ (B/T)}^2 \text{ (L/B)} + 0.27256E-00 \text{ (B/T)}^2 \text{ (C}_V\text{)} + 0.58213E-02 \text{ (C}_V\text{)}^2 \text{ (L/B)} + 0.52824E-02 \text{ (C}_V\text{)}^2 \text{ (C}_WS\text{)}\]

Statistical measures:

Multiple correlation coefficient = 0.9964
Standard error of estimate = 0.4953 E-4
F-values for inclusion and deletion = 0.00001
Tolerance level = 0.00001
Table VIII: Regression equation with 45 independent variables at Froude number = 0.17

\[
C_R = 
-0.70672E-03 \ (L/B) \\
+ 0.11261E-03 \ (C_{WS}) \\
-0.59554E-03 \ (L/B)(B/T) \\
-0.49819E-05 \ (L/B)^3 \\
-0.92531E-04 \ (B/T)^3 \\
-0.15310E 05 \ (C_V)^3 \\
+ 0.16688E-02 \ (C_B)^2(L/B) \\
-0.35594E-02 \ (C_B)^2(C_{WS}) \\
+ 0.94751E-04 \ (L/B)^2(B/T) \\
+ 0.15280E-02 \ (B/T)^2(C_B) \\
-0.12069E-03 \ (B/T)^2(L/B) \\
+ 0.38688E-04 \ (B/T)^2(C_{WS}) \\
+ 0.48500E-01 \ (C_{WS})^2(C_V) \\
+ 0.84527E 01 \ (C_V)^2(L/B)
\]

Statistical measures:

Multiple correlation coefficient = 0.9954

Standard error of estimate = 0.6882 E-4

F-values for inclusion and deletion = 0.00001

Tolerance level = 0.00001
Table IX: Regression equation 45 independent variables at Froude number = 0.18

\[ C_R = \]
\[ -0.93931E-03 \quad (C_{WS}) \]
\[ -0.16741E-03 \quad (L/B)^2 \]
\[ + 0.37866E-02 \quad (C_B)(C_{WS}) \]
\[ -0.14179E-02 \quad (L/B)(B/T) \]
\[ -0.11011E-03 \quad (B/T)^3 \]
\[ + 0.17133E-02 \quad (C_B)^2(L/B) \]
\[ -0.73467E-02 \quad (C_B)^2(C_{WS}) \]
\[ + 0.20476E 01 \quad (C_B)^2(C_V) \]
\[ + 0.17675E-03 \quad (L/B)^2(B/T) \]
\[ + 0.19050E-02 \quad (B/T)^2(C_B) \]
\[ -0.10805E-03 \quad (B/T)^2(L/B) \]
\[ + 0.15162E 00 \quad (B/T)^2(C_V) \]
\[ + 0.72594E-01 \quad (C_{WS})^2(C_V) \]
\[ -0.13581E 03 \quad (C_V)^2(B/T) \]

Statistical measures:

Multiple correlation coefficient = 0.9952
Standard error of estimate = 0.9100 E-4
F-values for inclusion and deletion = 0.00001
Tolerance level = 0.00001
4.2 Regression with 11 Variables at Each Speed

Although this stepwise multiple linear regression produces a very accurate fit of the sample by virtue of the great number of terms involved it also has some drawbacks in the practical application of its results. There are too many terms in the regression equation to arrive at a design-oriented, physical interpretation of the trends in the sample and, moreover, the set of independent variables producing this "most accurate" fit is a different one at each speed.

In the interest of greater simplicity and uniformity it was therefore desirable to attempt to reduce the number of independent variables to a reasonable minimum still ensuring adequate accuracy, and to use a standard set of these variables throughout the speed range.

It was logical to first eliminate those "independent" variables that showed a strong dependence on others in the set. This suggested itself especially for the wetted surface coefficient whose strong dependence on other hull form parameters is well known. This was also attractive since the wetted surface in the initial design stage generally cannot be treated as an independent design variable.

It was therefore attempted to express the wetted surface in the manner of the well known Denny formula, which reads (Ref. 3):

\[ S = 1.7 \, (L \cdot T) + \frac{V}{T} \]

The coefficients in this formula were redervized by multiple linear regression of the 50 Great Lakes bulk carriers in our sample to yield:
\[ S = 1.667 \, (L \cdot T) + 1.047 \, \frac{\bar{V}}{T} \]

with extremely small statistical error (multiple correlation coefficient = 0.9997, standard error estimate = 1.068 \cdot 10^3).

To further test the significance of the wetted surface coefficient in the regressions, a stepwise multiple linear regression was then run at each Froude number with \( C_{WS} \) terms removed which resulted in only a small loss of accuracy. This further supported eliminating \( C_{WS} \) from the set of independent variables.

At the next stage we looked for any other terms in the regression equation whose role was relatively insignificant. This could be judged by the significance tests carried out during the stepwise regression, which identified the statistically less influential terms by their partial correlation values, as well as by judging the relative magnitude of the contributions from each term throughout the speed range.

On this basis it was possible to select 11 variables as appearing to be the most significant.

These were:

\[
\begin{align*}
(C_B)^3 & \quad (L/B)^3 & \quad (B/T)^3 & \quad (C_V)^3 \\
(C_B)^2(B/T) & \quad (L/B)^2(B/T) & \quad (B/T)^2(C_B) \\
(L/B)^2(C_V) & \quad (B/T)^2(C_V) \\
(B/T)^2(L/B) & \quad (B/T)^2(C_V) \\
(C_V)^2(L/B) &
\end{align*}
\]
At each Froude number, a multiple linear regression was run using these independent variables. The coefficients obtained, $A(i,j)$, are defined in Table X according to:

$$C_R = \sum_{i=1}^{11} A(i,j) \cdot x_i$$

for a given Froude number $F_{nj}$ where $x_i$ = independent variable, and their numerical values are given in Table XI.
<table>
<thead>
<tr>
<th>Variable</th>
<th>( x_i )</th>
<th>0.11</th>
<th>0.12</th>
<th>0.13</th>
<th>0.14</th>
<th>0.15</th>
<th>0.16</th>
<th>0.17</th>
<th>0.18</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (( C_B ))^3</td>
<td>(A1,1)</td>
<td>(A1,2)</td>
<td>(A1,3)</td>
<td>(A1,4)</td>
<td>(A1,5)</td>
<td>(A1,6)</td>
<td>(A1,7)</td>
<td>(A1,8)</td>
<td></td>
</tr>
<tr>
<td>2 (L/B)^3</td>
<td>(A2,1)</td>
<td>(A2,2)</td>
<td>(A2,3)</td>
<td>(A2,4)</td>
<td>(A2,5)</td>
<td>(A2,6)</td>
<td>(A2,7)</td>
<td>(A2,8)</td>
<td></td>
</tr>
<tr>
<td>3 (B/T)^3</td>
<td>(A3,1)</td>
<td>(A3,2)</td>
<td>(A3,3)</td>
<td>(A3,4)</td>
<td>(A3,5)</td>
<td>(A3,6)</td>
<td>(A3,7)</td>
<td>(A3,8)</td>
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Table X: Definition of coefficients in 11 term regression
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<td>A(11,8) = 0.43452E 02</td>
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4.3 Cross-fairing of Regression Coefficients Against Speed

In order to further simplify the use of the regression equation, at the expense of some loss of accuracy, the coefficients for each of the 11 independent variables, A(i,j), were cross-faired against Froude number, \( F_{nj} \), in the range of the eight given speeds, \( 1 \leq j \leq 8 \), in terms of cubic polynomials of \( F_n \). This results in one speed-dependent function for the coefficient, \( \bar{A}(i) \), for each term in the regression equation:

\[
\bar{A}(i) = \sum_{k=0}^{3} B(i,k) F_n^k, \quad 1 \leq i \leq 11
\]

which will serve to estimate the residual resistance coefficient by

\[
C_R = \sum_{i=1}^{11} \bar{A}(i) x_i
\]

The coefficients \( B(i,k) \) were obtained by polynomial regression, to the third degree, of the \( A(i,j) \) against the independent variables \( F_n \), and are presented in Table XII. The functions \( \bar{A}(i) = f(F_n) \) are shown in Figs. 6 - 16, where they are compared to the coefficients \( A(i,j) \) prior to cross-fairing. The agreement is reasonable despite obvious discrepancies in some terms at some speeds. A more exacting test of the simplified, cross-faired regression formula is performed in Appendix I, where full scale total resistance coefficients are estimated using the exact 11 term regression at each individual speed versus the cross-faired regression formula. The agreement is fairly close in these instances, yet from a
cautious viewpoint we must recommend the exact regression to be used for greater accuracy, the cross-faired version only when simplicity is at a premium.

It may be mentioned in passing that we did not want to include speed-dependent terms as independent variables, together with the set of 11 others we chose to start with, in order to conserve any differences in the physical trends at differing speeds, instead of smoothing them out from the beginning. Further, we could clearly have obtained a slightly more accurate speed-dependent regression in a single analysis with speed included, but our goal in this context was simplicity and transparency, and not primarily accuracy.
Table XII: Coefficients \( B(i,k) \)

| \( B(i,0) \) | \( 0.49349E-04 \) | \( B(7,0) \) | \( 0.68194E-00 \) |
| \( B(i,1) \) | \( 0.58267E-01 \) | \( B(7,1) \) | \( -0.15932E-02 \) |
| \( B(i,2) \) | \( -0.71357E-02 \) | \( B(7,2) \) | \( 0.11958E-03 \) |
| \( B(i,3) \) | \( 0.17137E-03 \) | \( B(7,3) \) | \( -0.29376E-03 \) |
| \( B(2,0) \) | \( 0.71518E-04 \) | \( B(8,0) \) | \( -0.23874E-01 \) |
| \( B(2,1) \) | \( -0.10038E-02 \) | \( B(8,1) \) | \( 0.54814E-00 \) |
| \( B(2,2) \) | \( 0.66723E-02 \) | \( B(8,2) \) | \( -0.42080E-01 \) |
| \( B(2,3) \) | \( -0.14141E-01 \) | \( B(8,3) \) | \( 0.10963E-02 \) |
| \( B(3,0) \) | \( 0.11613E-02 \) | \( B(9,0) \) | \( 0.19879E-02 \) |
| \( B(3,1) \) | \( 0.35475E-02 \) | \( B(9,1) \) | \( -0.46226E-01 \) |
| \( B(3,2) \) | \( -0.68280E-01 \) | \( B(9,2) \) | \( 0.34755E-00 \) |
| \( B(3,3) \) | \( -0.85950E-00 \) | \( B(9,3) \) | \( -0.85950E-00 \) |
| \( B(4,0) \) | \( 0.43311E-06 \) | \( B(10,0) \) | \( -0.14838E-01 \) |
| \( B(4,1) \) | \( -0.10466E-02 \) | \( B(10,1) \) | \( 0.32257E-02 \) |
| \( B(4,2) \) | \( 0.79774E-08 \) | \( B(10,2) \) | \( -0.22939E-03 \) |
| \( B(4,3) \) | \( -0.19831E-09 \) | \( B(10,3) \) | \( 0.52907E-03 \) |
| \( B(5,0) \) | \( 0.19945E+00 \) | \( B(11,0) \) | \( -0.74263E-03 \) |
| \( B(5,1) \) | \( -0.44088E+01 \) | \( B(11,1) \) | \( 0.18117E+05 \) |
| \( B(5,2) \) | \( 0.32371E+02 \) | \( B(11,2) \) | \( -0.13903E+06 \) |
| \( B(5,3) \) | \( -0.79147E+02 \) | \( B(11,3) \) | \( 0.34815E+06 \) |
| \( B(6,0) \) | \( -0.10489E-02 \) | \( B(6,0) \) | \( -0.10489E-02 \) |
| \( B(6,1) \) | \( 0.23742E+01 \) | \( B(6,1) \) | \( 0.23742E+01 \) |
| \( B(6,2) \) | \( -0.17495E+00 \) | \( B(6,2) \) | \( -0.17495E+00 \) |
| \( B(6,3) \) | \( 0.42171E+00 \) | \( B(6,3) \) | \( 0.42171E+00 \) |
Coefficients $A(i,j)$ and $\tilde{A}(i)$, $i=1$

Coefficients $A(i,j)$ and $\tilde{A}(i)$, $i=2$
Fig. 8

Coefficients $A(i,j)$ and $A(i)$, $i=3$

Fig. 9

Coefficients $A(i,j)$ and $A(i)$, $i=4$
Fig. 10

Coefficients $A(i,j)$ and $\bar{A}(i)$, $i=5$

Fig. 11

Coefficients $A(i,j)$ and $\bar{A}(i)$, $i=6$
Fig. 12

Coefficients $A(i,j)$ and $\bar{A}(i)$, $i=7$

Fig. 13

Coefficients $A(i,j)$ and $\bar{A}(i)$, $i=8$
Fig. 14

Coefficients $A(i,j)$ and $\bar{A}(i)$, $i=9$

Fig. 15

Coefficients $A(i,j)$ and $\bar{A}(i)$, $i=10$
Coefficients $A(i,j)$ and $\bar{A}(i)$, $i=11$
4.4 Discussion of Trends in the Sample

A physical, design-oriented interpretation of a regression formula is always difficult because of the multiplicity of terms and, moreover, cross-coupled terms involved. Further there is always the risk that the set of independent regression variables picked may not include the physically most relevant quantities. This leads the pure statistician to refrain from any physical interpretation, and to simply state that the regression formula represents the best possible fit, at the level attempted, of the population of physical observations in the sample.

Despite some reservations on our part that we might have missed some relevant physical parameters in the analysis, for instance some parameter of local after-body shape influencing the extent of separation, we nonetheless wanted to discuss the trends exhibited by the variables in our regression in a design-oriented fashion without attempting a physical explanation.

For this purpose it was necessary to collect terms in the regression equation (ll term version at discrete speeds) forming a small set of functions each of which preferably should express the influence of some dominant variable modified by one or two weaker variables. The dominant variables should appear in only one function if possible. The basic scheme resulting from this is in full analogy to the approach taken by Doust and O'Brien in their trawler regression, Ref. 4.

After some experimentation the following set of functions appeared to be best suited to discuss the trends in the sample:

35
\[ F_1 = f(C_B, B/T) = \]
\[ = A_1(C_B)^3 + A_5(C_B)^2(B/T) + A_8(C_B)(B/T)^2 \]

\[ F_2 = f(B/T, C_V) = \]
\[ = A_3(B/T)^3 + A_4(C_V)^3 + A_{10}(C_V)(B/T)^2 \]

\[ F_3 = f(L/B, B/T, C_V) = \]
\[ = A_2(L/B)^3 + A_6(B/T)(L/B)^2 + A_7(C_V)(L/B)^2 \]

where \( A_1, \ldots, A_{10} \) correspond to the coefficients \( A(1,j), \ldots, A(10,j) \) at a particular speed, \( F_{nj} \), as defined earlier.

The trends in these functions against the basic regression variables are displayed in Figs. 17 to 30 for \( F_n = 0.14 \) and 0.16. Appendix I illustrates the use of the graphs in a sample calculation.
Fig. 17

\[ F_n = 0.14 \]

\[ B/T = 4.0 \]

\[ B/T = 3.5 \]

\[ B/T = 3.0 \]

\[ B/T = 2.5 \]

\[ B/T = 2.0 \]

\[ F_1 \times 10^3 \]

\[ C_B \]
Fig. 18

\[ B/T \]

\[ F_n = 0.14 \]

\[ F_2 \times 10^3 \]

\[ C_p = 2 \times 10^{-3} \]

\[ C_p = 3 \times 10^{-3} \]

\[ C_p = 4 \times 10^{-3} \]

\[ C_p = 5 \times 10^{-3} \]
Fig. 22

$B/T = 3.5$  $F_n = 0.14$

$C_p = 5 \times 10^{-3}$

$C_p = 4 \times 10^{-3}$

$C_p = 3 \times 10^{-3}$

$C_p = 2 \times 10^{-3}$

$L/B$
Fig. 24

\[
\begin{array}{c|c}
F_{n} = 0.16 & \\
10.0 & B/T = 4.0 \\
8.0 & B/T = 3.5 \\
6.0 & B/T = 3.0 \\
4.0 & B/T = 2.5 \\
2.0 & B/T = 2.0 \\
\end{array}
\]

\[F_{l} \times 10^{3}\]

\[C_{B}\]
Fig. 25

B/T

$F_n = 0.16$

$F_2 \times 10^3$

$C_V = 2 \times 10^{-3}$

$C_V = 3 \times 10^{-3}$

$C_V = 4 \times 10^{-3}$

$C_V = 5 \times 10^{-3}$
Fig. 26

B/T = 2.0  \hspace{0.5cm} F_n = 0.16

\[ F_3 \times 10^4 \]

- \( C_d = 5 \times 10^{-3} \)
- \( C_l = 4 \times 10^{-3} \)
- \( C_v = 3 \times 10^{-3} \)
- \( C_s = 2 \times 10^{-3} \)

L/B
Fig. 27

B/T = 2.5

F_3 = 5 \times 10^{-3}

F_3 = 4 \times 10^{-3}

F_3 = 3 \times 10^{-3}

F_3 = 2 \times 10^{-3}

L/B
Fig. 29

B/T = 3.5  \quad \text{F}_n = 0.16

\begin{align*}
C_v &= 5 \times 10^{-3} \\
C_v &= 4 \times 10^{-3} \\
C_v &= 3 \times 10^{-3} \\
C_v &= 2 \times 10^{-3}
\end{align*}

\begin{align*}
P_3 \times 10^4
\end{align*}

L/B

49
Fig. 30

L/B

$B/T = 4.0$  
$F_n = 0.16$

$F_3 \times 10^4$

$C_{p} = 5 \times 10^{-3}$

$C_{p} = 4 \times 10^{-3}$

$C_{p} = 3 \times 10^{-3}$

$C_{p} = 2 \times 10^{-3}$
5. Conclusion

A sample of model test data for Great Lakes bulk carriers was compiled from various sources which includes the great majority of all experiments conducted for this type of ship during the last thirty years.

The residuary resistance coefficient of these models was then regressed against a set of standard hull form parameters at three different levels of approximation:

1. A regression equation with 45 independent variables at each given speed \((0.11 \leq F_n \leq 0.18)\), the most accurate fit attempted.
2. A regression equation with 11 independent variables at each given speed, a simplified version for initial design use.
3. A modified version of the 11 term regression with the coefficients cross-faired against speed, a further simplification for the designer's convenience.

Sample power estimates based on these formulas are presented in the Appendix.

The relative significance of the hull form parameters in the 11 term regression is discussed in terms of a graphical representation of three standard functions, of which the residuary resistance is composed, at two different speeds.

We hope that the results presented in this paper will offer the design community a choice of power estimating formulas for Great Lakes bulk carriers suitable for initial design work by manual or computer-aided methods.
6. Acknowledgements

We want to express our sincere gratitude to the following individuals and organizations:

Mr. R. A. Stearn of R. A. Stearn, Inc. for his initiative in starting the project, and the financial support and assistance in the data collection provided by his company.

The late Captain L. A. Baier, who contributed his file of test data taken in the University of Michigan model basin.

Mr. S. T. Mathews, Ship Laboratory, National Research Council, Ottawa, who released a large set of Canadian test data and went to great effort to have these data compiled and uniformly documented in a new report, prepared by Mr. M. Michailidis.

The following Great Lakes shipping and ship design firms, who either released their test data or assisted in obtaining the release from the owners:

American Ship Building Company, Lorain, Ohio
Bethlehem Steel Corporation, Sparrows Point, Maryland
Columbia Transportation, Cleveland, Ohio
Hanna Mining Company, Cleveland, Ohio
Inland Steel Company, Chicago, Illinois
Marine Consultants and Designers, Cleveland, Ohio

U. S. Steel Corporation, Duluth, Minnesota

Mr. S. I. Posner, who worked on the University of Mich-
igan staff and assisted in the data acquisition. Messrs. S. Callis, V. Chen, P. Majumdar and C. Mariscal, students at the University of Michigan, for the excellent art work for this paper.
REFERENCES


2. "Model and Expanded Resistance Data Sheets," SNAME.


Appendix I

Examples illustrating the use of the regression formulas in estimating the full scale resistance.
**Examples:**

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<thead>
<tr>
<th></th>
<th>Vessel A</th>
<th>Vessel B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, $L$</td>
<td>998.0 ft.</td>
<td>661.2 ft.</td>
</tr>
<tr>
<td>Beam, $B$</td>
<td>104.6 ft.</td>
<td>70.0 ft.</td>
</tr>
<tr>
<td>Draft, $T$</td>
<td>25.75 ft.</td>
<td>24.5 ft.</td>
</tr>
<tr>
<td>Block coefficient, $C_B$</td>
<td>0.915</td>
<td>0.864</td>
</tr>
<tr>
<td>Wetted surface, $S$</td>
<td>150,450 ft.$^2$</td>
<td>69,700 ft.$^2$</td>
</tr>
<tr>
<td>Wetted surface,</td>
<td>142,850 ft.$^2$</td>
<td>68,900 ft.$^2$</td>
</tr>
<tr>
<td>from regression formula</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L/B$</td>
<td>9.54</td>
<td>9.45</td>
</tr>
<tr>
<td>$B/T$</td>
<td>4.06</td>
<td>2.86</td>
</tr>
<tr>
<td>$C_{WS}$</td>
<td>8.26</td>
<td>7.06</td>
</tr>
<tr>
<td>$C_V$</td>
<td>2.48</td>
<td>3.39</td>
</tr>
</tbody>
</table>
Calculation procedure for full scale resistance prediction

\[ C_T = C_R + C_F + C_A \]

\[ C_F = 0.075/(\log_{10} R_n - 2)^2 \quad \text{(ITTC line)} \]

where \( R_n = \frac{VL}{\nu} \) = ship Reynold's number

\[ C_A = \text{appropriate model-ship correlation allowance} \]

\[ R_T = \frac{\rho V^2 S C_T}{2} \]

EHP

\[ P_E = \frac{R_T V}{550} \quad , \quad R_T \text{ in lbs., } V \text{ in ft./sec.} \]
Vessel A

Full scale resistance prediction from test observation and three different regression techniques

<table>
<thead>
<tr>
<th>$F_n$</th>
<th>MPH</th>
<th>$C_R \times 10^3$</th>
<th>$C_T \times 10^3$</th>
<th>EHP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Observed</td>
<td>45 variables</td>
<td>1L variables</td>
</tr>
<tr>
<td>0.11</td>
<td>13.44</td>
<td>0.911</td>
<td>0.907</td>
<td>0.831</td>
</tr>
<tr>
<td>0.12</td>
<td>14.67</td>
<td>0.987</td>
<td>0.967</td>
<td>0.892</td>
</tr>
<tr>
<td>0.13</td>
<td>15.89</td>
<td>1.051</td>
<td>1.074</td>
<td>0.967</td>
</tr>
<tr>
<td>0.14</td>
<td>17.11</td>
<td>1.219</td>
<td>1.193</td>
<td>1.118</td>
</tr>
<tr>
<td>0.15</td>
<td>18.33</td>
<td>1.462</td>
<td>1.385</td>
<td>1.338</td>
</tr>
<tr>
<td>0.16</td>
<td>19.56</td>
<td>1.785</td>
<td>1.720</td>
<td>1.673</td>
</tr>
<tr>
<td>0.17</td>
<td>20.78</td>
<td>2.189</td>
<td>2.122</td>
<td>2.053</td>
</tr>
<tr>
<td>0.18</td>
<td>22.00</td>
<td>2.674</td>
<td>2.587</td>
<td>2.666</td>
</tr>
</tbody>
</table>
Vessel B

Full scale resistance prediction from test observation and three different regression techniques

<table>
<thead>
<tr>
<th>$F_n$</th>
<th>MPH</th>
<th>CR x 10^3</th>
<th>CF x 10^3</th>
<th>CA x 10^3</th>
<th>CT x 10^3</th>
<th>EHP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11</td>
<td>10.94</td>
<td>0.393</td>
<td>0.418</td>
<td>0.440</td>
<td>0.441</td>
<td>1.558</td>
</tr>
<tr>
<td>0.12</td>
<td>11.94</td>
<td>0.438</td>
<td>0.464</td>
<td>0.475</td>
<td>0.469</td>
<td>1.542</td>
</tr>
<tr>
<td>0.13</td>
<td>12.93</td>
<td>0.504</td>
<td>0.502</td>
<td>0.500</td>
<td>0.508</td>
<td>1.528</td>
</tr>
<tr>
<td>0.14</td>
<td>13.93</td>
<td>0.589</td>
<td>0.566</td>
<td>0.574</td>
<td>0.573</td>
<td>1.512</td>
</tr>
<tr>
<td>0.15</td>
<td>14.92</td>
<td>0.701</td>
<td>0.684</td>
<td>0.685</td>
<td>0.681</td>
<td>1.500</td>
</tr>
<tr>
<td>0.16</td>
<td>15.92</td>
<td>0.887</td>
<td>0.852</td>
<td>0.850</td>
<td>0.847</td>
<td>1.488</td>
</tr>
<tr>
<td>0.17</td>
<td>16.91</td>
<td>1.080</td>
<td>1.065</td>
<td>1.082</td>
<td>1.088</td>
<td>1.477</td>
</tr>
<tr>
<td>0.18</td>
<td>17.91</td>
<td>1.424</td>
<td>1.397</td>
<td>1.419</td>
<td>1.417</td>
<td>1.467</td>
</tr>
</tbody>
</table>
Example:

Use of function charts.

$L/B = 9.5 \quad C_B = 0.86 \quad B/T = 2.75 \quad C_V = 3.5$

$F_n = 0.14$

---

Fig.17 $C_B = 0.86, B/T = 2.75 \quad \rightarrow \quad F_1 = 2.38 \times 10^{-3}$

Fig.18 $B/T = 2.75, C_V = 3.5 \quad \rightarrow \quad F_2 = -1.53 \times 10^{-3}$

Fig.20 $B/T = 2.5$

$L/B = 9.5, C_V = 3.5 \quad \rightarrow \quad F_3 = -0.8 \times 10^{-4}$

$B/T = 2.75, L/B = 9.5, C_V = 3.5 \quad \rightarrow \quad F_3 = -3.0 \times 10^{-4}$

Fig.21 $B/T = 3.0$

$L/B = 9.5, C_V = 3.5 \quad \rightarrow \quad F_3 = -5.2 \times 10^{-4}$

$C_R = F_1 + F_2 + F_3 = 0.55 \times 10^{-3}$

$F_n = 0.16$

---

Fig.24 $C_B = 0.86, B/T = 2.75 \quad \rightarrow \quad F_1 = 3.84 \times 10^{-3}$

Fig.25 $B/T = 2.75, C_V = 3.5 \quad \rightarrow \quad F_2 = -2.68 \times 10^{-3}$

Fig.27 $B/T = 2.5$

$L/B = 9.5, C_V = 3.5 \quad \rightarrow \quad F_3 = -0.9 \times 10^{-4}$

$B/T = 2.75, L/B = 9.5, C_V = 3.5 \quad \rightarrow \quad F_3 = -3.1 \times 10^{-4}$

Fig.28 $L/B = 9.5, C_V = 3.5 \quad \rightarrow \quad F_3 = -5.3 \times 10^{-4}$

$C_R = F_1 + F_2 + F_3 = 0.85 \times 10^{-3}$
Appendix II

Speed-length plot of Froude numbers
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