Ship Routeing for Optimum Performance

J.M.J. Journée* and J.H.C. Meijers**

* Delft University of Technology
** Royal Dutch Shipowners Association

Synopsis

A prediction method of speed and power of a ship in a seaway is described here. In determining the speed, two factors are considered: the natural speed reduction due to added resistance caused by wind, waves, etc. and the voluntary speed reduction by the ship’s captain, in order to prevent severe motions. Part I of this paper shows a tool to be used in Part II. A breakdown of the operational costs into independent cost factors commonly used by shipowners is given in Part II. For each of the cost factors the possible consequences of routeing of ships on the magnitude of the considered cost factor is discussed. The most important cost factor, the cost of fuel and lubricating oil, is found to be more affected by routeing than the other cost factors. One crossing of the Atlantic using four alternative routes is analysed. It appeared that (in the considered unique, hypothetical case) a saving in the operational costs of 7 per cent could be achieved. Some remarks on the effects of increasing fuel prices with respect to routeing and operational costs are also given.

Part I

Prediction of Speed and Power of a Ship in a Seaway

J.M.J. Journée

1 Introduction

For the past twenty years, ship’s officers have been able to make use of routeing advises from weather routeing departments, connected with meteorological institutes. With a known or expected rough weather pattern on the ocean, an optimum
ship’s route, with respect to a minimum travelling time, fuel consumption or risk of damage, can be found. The forecast of wind and waves is a meteorological problem. The prediction of the ship’s reaction to wind and waves, in particular the ship’s speed, is usually based on routeing experience with the ship under consideration, or with similar ships. For an accurate routeing of ships the routeing officer needs reliable speed loss information for every sea condition. Developments in the last decade make it possible to calculate the speed in a seaway. In 1974 the Shipbuilding Institute of Hamburg University published a program system with respect to this subject [1]. The Delft University of Technology has also published a prediction method for speed, power and motions in a seaway [2]. These computer programs can help to avoid dangerous situations, minimise travelling time and reduce fuel consumption.

The speed of a ship in a seaway depends on the ship’s resistance, the action of propeller and engine, and the behaviour of the ship in waves, and is discussed below.

2 Resistance

The total resistance of a ship in a seaway can be split up into several parts and contributions, the most important of which follow below.

Still Water Resistance

Until now it has not been possible to make theoretical calculations of the ship’s resistance in still water. For the estimation of the required power in a design state, use must be made of model experiments carried out in a towing tank. These experimental results are extrapolated to full scale by techniques based on physical laws and experience. The accuracy of the achieved results is generally acceptable. During the ship’s trial, measuring the ship’s speed and power can check this prediction. Numerous empirical methods can be found to estimate the still water resistance. They are all based on model experiments and trial data. Best known are: the method published by Taylor in 1943 [3] and reanalysed by Gertler in 1954 [4], the method by Lap published in 1954 [5] and extended for full ship forms by Auf ‘m Keller in 1973 [11] and Guldhammer and Haryald’s method published in 1974 [7]. Holtrop’s method published in 1977 [11] has the advantage that the results are presented in empirical formulae suitable for computer use. For high speed cargo-liners the Shipbuilding Research Association of Japan published in 1964 [9] a method with polynomials for three different loading conditions, obtained from model experiments with systematically varied ship forms. Usually the resistance can only be obtained for fully loaded ships with a breadth-draught ratio of about 2.5. If no other information is available a rough estimation can be made for other loading conditions with, for instance, the assumption that the still water resistance is proportional to the third order root of the volume of displacement squared. It may be noted here that for high breadth-draught ratios, as found with gas tankers and ships in ballast condition, these methods can give less accurate results. Also the effects of trim and bulbous bows at several draughts cannot be accurately taken into account.

Wind Resistance

For ships with high superstructures or with a lot of cargo on deck, such as, containerships, the wind resistance can be considerable. A reliable method for estimating the wind resistance was published by Isherwood in 1973 [10]. He has analysed the results of wind resistance experiments carried out at different laboratories with models covering a wide range of merchant ships. He gives empirical formulae for the determination
of the two horizontal components of the wind force and the wind-induced yawing moment on any merchant ship form for a wind from any direction.

For calculations in a seaway, the following relation between the absolute wind speed and the significant wave height based on ITTC recommendations can be used:

\[ V_w = 10 \cdot H_{1/3}^{2/3} \]

with \( V_w \) in knots and \( H_{1/3} \) in metres.

**Added Resistance due to Vertical Ship Motions**

The relative motions of a ship with respect to the water surface cause an added resistance. In 1970, Boese published, a theory to calculate the added resistance from the water pressures on the hull caused by the relative motions in regular waves [11]. He showed a close agreement between theory and experiments in regular waves from all directions. In 1972 Gerritsma and Beukelman published another theory based on the relation between the radiated energy of the damping waves and the added resistance [12]. A close agreement is shown between theory and experiments in head to beam regular waves. In quartering and following waves, however, the agreement is rather poor, probably as a result of inaccurate values for added mass and damping at low frequencies. These calculations are based on the assumption of the linearity of the ship’s response. The added resistance varies with the wave amplitude squared. The calculation in irregular waves is based on the superposition principle for the components of the wave, motion and resistance spectra. This leads to the following formula for the calculation of the mean added resistance in a given wave spectrum:

\[ \overline{R}_{aw} = 2 \int_{0}^{\infty} R_{aw} \cdot S_{\zeta} \cdot \omega \cdot d\omega \]

in which:

- \( \zeta \) = regular wave amplitude,
- \( S_{\zeta} (\omega) \) = wave spectral value and
- \( \omega \) = circular wave frequency.

**Added Resistance due to Steering**

In a seaway wind and waves will disturb the ship’s heading. To maintain a heading at a beam wind, rudder angles are necessary to counteract the wind moment at any instant. For instance, a beam wind with a strength of 9 on the Beaufort scale can cause rudder angles of 15° or more. This results in an increase in the ship’s resistance.

In waves, the ship will sail with yaw motions caused by the sea and the correcting autopilot. These yaw motions cause centrifugal forces, of which the components in the longitudinal direction mean an added resistance; see Figure 1.

![Figure 1](image)

Assuming a fixed position of the pivot point at 10 per cent from the forward perpendicular and an added mass of 80 per cent of the ship’s mass, the mean added resistance during a harmonic yaw motion will be in the order of:

\[ \overline{R}_{ST} = 0.0312 \cdot V \cdot L \cdot \psi_a^2 \] kN

with:
- \( V \) = volume of displacement in m³,
- \( L \) = length of the ship in m and
- \( \psi_a \) = rate of turn amplitude in deg/min.
This means for a 200 meter container vessel, with rate of turn amplitudes of 30°/min at the service speed in following waves, a resistance increase of 20 per cent of the still water value. The course deviations in this example are less than 2°. This shows that the setting of the autopilot is important.

Sway motions mean an increased covered distance with - as a result - a reduced average speed along a given track.

**Added Resistance due to Fouling**

Fouling of the ship’s hull can cause a considerable increase in the ship’s resistance. The extent of fouling depends on the sailing routes and the time during which the ship will sail in areas with large fouling effects. As fouling is a biological process - depending on the paint used - it is not easy to give accurate mean values for all ships, seasons and areas. Moreover, the effect of fouling depends on the docking period and the time since the last docking of the ship.

Fouling will only affect the friction part of the ship’s resistance, $R_F$. Aertssen [13] carried out full-scale experiments to investigate the problem of fouling. From his results it appears that, for a ship sailing on the Atlantic route, the effect of fouling will be in the order of:

$$\frac{\Delta R_F}{R_F} \cdot 100\% = 3.6 \cdot y_a + \frac{40 \cdot y_d}{1 + 2 \cdot y_d},$$

in which:

- $y_a$ is the age of the ship in years and
- $y_d$ is the years since the last docking.

This means, for instance, an increase of the frictional resistance by about 30 per cent for a ship with an age of five years and a time since last docking of year. However, the overall effect on the total resistance is smaller and depends on speed and ship type. With low speeds and full ship forms, e.g. tankers, the frictional resistance is the major part of the total resistance, whereas in the case of high-speed container ships the wave-making resistance is in excess of the frictional part. This means that the effect of fouling is much larger for tankers than for container ships.

An investigation made by the author from log data of a 200,000 tdw tanker, sailing from Europe to the Persian Gulf, showed an increase of the still water resistance. For full load and ballast condition, this increase was as 26 to 29 per cent one year after the last docking, and 47 to 52 per cent two years after the last docking. After the oil crisis these ships reduced power by 50 per cent, resulting in a speed reduction for the clean hull of 16 to 13 knots. To maintain this speed two years after the last docking the power of a fully loaded ship had to be increased from 50 to over 80 per cent; see Figure 2.

![Figure 2: Power Increase due to Fouling](image-url)

So, fouling is a factor in speed calculations, which should not be neglected.
3 Propulsion

The propeller behind a ship can be considered as an energy-transformer: torque with engine speed will be transformed into thrust with a speed of advance of the propeller, relative to the mean velocity of the incoming water. At a constant engine setting there should be equilibrium between the engine speed and the ship’s speed in a way that two conditions are fulfilled. The torque required by the propeller must be in equilibrium with the torque delivered by the engine and the thrust delivered by the propeller must be in equilibrium with the total resistance of the ship in the self-propelled condition.

Propeller

The thrust constant $K_T$, the torque constant $K_Q$ and the speed ratio $J$ gives the characteristics of a propeller in its normal operating range:

$$K_T = \frac{T}{\rho D^2 n^2}, \quad K_Q = \frac{Q}{\rho D^2 n^2}, \quad J = \frac{V_a}{nD}$$

In these definitions:

- $T$ thrust,
- $Q$ torque,
- $\rho$ density of water,
- $D$ diameter,
- $n$ rev/sec an
- $V_a$ speed of advance.

These characteristics depend on the number of propeller blades, the pitch ratio, and the expanded blade area ratio, and can be obtained by means of open-water model experiments. Results of such experiments with systematically varied propeller series can be found in various publications. One of the best known is the Wageningen B-Series propellers of the NSMB [14]. Over 120 systematically varied propeller models have been tested and the results are given in polynomials, together with a correction for scale effect. These results are valid for the open water condition. For the “behind the ship condition” the torque must be divided by the relative rotative efficiency, which varies from about 1.04 for single-screw ships to about 0.97 for twin-screw ships.

The speed of the water into the propeller disc $V_a$ is not equal to the ship’s speed $V$:

$$V_a = V \cdot (1 - w)$$

The wake fraction $w$ varies from 0.2 to 0.4. It can be obtained directly from model experiments, taking into account the scale effect, or from empirical formulae given in literature. From model experiments it appears that the wake fraction is hardly affected by an increase of the propeller loading, caused by some resistance increase.

The thrust of the propeller $T$ is not equal to the ship’s resistance $R$, if defined by the common resistance test:

$$R = T \cdot (1 - t)$$

The thrust deduction fraction $t$ in still water is usually 60 to 80 per cent of the wake fraction and can also be obtained from model experiments or empirical formulae. This fraction, however, will decrease with increased loading of the propeller. In the bollard condition for instance this fraction will be about 0.03 to 0.05. From model experiments it appears that, for practical purposes, it can be assumed that the thrust deduction fraction decreases linearly with the speed to zero at a constant number of revolutions of the propeller and an increasing loading.

The influence of oscillations of the propeller behind a ship in waves on the efficiency can be neglected for practical purposes.

Engine

The relation between the delivered torque of an engine and the engine speed at a constant setting and an increased loading in a seaway is also important. In this connection two different types of engines
are distinguished: a turbine and a diesel engine.

For a turbine it is often accepted that - at an increasing loading and a constant setting of the engine - the delivered power remains constant. This means a hyperbolic relation between the torque at the propeller and the engine speed:

\[ Q = c \cdot \eta_m \cdot Q_0 \cdot \frac{n_0}{n} \]

in which:
- \( c \) engine setting,
- \( \eta_m \) mechanical efficiency of the shaft bearings and
- \( 2\pi Q_0 n_0 \) maximum continuous rating power with \( n \) in rev/sec.

According to several authors, there is a linear relation in practice between torque and engine speed:

\[ Q = c \cdot \eta_m \cdot \left\{ a \cdot \left( a - 1 \right) \cdot \frac{n_0}{n} \right\} \]

in which the coefficient \( a \) depends on the type of the turbine \( 2 \leq a \leq 3 \).

If one takes into account that at a constant setting the engine speed will not reduce by more than 15 per cent, the assumption of constant power is sufficiently accurate for practical purposes such as the calculation of the ship’s speed.

For a diesel engine it is mostly accepted that the torque remains constant at an increasing loading of the engine at a constant setting:

\[ Q = c \cdot \eta_m \cdot Q_0 \]

This means that the coefficient \( a \), mentioned above, is 1.0.

In practice, there are some deviations from this assumption. At a constant engine setting and an increasing loading of the engine the torque will increase first then obtain a maximum value and, afterwards, will decrease again. A linear relation between torque and engine speed can approximate this, provided that the number of rev/min will not reduce by more than 15 per cent. Then the linear relation mentioned before can be used, with for instance \( a = 1.0 \) to 1.5. Often the engine speed will be kept constant. This means that the value \( a \) goes to infinity. It may be noted that the engine setting \( c \) no longer has a meaning in the formula; \( n \) will be equal to \( n_0 \).

4 Vertical Motions

A statistical description of ship motions in irregular waves can be given when the principle of linear superposition is valid for both waves and ship motions. The sea surface is assumed to be the result of the superposition of many simple harmonic waves, each with its own amplitude, frequency and direction of wave travel. Over a large range of waves, the ship is regarded as a linear system with respect to its motions in regular waves: when the wave height is doubled at the same ship speed, course and wave length, the resultant motion amplitude will also be doubled.

The phase of the motion relative to the wave does not change. Model experiments have shown that a sufficient linearity exists between the wave amplitudes and the resultant motion amplitudes, at least for practical purposes. The frequency response functions of a ship in regular waves, non-dimensionalised by the wave amplitude, are the base for the calculation of ship motions in irregular waves.

A ship is a three-dimensional object. An important simplification of the difficult three-dimensional hydrodynamic problems for the oscillating ship in regular waves has been obtained by using an integration of the two-dimensional solutions of the cross sections over the length of the ship. This simplification is known as the strip theory method. Another simplification is the Froude-Krilov hypothesis that the pressure in the waves, which acts on the ship’s hull surface, is not influenced by the presence of the ship. However, corrections will be made.
For the calculation of the two-dimensional added mass and damping of the cross-sections, a two-coefficient formula for the conformal transformation of the cross sections to the unit circle can be used: the so-called Lewis transformation. By using another $N$-parameter transformation instead of the Lewis transformation, added mass and damping will be calculated more precisely. The vertical motions, however, will hardly be influenced by this higher accuracy. This strip theory method includes speed effect in the damping cross-coupling terms in the equations for heave and pitch and the speed-depending acceleration coefficient [15].

In a complex notation, the heave motion in regular waves can be written as:

$$z = \zeta_a \cdot |H_{z \zeta} (\omega_e)| \cdot e^{i(\omega_e \tau + \epsilon_{z \zeta})}$$

where:

$$|H_{z \zeta} (\omega_e)| = \frac{\zeta_a}{\zeta_a}$$

is the response function of the heave motion with:

- $\zeta_a$: regular wave amplitude,
- $z_a$: heave response amplitude
- $\epsilon_{z \zeta}$: phase lag and
- $\omega_e$: frequency of encounter.

The superposition principle enables the calculation of the variance of the heave motion in a known wave spectrum:

$$m_{0z} = \int_0^\infty S_{z \zeta} (\omega) \cdot d\omega$$

where:

$$S_{z \zeta} = |H_{z \zeta} (\omega)|^2 \cdot S_{\zeta} (\omega)$$

is the heave spectrum.

For most practical applications it may be assumed that motion velocity and acceleration amplitudes follow the Rayleigh distribution law. In this example the probability that the heave amplitude exceeds a certain limit $p$ is given by:

$$\Pr \{z_a > p \} = e^{\frac{-p^2}{2m_{0z}}}$$

The significant heave amplitude is given by:

$$z_{a1/3} = 2 \cdot \sqrt{m_{0z}}$$

5 Description of the Sea Surface

For the description of the sea surface often a modified Pierson-Moskowitz wave spectrum is used as an approximation of the frequency distribution of the energy:

$$S_{\zeta} (\omega) = \frac{\alpha}{\omega^5} \cdot e^{-\frac{\omega_T}{\omega}}$$

and

$$\alpha = \frac{124}{T_2^4}$$

with the spectral moments:

$$m_n = \int_0^\infty S_{\zeta} (\omega) \cdot \omega^n \cdot d\omega$$

where:

- $\omega$: circular wave frequency,
- $H_{1/3}$: significant wave height and
- $T_2$ = $2\pi \sqrt{m_0 / m_2}$ average zero-crossing wave period.

So, the spectral values vary with the squared significant wave height.

![Figure 3](image-url)

**Figure 3** Measured and Ideal Wave Spectrum

In reality the spectral form differs from this formula and gives only a mean distribution. Figure 3 shows a comparison...
between a measured wave spectrum and the corresponding Pierson-Moskowitz wave spectrum during a storm in the Atlantic Ocean on 4 February 1979.

Another important factor is the distribution of the wave energy over all directions. Often a cosine-squared spreading will be used:

\[ S_{\xi} (\omega, \mu) = \frac{2}{\pi} \cdot \cos^2 \left( \mu - \bar{\mu} \right) \cdot S_{\xi} (\omega) \]

with:

\[ -\frac{\pi}{2} \leq \mu - \bar{\mu} \leq +\frac{\pi}{2} \]

where \( \bar{\mu} \) is the dominant wave direction. It has been assumed here that for each direction the shape of the energy distribution over the frequency range is the same. In reality this distribution depends on the instantaneous local weather situation (sea) and the weather in the whole ocean in the recent past (swell). So deviations of these distributions will certainly appear as for instance when sea and swell come in from different directions.

6 Calculation of Speed

A computer program - named ROUTE - to calculate the ship’s speed in a seaway at a given engine-setting is available at the Delft University of Technology. The program includes all elements mentioned before, except the yaw motions. Comparisons with published full-scale data have shown a reasonable agreement between theory and experiments. For a number of ship speeds, the relation between the torque required by the propeller and the rev/min are calculated from the torque characteristics of the assumed B-series propeller behind the ship and a wake fraction. The relation between the torque delivered by the engine to the propeller and the rev/min is known from engine-characteristics and shaft losses. These relations give a relation of equilibrium for speed and rev/min which, together with the thrust deduction faction, results in a resistance that can be overcome by propeller and engine, as a function of the speed. The actual total resistance of the ship in a seaway as a function of the speed is known by calculations carried out with the program, and the required equilibrium yields the ship’s speed (see Figure 4).

![Figure 4 Scheme of Speed Calculation](image)

If a high accuracy of the calculated speed is required, speed rev/min and power data, for instance derived at the ship’s trial, can be used to adapt the resistance curve and the propeller characteristics. In Figure 5 a result of calculations in head waves is given for a 200,000 tdw tanker. This figure shows a striking influence of the wave period on the ship’s speed. In addition to the speed, the program ROUTE also calculates the vertical motions and the probabilities of shipping green water, slamming, propeller-racing and of the exceeding of certain limits by the relative motions and accelerations.
Voluntary Speed Reduction

When a ship enters a severe storm the ship's captain can reduce speed to reduce severe vertical motions. Figure 6 shows a considerable influence of the ship's speed on the vertical accelerators forward, of a container vessel. Phenomena that are important for the decision to reduce speed are: the shipping of green water, slamming, heavy vertical accelerations forward and racing of the propeller. The shipping of green water is defined here as an exceeding of the elective freeboard \( f \), by the relative motion of the bow. The probability of occurrence is expressed by:

\[
\Pr\{\text{shipping}\} = e^{-f^2 / 2m_{o_v}}
\]

in which \( m_{o_v} \) is the variance of the relative motion.

Slamming occurs in rough seas when the forefoot of the ship emerges from the water as a result of large heave and pitch motions and then violently impacts the water-surface as it re-enters. The ship's forward bottom thereby sustains a heavy impulsive pressure from the water and this impulsive force produces a shudder throughout the hull.

According to Ochi [16] the probability of occurrence of slamming is the joint probability that the bow at 10 per cent of the ship length from forward emerges and that the relative velocity here exceeds a threshold value at the moment of re-entry. As a good threshold value can be taken \( 0.093 \cdot \sqrt{g \cdot L} \).

The probability of occurrence of slamming is expressed by:

\[
\Pr\{\text{slamming}\} = e^{-\left(\frac{T^2}{2m_{o_v}} + 0.093 \cdot \sqrt{\frac{g \cdot L}{2m_{o_v}}}\right)}
\]

in which:
- \( T \) draught,
- \( L \) ship length and
- \( m_{o_v}, m_{o_v} \) variance of the relative vertical motion and velocity at 10% of \( L \) from forward.

Accelerations forward, exceeding certain limits, can damage ship or cargo and can also be a reason to reduce speed.

Propeller racing is largely prevented nowadays by rev/min governors; however, large thrust and torque fluctuations occur in waves, even at a constant rev/min.
Aertssen [17] defined racing as an emergence of the propeller which causes a decrease of torque in excess of 25 per cent. Fukuda [18] defined racing of the propeller as an emergence of the propeller by one-third of the diameter.

In various publications, criteria for reducing speed can be found; commonly expressed in probability limits for the occurrence of the shipping of green water and slamming, between 3 and 7 per cent. Ochi and Motter [19], for the estimation of a limit, below which no voluntary speed reduction is expected, distinguish between two ships’ loading conditions:

1) Full load condition

In this condition voluntary speed reduction is depending on deck wetness and accelerations at the bow:

$$\Pr \left[ \begin{array}{c} \text{deck} \\ \text{wetness} \\ \text{at} \\ \text{Station} \ 20 \\ \end{array} \right] \text{and/or} \left[ \begin{array}{c} \text{sign. ampl.} \\ \text{of bow} \\ \text{acc. will} \\ \text{exceed} \\ \text{0.4} \cdot g \\ \end{array} \right] \leq 0.07$$

2) Light load condition

Slamming at station 17 and bow acceleration are in this condition reasons for voluntary speed reduction.

$$\Pr \left[ \begin{array}{c} \text{slam} \\ \text{impact} \\ \text{at} \\ \text{Station} \ 17 \\ \end{array} \right] \text{and/or} \left[ \begin{array}{c} \text{sign. ampl.} \\ \text{of bow} \\ \text{acc. will} \\ \text{exceed} \\ \text{0.4} \cdot g \\ \end{array} \right] \leq 0.03$$

The program ROUTE also includes these somewhat moderate criteria. In fact these criteria also depend on the ship’s type and on the cargo.

8 Concluding Remarks

In designing a ship much attention will be paid to the still water resistance with respect to hull form, expensive bulbous bows and design of the propeller. At the North Atlantic, however, a sea-state of Beaufort 6 is exceeded 70 per cent of the time during the winter season and 45 per cent during the summer season [20]. Depending on the ship’s size, the added resistance caused by vertical ship motions can be considerable. In a sea-state of Beaufort 6 a ship with a length of 136 m and a speed of 16 knots in still water will have an added resistance equal to the still water resistance at the speed which is reduced to 12 knots [2]. So, it is worthwhile to pay attention to the added resistance caused by vertical ship motions in a seaway.

As has already been mentioned in the introduction, speed and power calculations of a ship in a seaway can be used to support the work of a routeing officer. Together with his meteorological information, accurate speed-loss graphs will help him to give well-founded routeing advice to the ship’s captain. This is not only of importance for the economy of the ship’s operation but also for its safety. Ship motions can be calculated with a fair accuracy but the insight in the limits with respect to the voluntary speed reduction lags behind. The calculations give moderate limits, if derived from the available literature. These limits can be adjusted aboard to those permitted by the ship’s captain.

This kind of calculation can also be used in developing operational performance systems on board ships. The calculated speed, power, and motion data can be used in these systems with respect to decisions for course deviations or speed reductions. Calculated fuel consumption data can be added easily.

Another application of these calculations can be found in economical studies of the operation of ships with respect to travelling time, fuel consumption, etc.

9 References


Part II

Some Economical Aspects of the Routeing of Ships

J.H.C. Meijers

1 Introduction

The aim of this part of the paper is to analyse the effects of routeing on the economy of a ship. Only the operational costs are dealt with. In some cases the building costs are affected by routeing, but this is not discussed here.

The master of a ship has two alternatives when confronted with a wave field (depression) during a voyage. When the ship is routed he has more information at his disposal to make a clearheaded decision. Either he decides to sail through the centre of the depression, or he chooses another route in order to bypass it. Whatever the decision may be, there will be certain effects on the operational costs.

Throughout the paper, the term ‘routeing’ is used wherever the “decisions made on the basis of the information obtained from the routeing office” is meant.

In section 2, “operational costs” are defined; a breakdown in independent cost factors is given and a qualitative discussion on the effects of routeing on these cost factors is performed.

In section 3, the changes in the operational costs due to routeing are calculated.

As it was very difficult to obtain exact cost data the results are presented in percentage increase or decrease, relative to a given quantitative breakdown of the operational costs.

Finally in section 4, some other aspects of ships’ economy, which can be affected by routeing, are discussed.

2 Breakdown of Operational Costs

The operational costs are defined as follows: “Operational costs are all costs involved in the operation of one or more ships (a fleet) not including the capital costs” [1].

A breakdown of the thus defined operational costs in independent cost factors that will be considered in this paper is listed in Table I; see reference [2].

In Figure 7 a typical example of the distribution of the operational costs over the various cost factors is shown; see references [2, 3].

Table I Breakdown of Operational Costs

<table>
<thead>
<tr>
<th>OPERATIONAL COSTS</th>
<th>Shipowners' costs</th>
<th>Sailing costs</th>
<th>Cargo costs</th>
<th>Capital costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personnel costs</td>
<td>Fuel and lubricating oil costs</td>
<td>Cargo stevedoring commissions</td>
<td>– Interest</td>
<td>– Depreciations</td>
</tr>
<tr>
<td>Stores costs</td>
<td>Port costs</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Maintenance and repair costs</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Insurance costs</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Overheads</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Figure 7 Operational Costs
In the forthcoming paragraphs the individual cost factors are defined. A short qualitative analysis of the effects of routeing on the considered cost factors is given. According to the definition, the capital costs are not incorporated in the operational costs. They may, however, be affected to some extent by routeing (see paragraph 2.4).

2.1 Shipowners' Costs

2.1.1 Personnel Costs
The personnel costs over a given period are composed of:

i) wages, including social security, etc., and

ii) costs involved in relief of the crew (travelling costs).

The number of personnel on board and the costs per member of the crew determine these costs over the considered period. From the breakdown of this cost factor and the parameters by which it is determined, it can be seen that this is not influenced by routeing. Personnel are needed on board (and receive payment for that), either for the operation and maintenance of the ship at sea or for the loading/discharging activities in ports.

2.1.2 Store costs
This cost factor is strongly related to the previous one. The amount of stores on board depends on the number of personnel and the length of time the personnel are on board.

For the effects of routeing on this cost factor the same reasoning applies as for the personnel costs; routeing does not influence this cost factor.

2.1.3 Maintenance and repair costs
Maintenance and repair costs can be divided into those, which are performed by the crew, and those performed by other organisations, e.g. docking and tank cleaning.

These costs depend on three parameters:

i) technical standard of the equipment;

ii) age of the equipment;

iii) quality of conservation.

It is rather difficult to establish the influence of routeing on the maintenance and repair costs.

Taking the conservation of the hull, for example, it can be expected that the hull paint will suffer less when the ship is sailing in light or moderate seas, whereas severe weather conditions can cause damage to the paint and introduce the need for repainting earlier than in the first case. For most, ships the reasoning applies that, in rough weather, greater amplitudes of the ship motions occur than in light or moderate weather conditions. With these increasing ship motions the chance of damage occurring also increases. As mentioned earlier, the relation between damage to hull construction, and hull painting and the weather conditions, is very hard to obtain; but the analysis of casualty data can provide some information. Even then it is still not known whether the damage has been repaired and, therefore, whether or not there will be an increase in this cost factor.

Recognising the effects of routeing on the maintenance and repair costs, these effects are not considered further because of the difficulty in obtaining useful information on the particular subject.

2.1.4 Insurance costs
Insurance costs are determined on the basis of the new building price of the ship as paid by the ship owner. For the purpose of this paper, considering the influence of routeing on the building costs of minor importance, the insurance costs are not influenced by routeing.

2.1.5 Overhead costs
The organisation and administration necessary to sail a ship, or a fleet of ships, are the main contributions to this cost factor. The additional work involved providing a ship with information on the
weather on its sailing route is of minor importance. Therefore, the effects of routeing on the overhead costs are negligible.

2.2 Sailing costs

2.2.1 Fuel- and lubricating-oil costs
Their respective prices and their consumption during that period determine the costs of fuel and lubricating oil over a given period. Distinction must be made between consumption at sea and in port, and for fuel consumption the difference between heavy and gas oil must be considered.

In the following only the fuel consumption is considered, since the same reasoning holds for the lubricating oil.

A ship is considered with a main engine running on heavy oil and auxiliary engines running on gas oil.

2.2.1.1 Fuel consumption at sea
One of the parameters on which the consumption of fuel and lubricating oil at sea is dependent is the type of weather encountered by the ship during the voyage in a given period.

In rough weather the resistance of a ship increases due to the effects of wind and waves. With the main engine set at constant rev/min sailing through a wave field implies a speed reduction and an increase of the engine output. Thus the time necessary to sail a distinct route increases together with the fuel consumption over that route.

An increase in output of the main engine also implies higher fuel consumption over the considered route. Gas oil consumption is only dependent on the length of the voyage. Additionally, whether the ship is at sea or in port, there is a need for auxiliary power either for domestic and navigational purposes or for domestic and loading/discharging purposes.

2.2.1.2 Fuel consumption in port

When the ship is in port no heavy oil is consumed. For the gas oil consumption see subparagraph 2.2.1.

2.2.2 Port costs
Pilotage and towing costs are the two main components of the total port costs. There are also daily costs of surveillance and of water and electricity obtained from ashore. It is quite obvious that routeing has no effect on this cost factor.

2.3 Cargo costs

2.3.1 Loading/discharging costs
This is mainly composed of stevedoring costs and commissions. Like the port costs, this cost factor is not affected by routeing either.

2.4 Capital costs

These are the sum of:
i) interest and payment of loans;
ii) interest and depreciation of own capital.

In the short term, routeing does not affect capital costs. However, considering the economical life of a ship as a whole a certain influence must be recognised.

A ship suffering only a little damage during its economic life (which can be the case if a ship is routed) will probably have a higher selling value than one, which has suffered more damage.

As the effects on this cost factor are hard to assess because of lack of information, they are not considered in this paper.

2.5 Summary

In the previous paragraphs a survey has been given of the cost factors involved in ship operations. The effect of routeing on those cost factors was analysed in a qualitative way. From this analysis it appears that only the costs of fuel- and
lubricating-oil at sea, and the costs of maintenance and repair, are influenced by routeing. All other factors are not affected, or the effects are so small that they can be ignored. Due to the lack of information about the effects of routeing on the maintenance and repair costs, the effects on this factor are not taken into account. Therefore, only the influence on the fuel and lubricating costs remains to be analysed.

3 Quantitative Analysis

3.1 Introduction

For the calculation of the increase or decrease of the fuel consumption a situation is considered based on the information of an actual crossing of the Atlantic. It must be emphasised that the performed calculation concerns a hypothetical case only meant to illustrate the reasoning given in the above section.

A ship sails the four alternative routes between two ports A and B shown in Figure 8, namely:

i) the quickest route;
ii) the great circle route;
iii) the rhumb line route;
iv) the route actually sailed.

During the crossing the ship would encounter three wave fields, also indicated in Figure 8. The characteristic wave heights of the wave, fields and the directions of sea and swell (in this case taken equal) are also shown.

Using the computer program ROUTE [5] mentioned in Part I the ship speed and the output of the main engine are calculated at a number of discrete points along each of the four routes. With an assumed specific fuel consumption of 200 g/kwh, the total fuel consumption during the crossing and the sailing time are calculated and the results are presented in Table 11. The given values are percentages relative to the values obtained for the great circle route.
A parameter also important for the behaviour of a ship in waves is the wave period. For the wave fields shown in Figure 8 only the wave heights are known. A fixed relation between wave period and, wave height is assumed, - based on a 12-hour developed sea [4]. The ship is considered to be sailing with a constant number of revolutions of the propeller.

Table II Calculated Fuel Consumption

The consumption of lubricating oil is normally taken to be equal to 10 per cent of the fuel consumption. This value is also used in the calculations discussed above.

3.2 Discussion of the Results

With the quantitative breakdown of the operational costs as shown in Figure 7 and the results of the calculations listed in Table II, the relative increase or decrease of the operational costs can be calculated. To achieve this, all factors other than the fuel and lubricating oil costs are considered to be constant.

The given values of the total operational costs for the three alternatives are also relative to the values obtained for the great circle route (see Table III).

From this Table it would appear that the reasoning of sub-paragraph 2.2.1.1 on the effects of routeing on the fuel costs would hold good.

As stated, the results are valid for one crossing only. Considering a fleet of vessels over a certain period, the effects of routeing on the total operational costs will probably not be very impressive. However, no data are available at the moment to support this statement.

4 Increase of Fuel Price

The increase of fuel price influences the operational costs and the percentages calculated in paragraph 3.2 will change when higher fuel prices are considered. To show this the results of Table III are recalculated using a 20 per cent higher price. Again all other cost factors are considered to be constant. The results of this calculation are shown in Table IV.

Table III Calculated Total Operational Costs (%) with 20% Increase in Fuel Price

Another consequence of the increasing fuel prices is the voluntary speed reduction. Because of the reduction of speed for almost every ship, the amplitude of the ship motions will decrease and with it the risk of severe damage. This implies that a ship can sail through the centre of a depression or wave-field, whereas if the ship sailed at normal speed the depression or wave field would need to be by-passed. Taking the example of section 3, it could well be that the great circle route, sailed with reduced speed, would be the most economical from the point of view of sailing time and fuel consumption.
5 Conclusions

The effect of routeing on the operational costs is to be found mainly in the fuel and lubricating oil costs. Maintenance and repair costs are also affected, but it is very difficult to find exact data on this subject. No other cost factors are influenced by routeing.

A possible saving of 12 per cent fuel is calculated. Considering the total operational costs this implies a maximum possible saving of 7 per cent.

A more complex analysis is necessary to obtain more realistic results. In this the success factor of routeing has to be taken into account. Not one vessel, but a fleet of vessels during a longer period needs to be considered.

The economical aspects of routeing become more and more important, due to the increasing fuel prices. Therefore, further investigations on this subject are recommended, in particular as to the effects of routeing on the maintenance and repair costs.

6 Acknowledgements

The author is indebted to his co-author for advice given in the preparation of this paper.

7 References


MR K. LINDEMANN (Det Norske Veritas) said that the problem area raised in the paper was of growing concern to ship operators. The surging cost of fuel oil had concentrated more efforts on improved fuel economy. In Part I, Journée had presented a method that might lead to substantial savings in operational expenses if properly applied. He had found the outlined principles most relevant and believed that the author had discovered a rational basis upon which to evaluate speed and power in the light of improved economy.

However, Mr. Lindemann had found the technology used to implement the principles on ships to be somewhat uncertain as it did not provide the necessary exactness. An important input to the analysis was, for instance, the directional wave spectrum that needed to be quite well known. Present technology did not allow for such estimates on board ships.

He believed that the principles used to estimate the different resistance components were also uncertain, and estimates of a maximum of 20 per cent accuracy were the best that could be achieved. When that was viewed in relation to the possible savings of 10 to 15 per cent presented in Part II of the paper, he believed that the principles outlined were currently of less practical value. But when technology improved, it was comforting to know that a method did exist to evaluate the speed/power relationship. He would limit his discussion to the problems associated with added resistance due to waves. The method employed by the author was that of Gerritsma and Beukelman, a method that seemed to be the most rational currently available to estimate added resistance. However, as pointed out by Faltinsen and Loken [1] "the rational basis for the formula (Gerritsma and Beukelman’s) was somewhat vague as it was based on a relative motion hypothesis".

The inaccuracy of the method was clearly demonstrated in Figure D3 where experimental values, as obtained by Strom-Tejsen et al. [2] were compared to the Gerritsma-Beukelman results (computed by Strom-Tejsen et al.).

![Figure D3](image)

Figure D3  Added resistance for a Series 60 Ship, $Fn = 0.207$ and $C_B = 0.70$

Large discrepancies were observed. However, it should be mentioned that the method depended on the exactness of the computed added mass and damping coefficients that might account somewhat for the poor resemblance. Better results had been obtained elsewhere, but the
Figure demonstrated the uncertainties associated with the method. For interest, he had included in the Figure the results of a new theory for computing added resistance developed jointly at DnV and the Norwegian Institute of Technology [3]. The method, which was a further development of Boese’s formula, seemed quite promising except, maybe, for the high frequency.


DR. A.C. FAIRLIE-CLARKE (Brown Bros. & Co. Ltd.) commented that Tables III and IV had shown the savings in fuel cost achieved by using the least time route. Use of that route would also result in a saving in time. Could the authors please comment on the significance of that time saving in terms of increased ship utilization and show whether that could be quantified in cost terms?

Authors’ Replies

MR. JOURNEE agreed with Mr. Lindemann that speed and power predictions required reliable information about the momentous energy spectrum of the sea. Section 5 had indicated that in the calculations the sea was approximated by a modified Pierson-Moskewitz spectrum, uni-directional or with a cosine-squared spreading. Visual estimations of an energy distribution over frequencies and directions were not possible. Other estimation techniques were not yet operational. The assumed spectral form could differ considerably from the actual spectrum. In that case mistakes would certainly appear in the predictions. The calculation method described would only give good results when the environmental conditions were known. That meant that reliable information about the sea and wind conditions had to be available. If the mentioned deviations up to 20 per cent appeared, the cause had not been the prediction method but mainly a bad estimation of the unknown environmental conditions.

Mr Lindemann had stated that the inexactness of the Gerritsma-Beukelman method for the calculation of the added resistance was clearly demonstrated in Figure D4, derived from a paper by Strom-Tejsen.

Figure D4 Added resistance for a Series 60 Ship, $Fn = 0.207$ and $C_B = 0.70$

That figure compared the Gerritsma-Beukelman theory and experiments for a
Series 60 ship with $C_B = 0.70$ and $Fn = 0.207$. It might be noted that those calculations and experiments had not been carried out at the Delft Shiphydromechanics Laboratory. The Delft calculations with the Gerritsma-Beukelman method had given much lower peak values. Figure D4 also showed the results of a new theory, based on Boese’s formula. That theory, not yet published, had a very good correlation with the experiments in that particular case, except in the high frequency part. According to their experience the original Boese formula resulted in peak values that were too high.

Mr Lindemann had suggested that the disagreement between the two calculations with the Gerritsma-Beukelman method could be caused by a difference between the calculated values of added mass and damping. Figure D5 showed a comparison between the calculated and experimental values of the coefficients of the heave and pitch equations of that ship at $Fn = 0.20$, carried out at Delft [1].

The Figure showed a fair agreement. Figure D6 also showed a fair agreement between the measured and calculated added resistance.

Figure D6  Added Resistance of a Series 60 ship, $Fn = 0.207$ and $C_B = 0.70$

It would seem from Mr. Lindemann’s reference [2] that the measured peak values of the added resistance in Figure D4 were too low, or reversed. Figure D7 showed the validity of the Gerritsma-Beukelman method for oblique head waves. The experiments were carried out by Nakamura and Fujii with a model of a 175 m containership.

Figure D7  Added Resistance in Oblique Head Waves

In the author’s opinion the Gerritsma-Beukelman method was currently the best method available for head to beam waves. In following waves, which were less
important, that method would fail and Boese’s formula could then be used.


MR MEIJERS said that Dr. Fairlie-Clarke had asked for comments on the possibilities of increasing the ship utilisation as a result of saving time. The effect of ship routeing on the ship’s utilisation was negligible, for the following reasons.

Table II had shown the savings in time and fuel for one Atlantic crossing which was a part of a total round trip of the vessel typically split up into:
1) loading part in Europe;
2) crossing cast-west;
3) discharging in America and the Caribbean;
4) loading part in the Caribbean and America;
5) crossing west-cast;
6) discharging, part in Europe.

The loading and discharging parts took approximately eleven days each, with a crossing of the Atlantic taking ten days. A total round trip for the vessel would then take approximately two months, resulting in six round trips a year.

It was well known that only on the westbound routes, results of weather routeing with regard to time-saving were obtained. With six crossings westbound the saying of 13 per cent as found in Table II implied a saying of eight days a year. So only once in eight years was an additional crossing possible, a result that was probably of less interest to a ship owner. The savings calculated above must be looked upon with some caution. It was assumed that in all cases the weather routeing was 100 per cent reliable. That implied a 100 per cent reliable weather forecast for a period of eleven days which at the moment was not possible, as could be seen from the example used in Part II of the paper. Also the possible delays in ports had not been taken into account, which could be an important factor, especially in Caribbean ports.