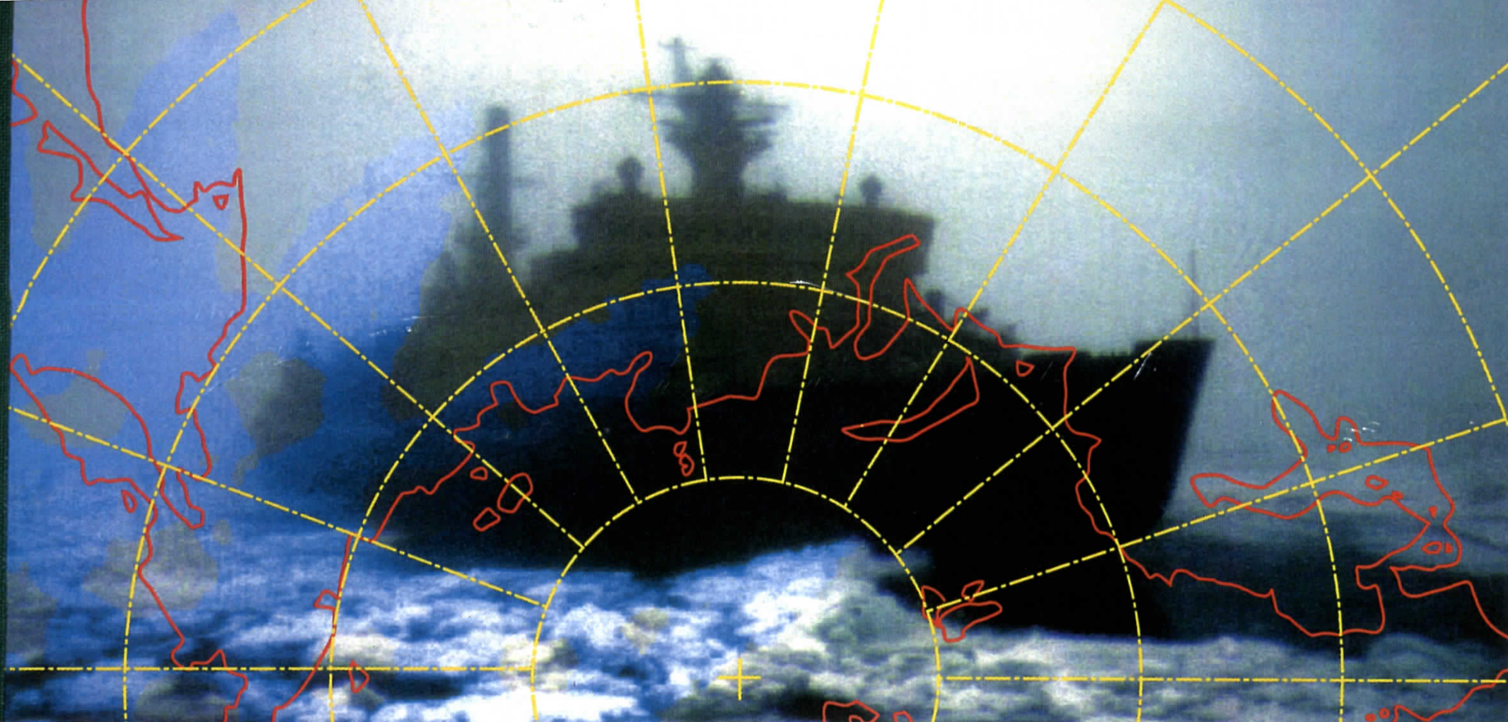
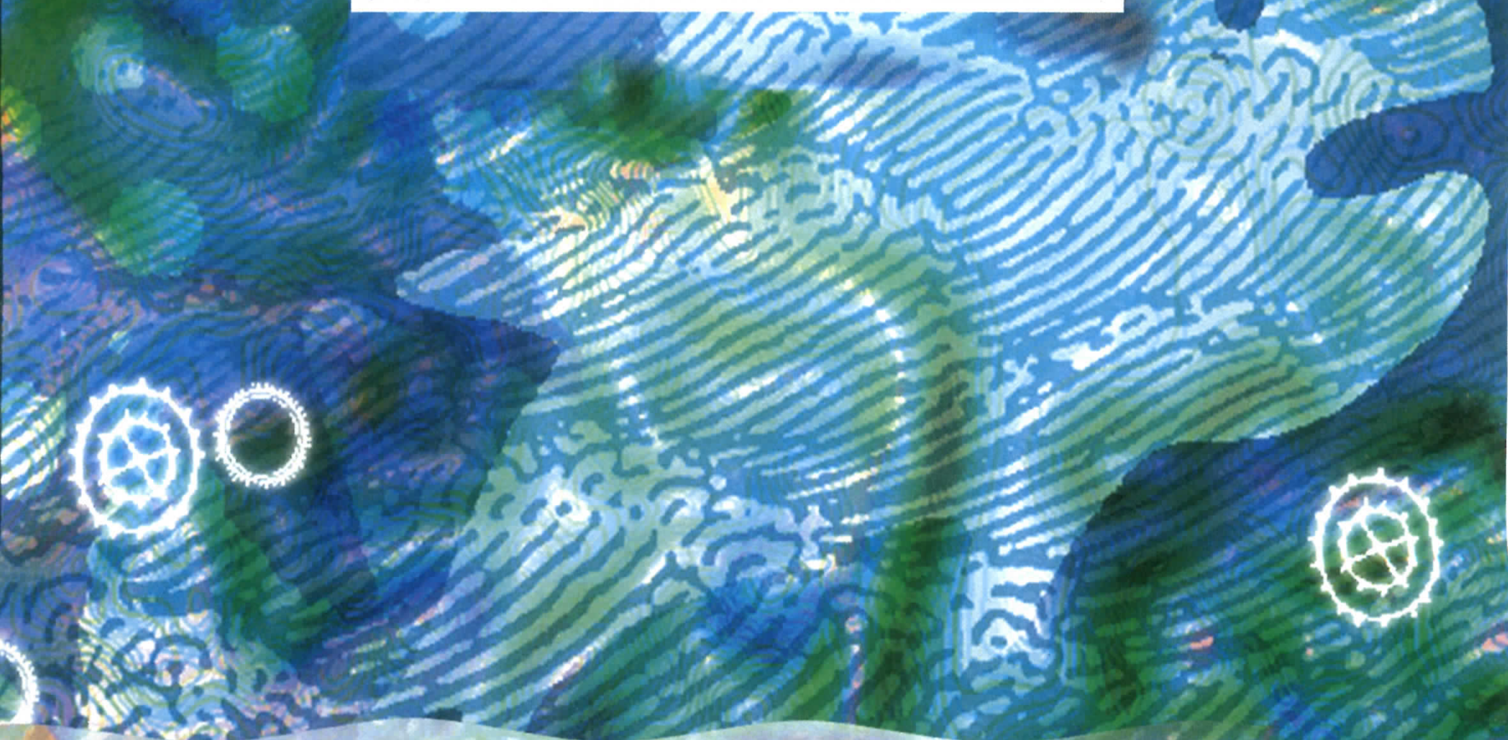


INSROP WORKING PAPER NO. 155 – 1999

The NSR Simulation Study Work Package 6: **Simulation of Ship Transit Through Ice**

By Matthew Patey and Kaj Riska



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INSROP WORKING PAPER NO. 155-1999

Box B: The Simulation Study of NSR Commercial Shipping

Work Package 6: Ship Transit Velocity Simulation Algorithm

Supervisor: Kaj Riska

Title: **Simulation of Ship Transit Through Ice**

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What is an INSROP Working Paper and how to handle it:

FOREWORD - INSROP WORKING PAPER

INSROP is a five-year multidisciplinary and multilateral research programme, the main phase of which commenced in June 1993. The three principal cooperating partners are **Central Marine Research & Design Institute** (CNIIMF), St. Petersburg, Russia; **Ship and Ocean Foundation** (SOF), Tokyo, Japan; and **Fridtjof Nansen Institute** (FNI), Lysaker, Norway. The INSROP Secretariat is shared between CNIIMF and FNI and is located at FNI.

INSROP is split into four main projects: 1) Natural Conditions and Ice Navigation; 2) Environmental Factors; 3) Trade and Commercial Shipping Aspects of the NSR; and 4) Political, Legal and Strategic Factors. The aim of INSROP is to build up a knowledge base adequate to provide a foundation for long-term planning and decision-making by state agencies as well as private companies etc., for purposes of promoting rational decisionmaking concerning the use of the Northern Sea Route for transit and regional development.

INSROP is a direct result of the normalization of the international situation and the Murmansk initiatives of the former Soviet Union in 1987, when the readiness of the USSR to open the NSR for international shipping was officially declared. The Murmansk Initiatives enabled the continuation, expansion and intensification of traditional collaboration between the states in the Arctic, including safety and efficiency of shipping. Russia, being the successor state to the USSR, supports the Murmansk Initiatives. The initiatives stimulated contact and cooperation between CNIIMF and FNI in 1988 and resulted in a pilot study of the NSR in 1991. In 1992 SOF entered INSROP as a third partner on an equal basis with CNIIMF and FNI.

The complete series of publications may be obtained from the Fridtjof Nansen Institute.

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Summary

Helsinki University of Technology's Ship Laboratory has developed a computer program for transit simulation along any ice covered navigation route. The program is capable of predicting the average speed and propulsion energy consumed for any ship for a variety of ice conditions on the basis of certain ship parameters (e.g. length between perpendiculars, beam, propeller diameter, etc.) and quantities describing the ice cover (e.g. level ice thickness, ridge density, etc.). The basis for the calculations is the determination of the vessel speed, obtained by equating net thrust available to total ice resistance. The program can simulate navigation of a ship in a navigation channel, in level ice, in ridged ice and in a floe ice field. For the ridged ice and floe ice fields probability distributions are used to model the spacing and size of floes and ridges. This results in statistically distributed vessel speeds for the set of parameters used to describe these two fields. Verification of the routine was performed using the data available on ship performance in level ice, floe ice and ridged ice.

The program was used to investigate the effect of variations in ice conditions on the average speed of the vessel. Level ice thickness, mean channel ice depth, ridge sail height, ridge density, floe size and coverage were the parameters describing the ice conditions that were studied during this project. For this sensitivity analysis a SA-15 series ship was used.

Figures

CONTENTS

1. INTRODUCTION

The evaluation of feasible marine transportation routes in ice covered areas requires knowledge of the ice conditions in the proposed area, the effect of these conditions on the transportation system under consideration and the various possibilities for marine transportation that can reasonably be considered for the environment in question. In the context of the feasibility of navigation along the Northern Sea Route (NSR), Helsinki University of Technology's (HUT) Ship Laboratory was contracted through The International Northern Sea Route Program (INSROP) to develop a transit simulation program for ice covered waters and, using this program, to investigate the effect of various ice cover states on the performance of ships in ice covered waters. The primary goal of the investigation was simply to gain insight into the effect of ice on navigation, whether it be level, channel, ridged or floe ice.

With this goal in mind, the Ship Lab developed an algorithm which is capable of simulating the transit of a ship along a route through ice covered waters. The route can have sections of open water, level ice, navigation channels through ice cut by icebreakers, floe ice fields of various concentrations and segments of ice that are ridged. In the simulation of floe ice and ridged ice, probability distributions are used to model the spacing and size of ridges and the size of ice floes. This necessitates the use of multiple simulations with identical input parameters (as no single fixed number describes these ice conditions in detail) to effectively capture the statistical nature of the ship's average speed when transiting a route having sections of ridged and/or floe ice. These input parameters are generally constants of the statistical distributions used. The main output of the program is the speed profile along the track, power consumed and total voyage time for the journey. The basis for the determination of these quantities is the comparison of the total net thrust available for the ship in question to the resistance of the ice, with the difference resulting in the acceleration of the vessel.

Having now the tool to investigate the effect of ice conditions on navigation it was decided that the most effective way of gaining insight into the transit problem is to systematically vary key ice condition parameters to see the effect on the average speed statistics of the ship. The study basically consisted of conducting a sensitivity analysis with as wide a range of ice parameters as feasible given the time constraints of the project. The average speed was examined as the most important output value, as it reflects the performance of the ship in the given ice conditions clearly - higher speeds meaning less detrimental effect on performance due to the ice. Thus it should be possible to correlate ship performance measured through average speed to the given ice conditions. The final goal in this context of understanding the transit problem is to be able to relate the statistics of the average speed to the statistics of ice conditions. By "statistics" is meant here the type of distribution and the parameters therein.

The simulations were conducted using the data for an SA-15 'Norilsk' Series arctic cargo vessel. This vessel was selected mainly because it is the only vessel for which there is any full scale data from the Russian arctic. The nature of the study did not require the selection of a particular type or class of vessel. However, it would be illogical to select a vessel that is not designed to operate in ice covered regions. Because the study was an investigation into the effect of ice conditions on ship performance in order to gain insight into the nature of the problem, the SA-15 ship would suffice for these purposes just as well as any other vessel.

The simulations were conducted varying the following ice parameters :

- level ice thickness
- average ridge spacing
- floe ice coverage
- average ridge sail height
- average floe size
- mean channel ice depth

Because probability distributions were used to model floe ice and ridged ice fields, it was necessary to conduct multiple simulations to examine the statistical distributions of the average ship speed. Section 3 of the report discusses the operation of the program and shows how these parameters come into play. Following the discussion of the code operation a sensitivity analysis of ship performance based on ice conditions is presented. Finally, verification of the ice resistance formulae used and the simulation routine is presented. First, however, theoretical aspects of ice resistance are covered in order to understand the basis of the simulation routine.

2. ICE RESISTANCE FORMULATIONS AND SHIP PERFORMANCE

The evaluation of ship performance is usually quantified by determining the vessel speed and energy consumed in transiting an ice covered route (Riska *et al*, 1997, p. 6). The ship speed and energy consumed are examined with respect to the parameters used to describe the ice conditions, e.g. level ice thickness. The basis for the calculation of vessel speed for all route sections is the comparison of the net thrust available to the total ice resistance the vessel encounters (Laprairie, Riska, and Wilhelmson, 1995). This principle of comparing net thrust T_{NET} to ice resistance R_i is shown graphically in **Figure 1**. The net thrust is the thrust available to overcome the ice resistance :

$$T_{NET} = T_{Total} - R_{ow} \qquad (1)$$

The total thrust available is estimated based on the bollard pull T_{pull} and the effect of open water resistance is taken into account by a speed factor *f(v)* :

$$\begin{aligned} T_{NET} &= T_{Pull} \cdot f(v) = R_i(v) \\ T_{Pull} &= K_e \cdot \left(D_p \cdot P_D\right)^{\frac{2}{3}} \end{aligned} \qquad (2)$$

where :

K_e	= 0,78 for single screw
	= 0,98 for double screw
	= 1,12 for triple screw vessels
D_p	is propellor diameter in meters
P_D	is shaft power in kW

(Tsoy, 1983)

The speed factor is here assumed to be of quadratic form :

$$f(v) = 1 - \frac{1}{3} \cdot \frac{v}{v_{ow}} - \frac{2}{3} \cdot \left(\frac{v}{v_{ow}}\right)^2 \qquad (3)$$

The speed which the vessel attains may be determined from equation (1) when the ice resistance is known.

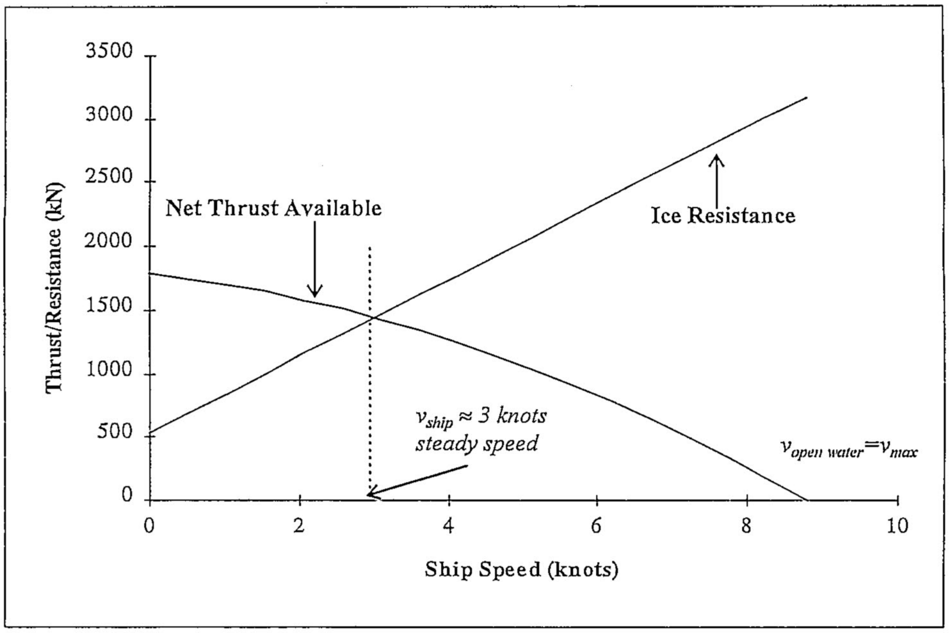


Figure 1 : Schematic of the solution for ship speed. Note that the ice resistance plotted is merely for illustrative purposes.

The evaluation of the total ice resistance is done using separate resistance formulae for channel ice, level ice and ridges. The relevant ice resistance equations are presented below.

Channel ice resistance, R_{CH}, is a quadratic function of ship speed. Setting R_{CH} equal to T_{NET} the ship velocity can be found. The channel ice resistance is evaluated using the formula given in Riska *et al* 1997 :

$$R_{CH} = \frac{1}{2} \cdot \mu_B \cdot \rho_\Delta \cdot g \cdot H_F^2 \cdot K_P \cdot \left[\frac{1}{2} + \frac{H_M}{2H_F}\right]^2 \cdot \left[B + 2 \cdot H_F \cdot \left(\cos\delta - \frac{1}{\tan\psi}\right)\right] \cdot$$
$$\left(\mu_h \cdot \cos\phi + \sin\psi \cdot \sin\alpha\right) + \mu_B \cdot \rho_\Delta \cdot g \cdot K_0 \cdot \mu_h \cdot L_{PAR} \cdot H_F^2 + \rho_\Delta \cdot g \cdot \left[\frac{L \cdot T}{B^2}\right]^3$$
$$\cdot H_M \cdot A_{WF} \cdot Fn^2 \tag{4}$$

where $(1-\mu_B)$ is brash ice porosity, μ_B being between 0.8 and 0.9, ρ_Δ is the difference in the densities of ice and sea water, g is the acceleration of gravity, K_P is a coefficient of passive stress (based on soil mechanics), H_M is the mean channel ice depth, i.e. the depth of the brash ice in the middle of the channel, δ the slope angle of the side wall of the brash ice (22.6° is used here), μ_H the coefficient of friction between the ice and the hull, ϕ the angle between the waterline and the hull at a distance of B/4 from the centerline, K_0 the coefficient of lateral stress at rest, L_{PAR} the length of the parallel midbody at the waterline, A_{WF} the waterline area of the foreship and Fn the ship Froude number. H_F is a term describing the thickness of the brash ice layer that is displaced by the bow and moves to the sides against the parallel midbody. It is a function of ship breadth, channel thickness and two slope angles dependent on the properties of the brash ice (see Riska *et al*, 1997, for details). All of these variables are held constant throughout the program, requiring a simple quadratic solution for ship velocity.

The level ice resistance is calculated using the formula of Lindqvist (Lindqvist, 1989). This formula is somewhat lengthy and not repeated here. It basically consists of three resistance terms : one for crushing of ice at the bow, one for bending of ice at the bow, and one for submergence resistance along the parallel midbody as broken floes pass beneath the ship. Each of these terms is multiplied by a speed dependent term to form the total level ice resistance :

$$R_{Level} = (R_C + R_B) \cdot \left(1 + 1{,}4 \cdot \frac{v}{\sqrt{g \cdot h_i}}\right) + R_S \cdot \left(1 + 9{,}4 \cdot \frac{v}{\sqrt{g \cdot L}}\right) \qquad (5)$$

where R_{Level} is the level ice resistance, R_C is the resistance due to crushing at the bow, R_B is the resistance due to bending and breaking of ice at the bow, R_S is the submergence resistance, v is the ship velocity, and h_i is the level ice thickness. The first two components are assumed to act at the bow. The third is assumed to be distributed uniformly over the parallel midbody of the vessel. Thus the submergence resistance is, if the vessel has penetrated a distance x less than L_{PAR} into the ice :

$$R_S = R_S \cdot \frac{x}{L_{PAR}} \cdot \left(1 + 9{,}4 \cdot \frac{v}{\sqrt{g \cdot L}}\right) \qquad (6)$$

Figure 2 illustrates the areas of the ship hull on which these resistance components act.

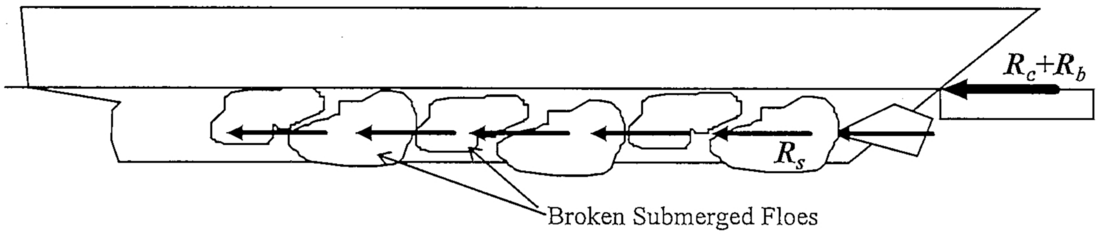


Figure 2 : Areas of the ship over which the level ice resistance is considered to act.

It can be seen in equation 5 that ship speed can be obtained by setting R_{Level} equal to T_{NET}. This is a single calculation as all ice properties, including the thickness of the ice are assumed constant throughout the entire level ice. The level ice thickness used here is also used for the thickness of the ice floes in the floe ice section and the thickness of the stretches of level ice between ridges in the ridged ice section.

Ridge resistance R_{Ridge} is evaluated using the formulations of Malmberg, (Malmberg 1983):

$$R_{Ridge} = R_{Bow} + R_{Par} \tag{7}$$

where the component of bow resistance R_{Bow} is:

$$R_{Bow} = C_1 \cdot T \cdot H \cdot \left(\frac{B}{2} + H \cdot \tan\phi \cdot \cos\alpha\right) \cdot (0{,}15 \cdot \cos\alpha + \sin\phi \cdot \sin\alpha)$$
(8)

and the component from the parallel midbody is, if the ship is in the ridge between positions x_1 and x_2 :

$$R_{Par} = \int_{x_1}^{x_2} f(x) \cdot dx \tag{9}$$

where :

$$f(x) = C_2 \cdot T \cdot \left(0{,}27 \cdot H(x) + \left(\frac{H(x)}{T} - 0{,}5\right) \cdot B\right) \quad \text{if} \quad \frac{H(x)}{T} > 0{,}5$$

$$f(x) = 0{,}27 \cdot C_2 \cdot T \cdot H(x) \qquad \text{if} \quad \frac{H(x)}{T} \leq 0{,}5$$
(10)

C_1 and C_2 are constants based on soil mechanics, T is draught, H is the depth of the ridge at a specific point along the hull, i.e. $H = H(x)$, B is beam, α is waterline entrance angle at the bow and ϕ is stem angle.

3. TRANSIT SIMULATION ALGORITHM

The transit simulation routine NEWSIM used in this study has been under development at the Helsinki University of Technology for three years (La Prairie, Wilhelmson, and Riska 1995, and Petten *et al* 1995). Previous versions of the routine had numerous parts which required reprogramming. The current version of the routine has the capacity to model channel, level, ridged, and floe ice sections of a route. A general outline of the program and its functioning is given in section 3.1 with a more detailed discussion of the different route sections following thereafter.

3.1. Overview of NEWSIM Program

The algorithm considers the transit route in five sections, divided according to ice conditions :

1. Open Water
2. Channel Ice
3. Level Ice
4. Ridged Ice
5. Floe Ice

The user inputs various ship and ice parameters listed below in **Table 1** which are held constant throughout the simulation.

Table 1 : Input Parameters

Ship Parameters (units)	Symbol	Ice Parameters	Symbol
Length Between Perpendiculars (m)	L_{pp}	Ice Density (kg/m³)	ρ_I
Length of Bow Region (m)	L_{Bow}	Ice Bending Strength (MPa)	σ_B
Length of Parallel Midbody (m)	L_{par}	Ice Compressive Strength (MPa)	σ_C
Beam (m)	B	Ice Elastic Modulus (MPa)	E
Draught (m)	T	Ship-Ice Friction Coefficient	μ
Maximum Open Water Speed (m/s)	v_{ma}	Speed of Converging Ice Between Ridges (m/s)	v_{ice}
Stem angle (°)	ϕ_x	Open Water Distance (km)	OW
Waterline Entrance Angle (°)	α	Channel Ice Distance (km)	CI
Number of Propellers		Mean Channel Ice Thickness (m)	H_M
Propellor Diameter (m)	D_p	Level Ice Distance (km)	LI
Shaft Power (kW)	P_D	Level Ice Thickness (m)	h
Longitudinal Center of Buoyancy (m, positive forward of amidships)	LCB	Ridge Field Distance (km)	RF_i
Block Coefficient	C_B	Mean Ridge Density (#/km)	μ
Midship Coefficient	C_M	Mean Ridge Sail Height (m)	h_s
Prismatic Coefficient	C_P	Ratio of Consolidated Layer in Ridges to Level Ice Thickness	h_{cons}/h_i
Waterplane Coefficient	C_{WP}	Ridge Keel-to-Sail Ratio	h_k/h_s
		Floe Ice Distance (km)	PI
		Floe Ice Coverage (% : 0 to 100)	C
		Floe Ice Mean Floe Diameter (m)	D

The output generated by the program depends on whether the user wishes to conduct a single or multiple simulations. A single simulation produces three output files :

1. A simple text file stating the speed, time, and energy consumed for each section of the route, with a voyage summary at the end of the file.
2. If a section of ridged ice is included, a data file containing the time, distance traveled and velocity of the vessel as it transits the ridge field so the user can see the nature of the ship's passage through the ridge field.
3. If a section of floe ice is included, a data file containing the time, distance traveled and velocity of the vessel as it transits the floe ice field, similar to that generated for the ridged ice section.

For multiple simulations two files are produced :

1. A file listing key ship and ice parameters. The average speed along with the ice parameters that define the ridged ice and floe ice sections of the route, i.e. level ice thickness, mean ridge sail height, mean ridge spacing, floe ice mean floe diameter, and floe ice coverage.
2. A file stating for what simulations the ship became stuck in the ice during the transit.

In this way the user can see both typical results for a single transit and also results for a range of ice conditions.

3.2. Route Sections

As stated before, the algorithm considers the route in five sections, with each section having its own particular ice conditions. The length of each of these route segments is input to the program. Only the total length of each type of section is required, i.e. if an actual route having three kilometers of level ice, 2 kilometers of open water and another 3 kilometers of level ice, the user would simply input 6 kilometers of level ice and 2 kilometers of open water.

Ice parameters describing the conditions for each segment are also input into the program. For level ice, channel ice and open water the evaluation of ice resistance on the basis of net thrust available results in a single calculation for maximum speed, due to the uniform nature of the ice conditions in these route sections. For floe ice and ridged ice, where ice conditions are non-uniform along the route, the vessel's progress must be tracked and the position of the vessel in relation to the varying ice features (i.e. ridges, stretches of level ice between ridges, ice floes and open water between floes) continually updated using discrete time intervals. The modeling and transiting of ridged ice and floe ice sections are discussed below.

3.2.1. Ridged Ice

Referring to **Figure 3** below, the ridge field consists of ice ridges, modeled as isosceles triangles with two 20 degree angles, separated by stretches of level ice having the same thickness as the level ice route section. Within the ice ridge there is a consolidated layer having a randomly generated thickness that is greater than the thickness of the surrounding level ice. In the program it is possible to have ridges which overlap up to half of their width. Ridges are constrained to having a sail height in meters of at least the thickness of the level ice.

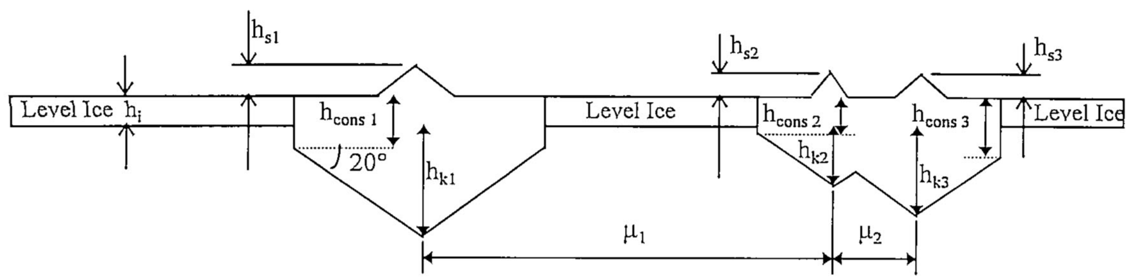


Figure 3 : Geometry of ridge field as implemented in the program. Note that any resistance due to the ridge sail is neglected.

As the description of the ridge field is stochastic the average value alone cannot represent the ridge. Therefore the Monte Carlo method is used in the routine to create the ridges along the ridged ice route section. The ridge field is generated using the probability distributions for ridge spacing and ridge sail height that are taken from Lensu *et al* (1996). The ridge spacing x and the sail height h_s are assumed to follow the exponential distribution :

$$p(x) = 1 - \exp(-\mu x) \tag{11}$$

$$p(h) = 1 - \exp(-\frac{h}{h_s}) \tag{12}$$

where p(·) is the probability density function. The use of the exponential distribution for ridge density is an assumption which is well established (Wadhams 1981). Using the Monte Carlo Method a random number is generated for $p(x)$ or $p(h)$ and equation (11) or (12) is solved for the ridge spacing x or sail height h.

The ridge size has often been stated to follow a log-normal distribution. However, it was decided here to use the exponential form as it has only one parameter, the average ridge size. It is easy, if need be, to change the distribution used in the program. The keel depth is found by multiplying the sail height by the ratio of the sail height to the keel depth, input by the user. In this study this ratio was set to 5.

The thickness of the consolidated layer in a ridge is generated using the following equation :

$$h_{cons} = h_i \cdot (1 + 0{,}8x) \tag{13}$$

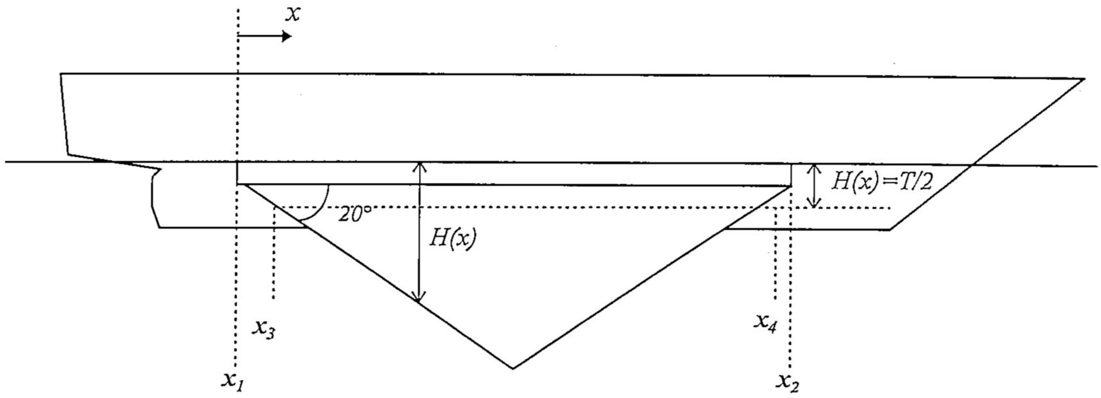
where h_{cons} is the thickness of the consolidated layer, h_i is the thickness of the surrounding level ice. The thermodynamic study of ridges has shown that the consolidated layer grows at most 1.8 times faster than the level ice (Leppäranta & Hakala 1989). This assumes that the ridge is built from ice rubble. A fully consolidated ridge has $x = 1$. The factor x represents the age of the ridge. Here it is assumed that x is a random number uniformly distributed between 0 and 1. Recent studies (Lensu, Tuhkuri, and Hopkins 1998) show that this might not be the case. Instead, rafting is pronounced in ridge building. Then it should be known when the ridge formed and from what thickness of ice. Here there are many uncertainties and thus the formulation above was selected.

The total ice resistance encountered by a ship in a ridge field can have the following individual components :

- level ice resistance due to the stretches of level ice between ridges. This component is evaluated using Lindqvist's formula (see equation 5) using the level ice thickness, h_i. The length of the parallel midbody used in the formula is the length of the parallel midbody that is located in the stretch of level ice in question. Crushing and bending at the bow is included only if the stem is in level ice.

- level ice resistance due to the consolidated layer. This is also evaluated using Lindqvist's formula, using the consolidated layer thickness and the length of the parallel midbody in the ridge. Crushing and bending at the bow is included if the stem is in the ridge. The consolidated layer resistance is counted for all ridges in which the ship lies.

- pure ridge resistance, evaluated using Malmberg's formula. The triangular profile of the ridge means that the integral to calculate parallel midbody resistance only includes the second term (which models resistance along the ship bottom) for the length of the parallel midbody for which the ridge depth is greater than half the draught. It also means that the function *H(x)* is also piecewise linear. The pure ridge resistance for the parallel midbody as defined by the integral above is illustrated below in **Figure 4**. An example of various components of ice resistance in a ridge field are illustrated in **Figure 5** below.



$$R_{Par} = C_2 \cdot T \cdot \left(0{,}27 \cdot \int_{x_1}^{x_2} H(x)dx + \int_{x_3}^{x_4} B \cdot \left(\frac{H(x)}{T} - 0{,}5 \right) dx \right) \qquad (14)$$

Figure 4 : The evaluation of pure ridge resistance, showing the limits of integration for the bottom and parallel midbody resistance.

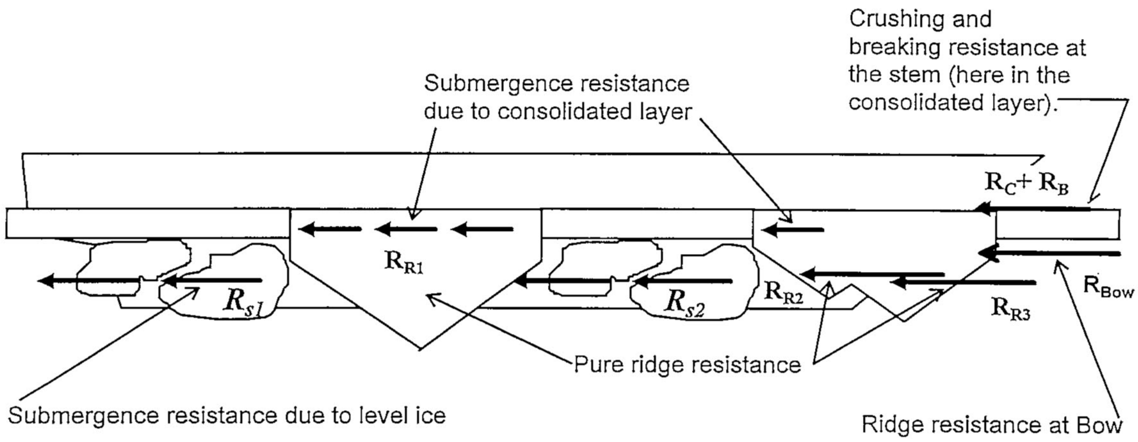


Figure 5 : Ice resistance components in a ridge field.

The use of the Monte Carlo method means that every ridge can have a different consolidated layer thickness, keel depth, width and spacing. As illustrated in Figure 5 the total ice resistance in the ridged ice depends on the position of the ship with respect to the ridges. If the ship is not in a ridge, then only level ice resistance need be considered ; if the ship is in a ridge, consolidated layer crushing and bending resistance is considered only if the bow stem is in the ridge, etc. Pure ridge resistance is considered for every ridge in which the ship lies. The positioning of the ship is tracked second by second to account for the variable nature of the total resistance encountered by the ship. The ship can also back up and ram ice features if its velocity drops to zero. In this case channel ice resistance and pure ridge resistance along the parallel midbody are the only resistance terms considered while reversing and then moving forward until the ship reaches its original position prior to which it got stuck. From that point on, resistance is evaluated using all the components that are normally considered when moving forward.

The random nature of the ridge field and the tracking of the vessel as it moves through the field, including backing and ramming of ridges, is illustrated with a typical plot of the ship speed versus the distance traveled into the ridge field, **Figure 6**. From this figure one can appreciate the complexity that results in the modeling of the ridge field transit using the method outlined above. Note also that there is a limit of 4 knots for the maximum ship speed in reverse. This limit is set in the program and cannot be changed by the user.

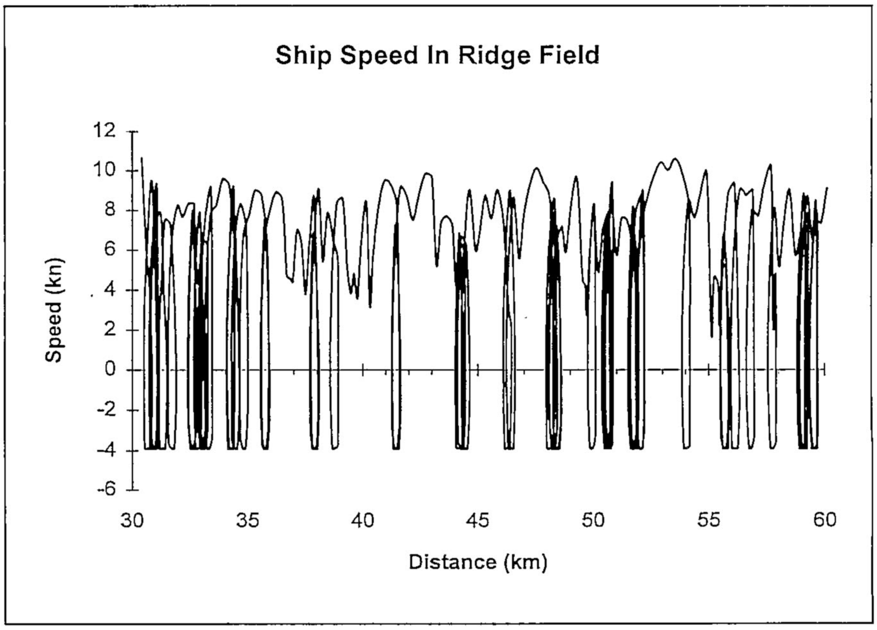


Figure 6 : Sample plot showing the general behaviour of the ship in a ridged ice section. Negative speeds indicate backing that happens before ramming the ridge in which the vessel became stuck.

3.2.2. Floe Ice Transit

The transiting of the floe ice section of the route is very similar to that of the ridge field although simpler. The floe ice field consists of individual ice floes separated by stretches of open water, as shown in **Figure 7**. Ice floes have a thickness equal to that of the level ice section of the route. Naturally the thickness of each floe could be different and again the Monte Carlo method could be used. The uncertainties in all ice parameters suggest, however, that this not be done.

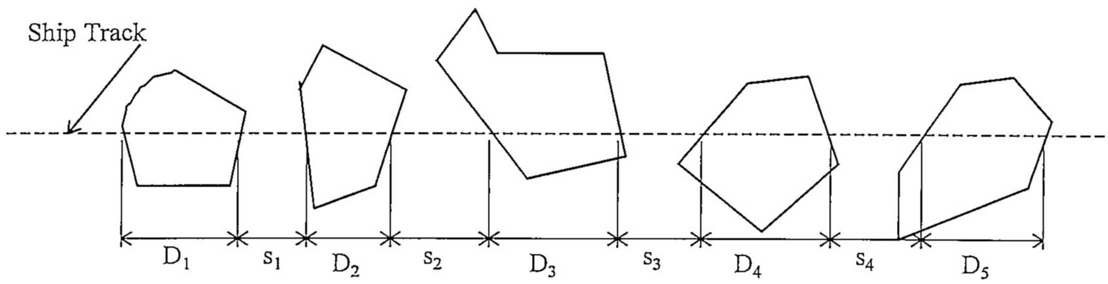


Figure 7 : Geometry of floe ice field showing track of ship.

The user inputs the floe ice concentration or coverage for the route section and the average floe size. Using an exponential distribution for ice floe size:

$$p(D) = 1 - \exp(-\frac{D}{D_m}) \tag{15}$$

and the Monte Carlo method randomly sized floes are generated in the same fashion as for the ridge sail heights, where *p(D)* is the probability density function and D_m is the average floe diameter. The term *diameter* refers to the length of the ship track in the ice floe and does not refer to any assumption of a particular geometrical shape for the floe. The open water spaces are sized according to the coverage and the size of the ice floe generated :

$$s = \frac{1-C}{C} \cdot D \tag{16}$$

where s is the length of the open water gap, C is the given coverage and D is the size of the floe immediately before the open water gap.

The position of the ship with respect to the floes is tracked in a similar fashion as for the ridge field. No backing and ramming occurs in the floe ice field. The ship velocity is calculated equating the net thrust to the total ice resistance. Total ice resistance is calculated using Lindqvist's method for level ice. Bow bending and crushing resistance is evaluated only if the stem is in an ice floe. Submersion resistance calculations use the length of the parallel midbody within each ice floe. This results in less ice resistance and higher average speeds for the floe ice section of a route than for level ice having the same thickness as the ice floes. This approximate method of calculating ice resistance in the floe ice field is used because no ice resistance formulations for floe ice are available. A sample plot showing the changes in the velocity of the ship during transiting of a typical floe ice section is shown in **Figure 8**.

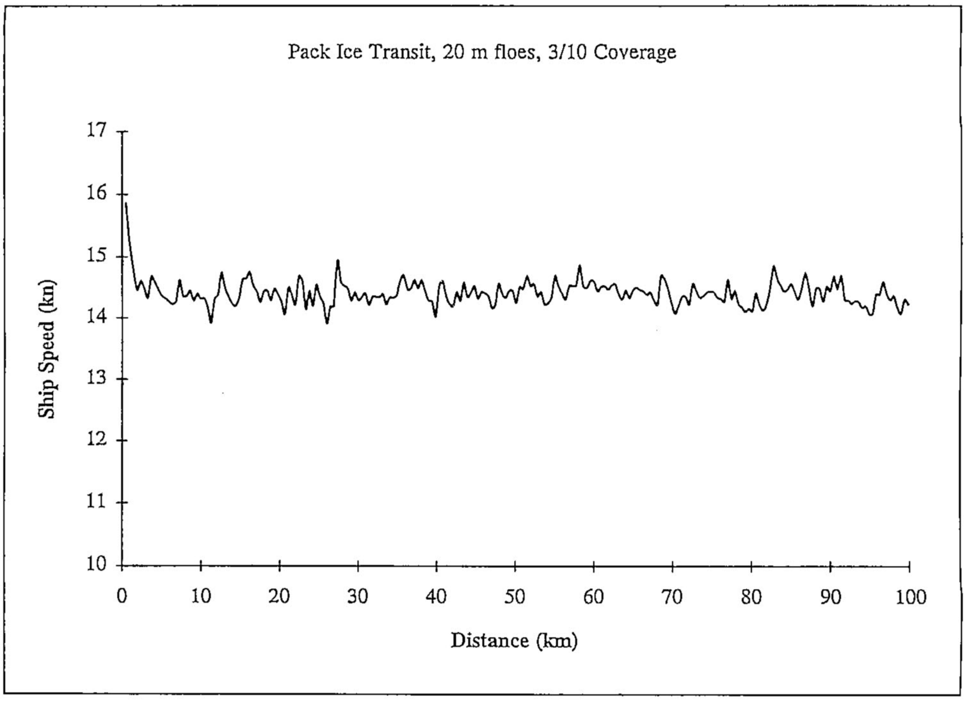


Figure 8 : Typical plot of ship speed versus distance traveled in a floe ice route section.

4. RESULTS OF TRANSIT SIMULATIONS

The present project was carried out to investigate the influence of various route segment conditions and ice parameters on the vessel performance. Systematic variation of relevant model parameters was conducted to investigate the influence on the ship velocity and, in the case of multiple simulations, velocity distributions.

The analysis used an SA-15 "Norilsk" Series arctic cargo vessel. The relevant input parameters for this ship are included in Appendix A. Throughout the analysis certain ice parameters were held constant. These parameters are also listed in Appendix A. The simulations were conducted by focusing separately on each particular type of route section.

4.1. Level Ice and Old Channel

Because level ice is the simplest type of ice field to consider it was first examined. For the SA-15 vessel, a specific vessel speed will result for each value of ice thickness, according to Lindqvist's formula. The ship speed can then be plotted versus ice thickness, as shown in **Figure 9**. The same can be done for channel ice and the ship speed for various mean channel ice depths is also included in Figure 9. The curve showing ship speed versus level ice thickness serves as a baseline for comparison of the effect of various floe ice and ridged ice parameters on the ship speed. This curve is used because it is a function of a single ice variable, i.e. ice thickness, and thus implies a natural analogy to a characteristic quantity describing the ice conditions for a given set of ice conditions.

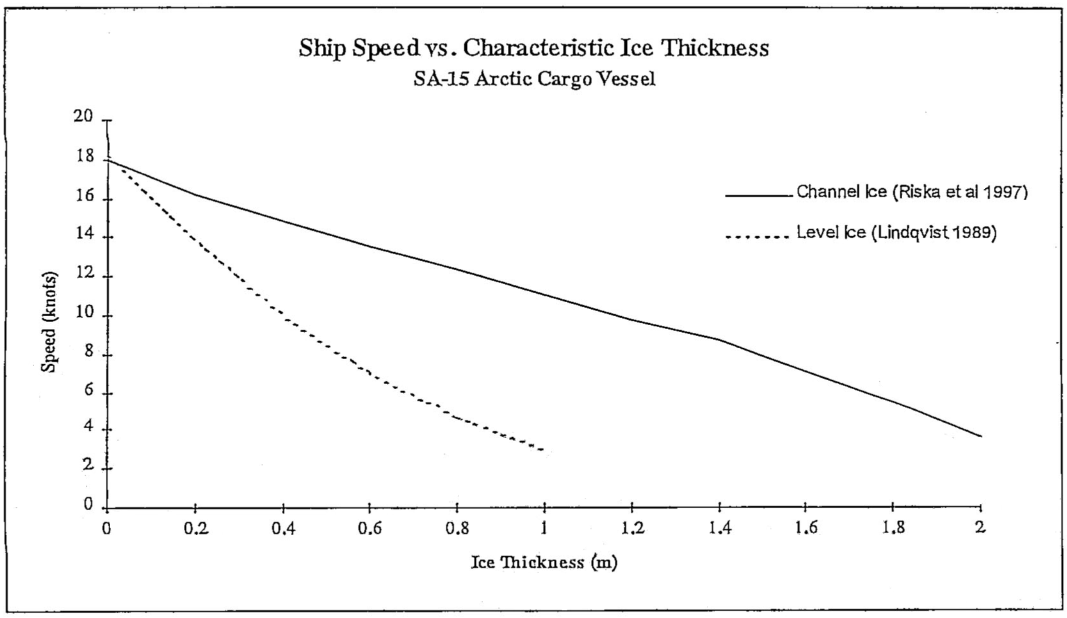


Figure 9 : Ship speed for an SA-15 vessel as a function of level ice thickness and mean channel ice depth.

4.2. Floe Ice Simulations

The parameters that govern the ship transit in floe ice are the coverage or concentration of floe ice C, the average floe size D_m, and the thickness of the floe ice h_i. The ranges of values for these variables used in the simulations were:

$h_i = \{0.2, 0.4, 0.6, 0.8, 1.0\}$ m
$C = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$ Tenths
$D_m = \{20, 40, 60, 80, 100, 120, 140, 160, 180, 200\}$ m

This resulted in 450 different sets of parameters to describe the floe ice field with each set of parameters used to model a single floe ice route section.

One transit simulation refers here to the generation of floe ice sections using the mean values used to describe the distributions listed in Section 3.2.2, and then the tracking and calculation of the vessel's speed as it moves through this section. At the end of the simulation the average speed of the vessel is calculated by dividing the given total distance by the total time it took the vessel to complete the transit. The random generation of the floe ice sections of the route means that each simulation will result in a different average speed. Thus for each set of model parameters (h_i, D_m and C) a different distribution of average velocities will result. An example of the statistical nature of the ship performance in floe ice route section is shown in **Figure 10**.

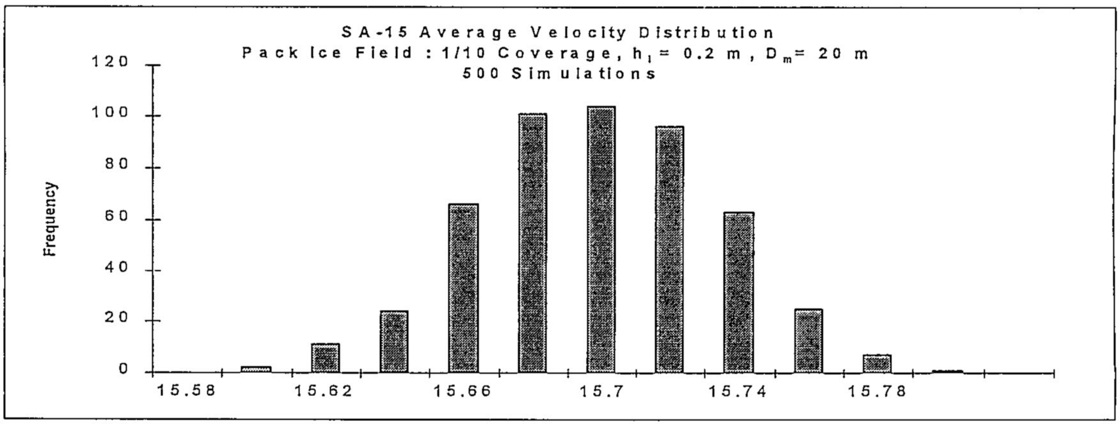


Figure 10 : Distribution of average velocities for one of the preliminary test cases. Note the very small range of values.

For all simulations a floe ice field length of 100 kilometers was used. Some preliminary testing was done to investigate the number of simulations required. The preliminary test cases showed very small standard deviations and ranges for the velocity distributions (e.g. Figure 10). Based on these preliminary cases it was decided that a minimal number of simulations need be conducted for the 450 sets of parameters describing the parameter space of the floe ice route section. Thus 50 simulations were conducted for each set of parameters. This resulted in 22 500 transit simulations and altogether 2 250 000 route kilometres were simulated.

For each parameter set, the average speed and standard deviation were calculated from the results of the entire set of 50 simulations, i.e. the mean and standard deviation of the *average velocity distribution* (Figure 10, for example) was found. This mean speed could then be plotted versus the parameters used. **Figures 11-15** show the mean speed plotted as functions of the coverage, with floe diameter as a parameter, for each ice thickness used. Note that the level ice speed (from Figure 9) is plotted as a straight line for comparison purposes. The data used in these figures is included in **Appendix B.**

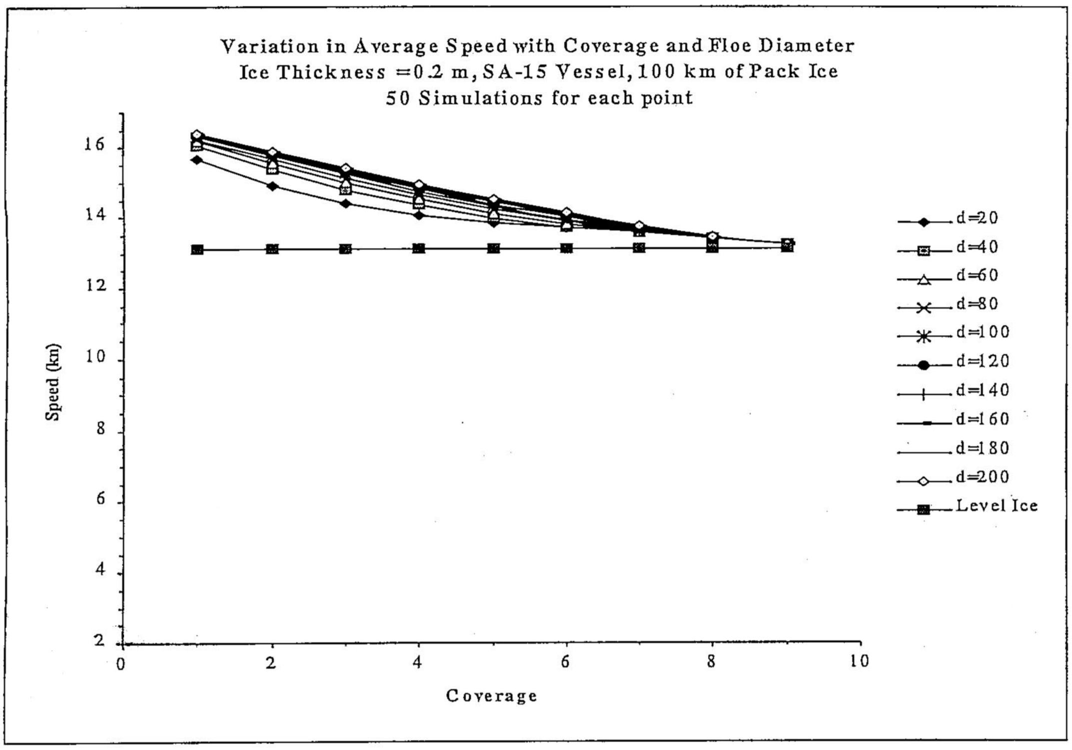


Figure 11 : Ship average speeds in floe ice of 0.2 m thickness.

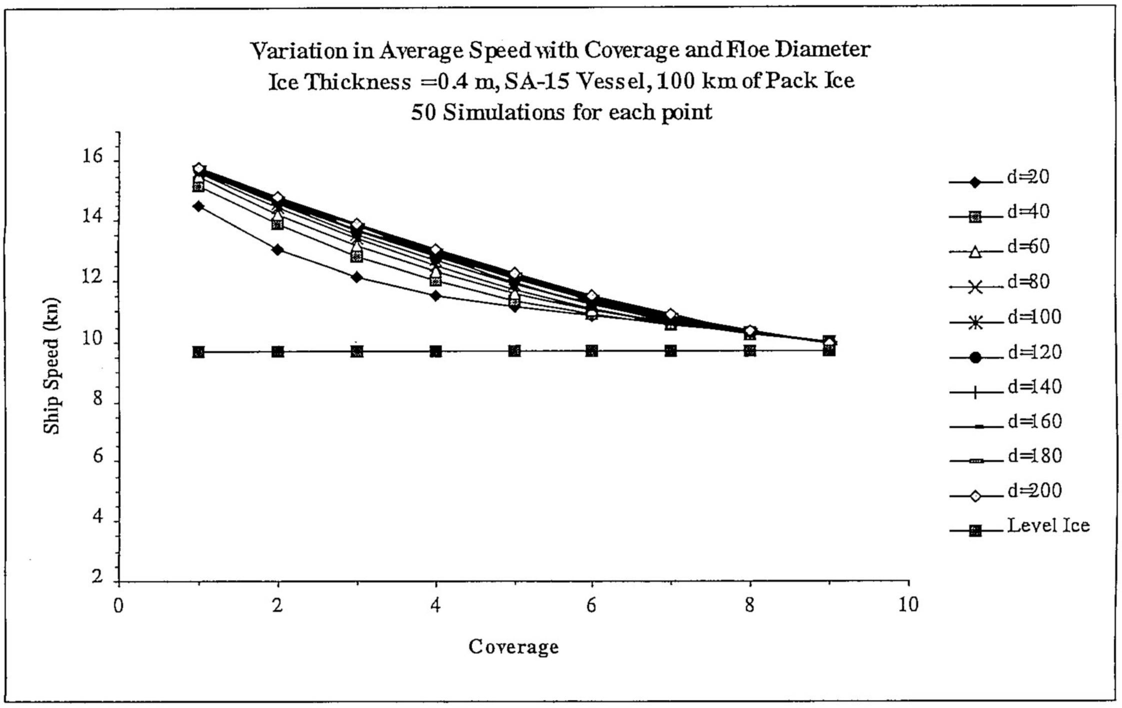


Figure 12 : Ship average speeds in floe ice of 0.4 m thickness.

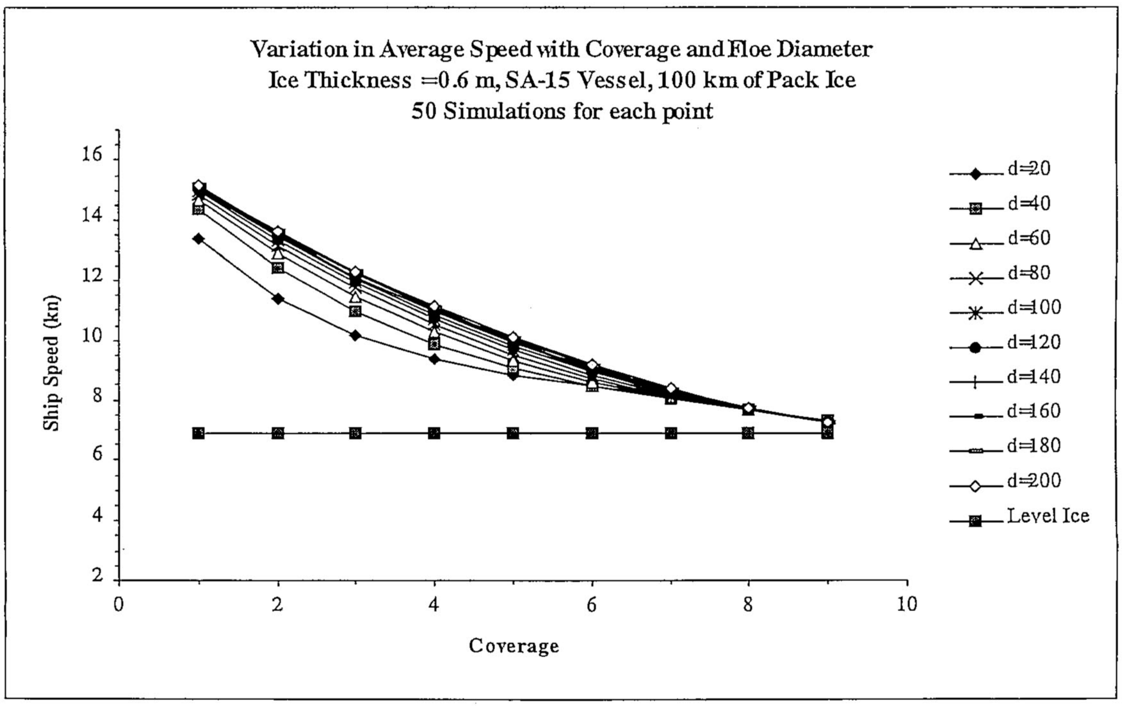


Figure 13 : Ship average speeds in floe ice of 0.6 m thickness.

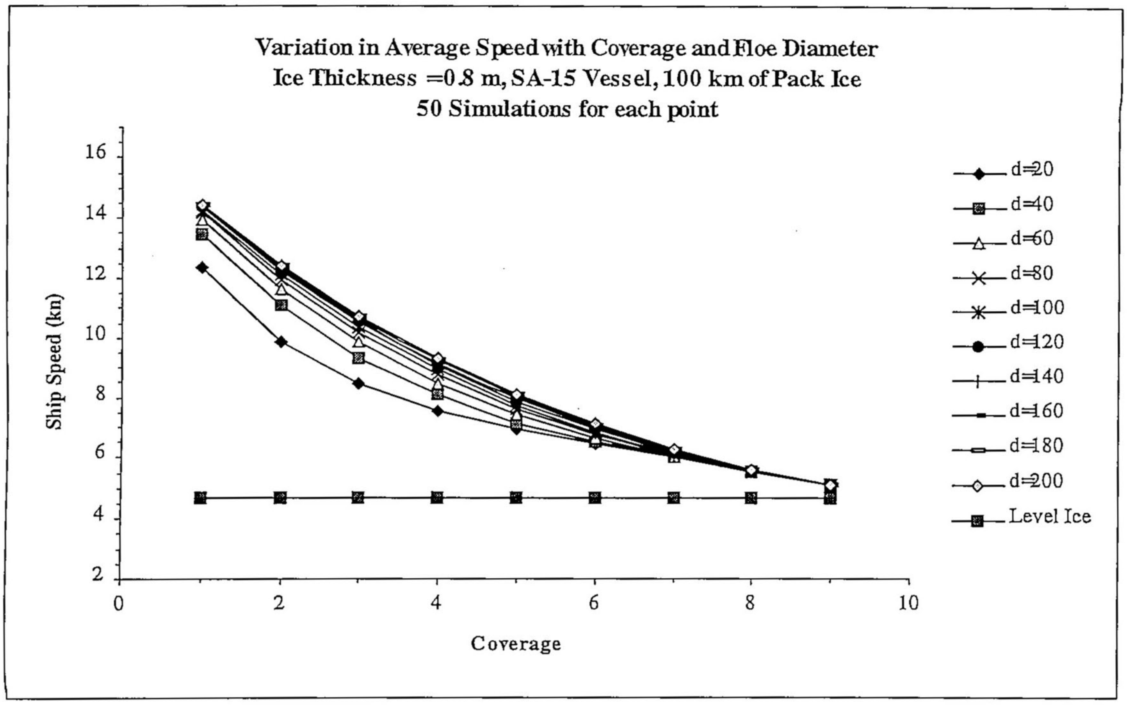


Figure 14 : Ship average speeds in floe ice of 0.8 m thickness.

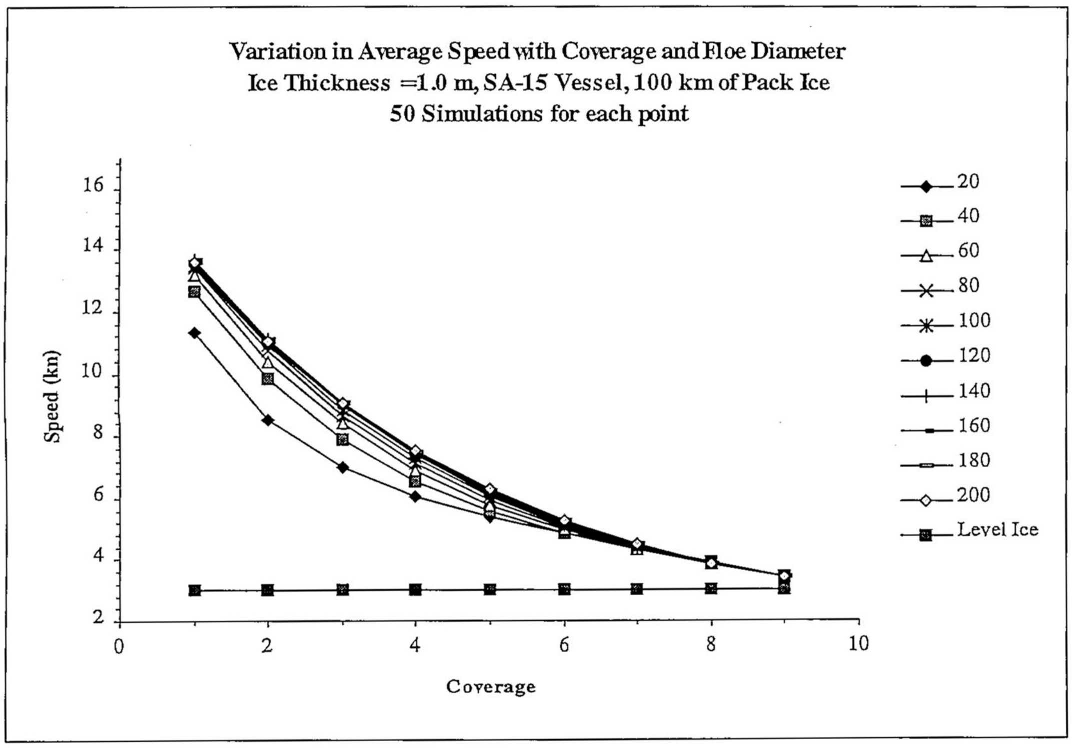


Figure 15 : Ship average speeds in floe ice of 1.0 m thickness.

The results show that the floe size has a slight influence on the speed (smaller floes result in lower speeds). Coverage has a strong influence on the speed. These results are reasonable in spite of the use of level ice resistance equations for the floe ice route section. The increase in speed with floe size is explained by the way the coverage was accounted for when modeling the floe field. A large ice floe is followed by a large open water gap (see equations 15 and 16) which would allow the vessel to accelerate for a greater amount of time between floes. Thus the speed entering the next floe is higher. The resulting average speed at the end of the simulation would be higher than for small floes. This result may be an artifact of the way in which the floe field was created. It should here be borne in mind that the floes are assumed to be immovable. This certainly is not the case for smaller floes.

Figures 16-24 show the variation in ship average speed as a function of floe thickness for each combination of floe average diameter and coverage.

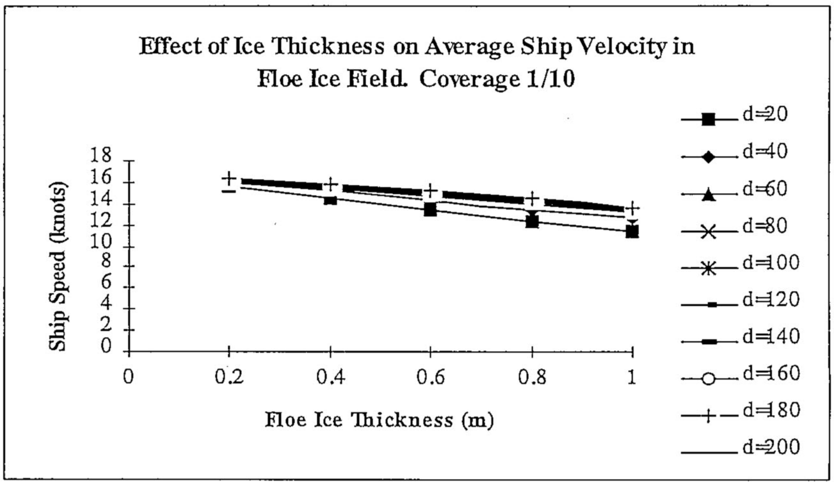


Figure 16 : Ship average speeds in floe ice of 1/10 coverage.

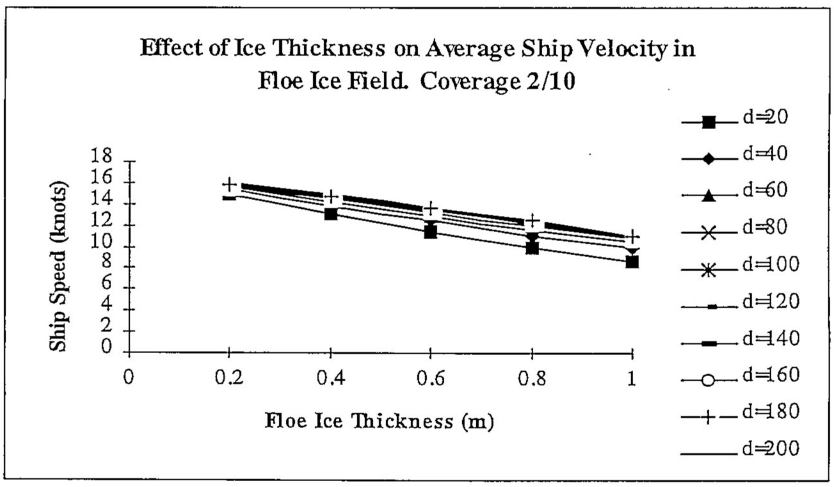


Figure 17 : Ship average speeds in floe ice of 2/10 coverage.

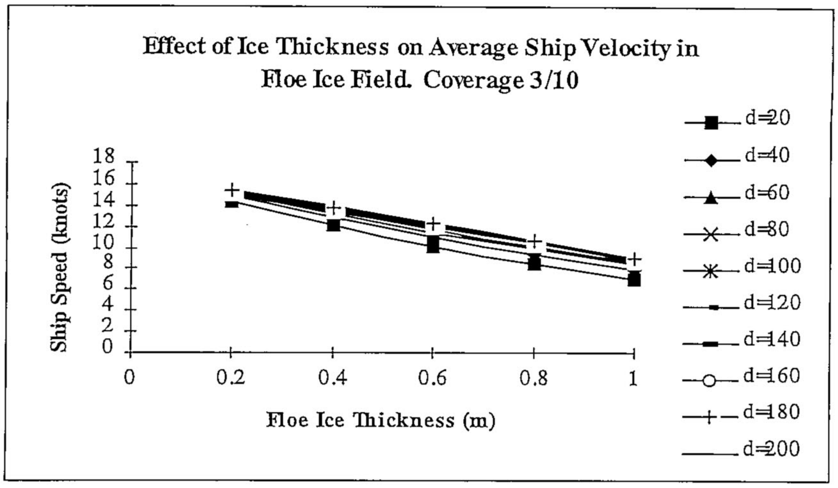


Figure 18 : Ship average speeds in floe ice of 3/10 coverage.

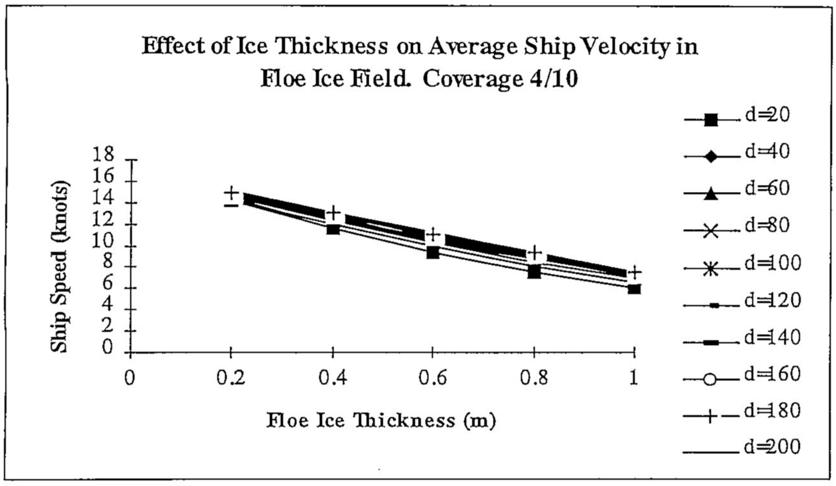


Figure 19 : Ship average speeds in floe ice of 4/10 coverage.

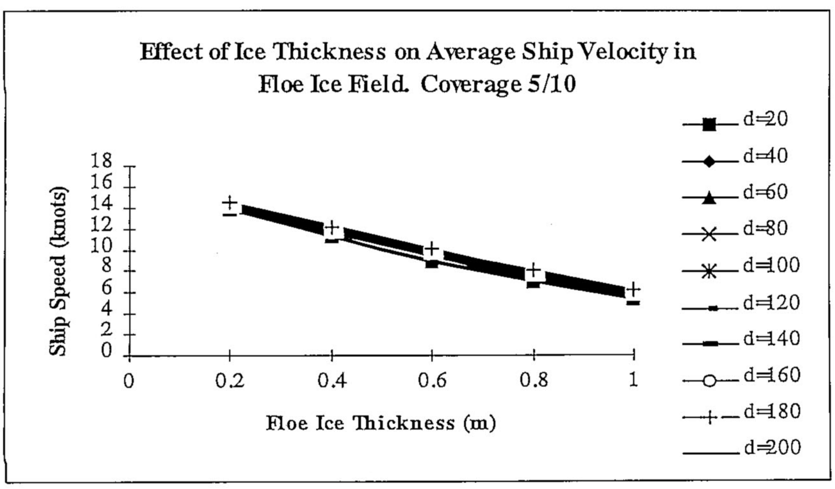


Figure 20 : Ship average speeds in floe ice of 5/10 coverage.

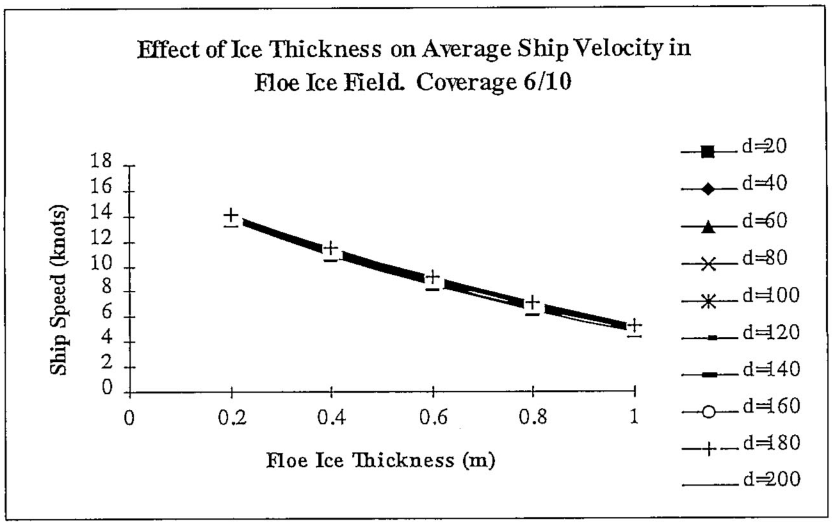


Figure 21 : Ship average speeds in floe ice of 6/10 coverage.

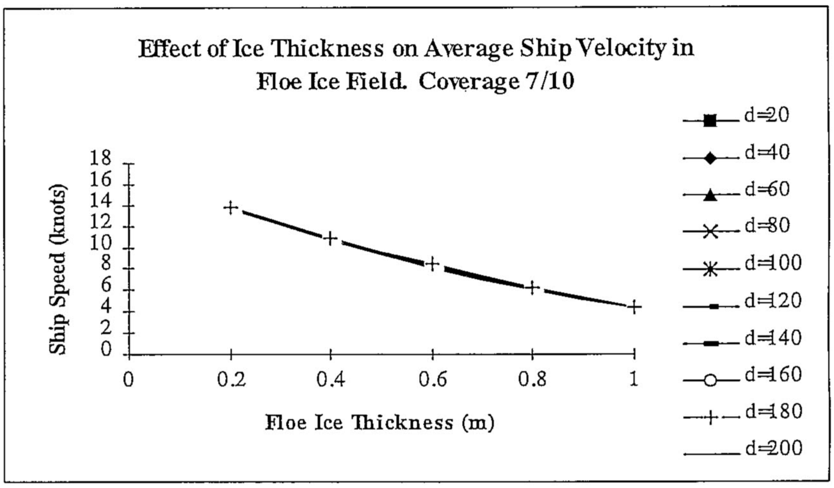


Figure 22 : Ship average speeds in floe ice of 7/10 coverage.

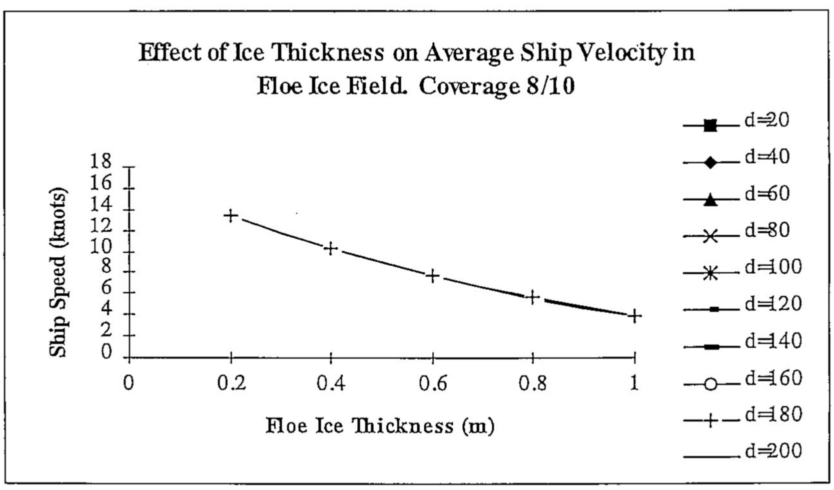


Figure 23 : Ship average speeds in floe ice of 8/10 coverage.

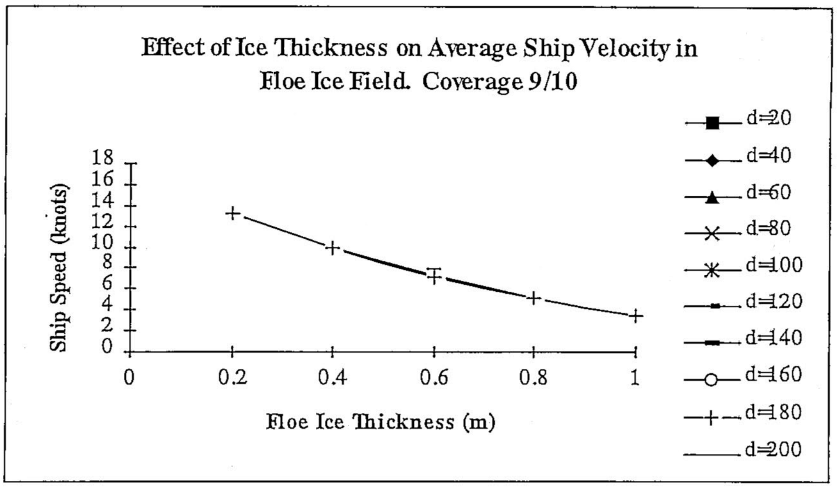


Figure 24 : Ship average speeds in floe ice of 9/10 coverage.

Note that as the coverage increases the influence of floe size diminishes until the ship speed becomes independent of floe size.

The sensitivity of the ship transit to ice conditions is evaluated here by examining the change in ship speed with changes in the ice parameters i.e. the derivative of ship speed with respect to the parameter in question. This can be done by taking first finite differences of the average speeds with respect to mean floe diameter, coverage and ice thickness. **Figures 25-43** show these changes in ship velocity with respect to these variables for the values used in the analysis.

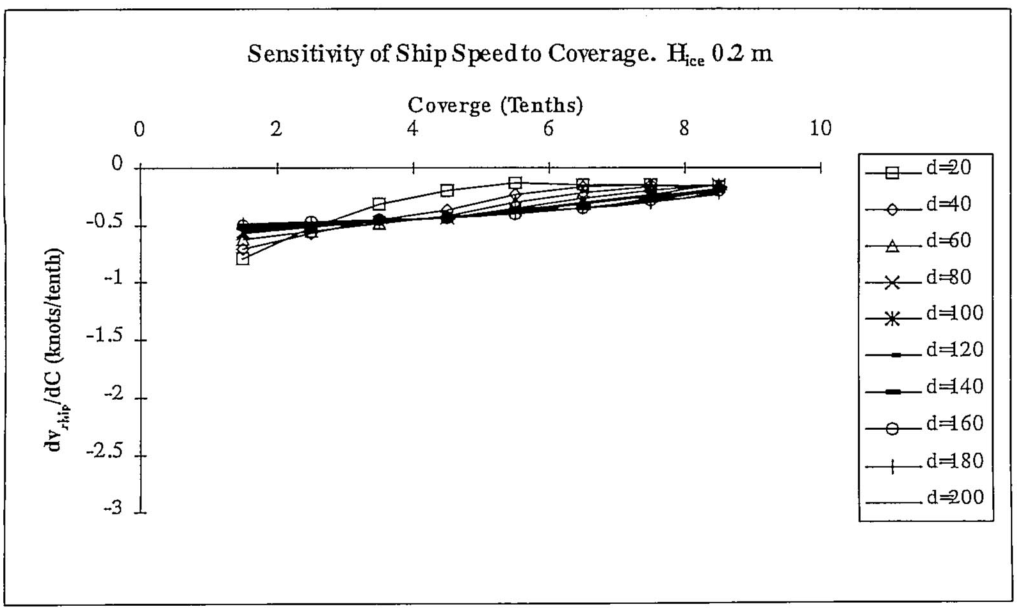


Figure 25 : Change in ship velocity with respect to coverage with average floe diameter as a parameter. Floe ice thickness 0.2 m .

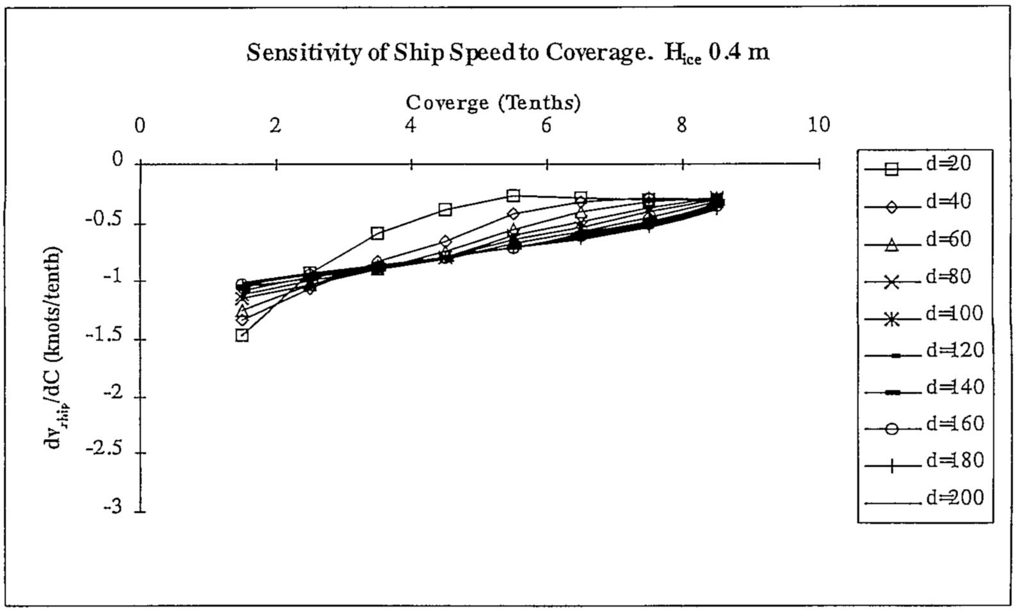


Figure 26 : Change in ship velocity with respect to coverage with average floe diameter as a parameter. Floe ice thickness 0.4 m .

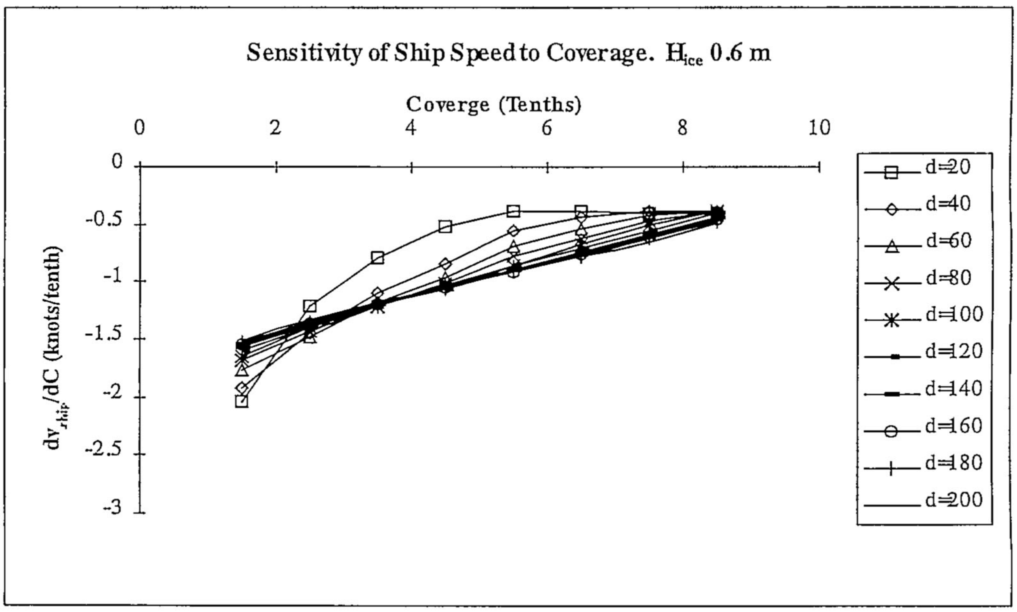


Figure 27 : Change in ship velocity with respect to coverage with average floe diameter as a parameter. Floe ice thickness 0.6 m .

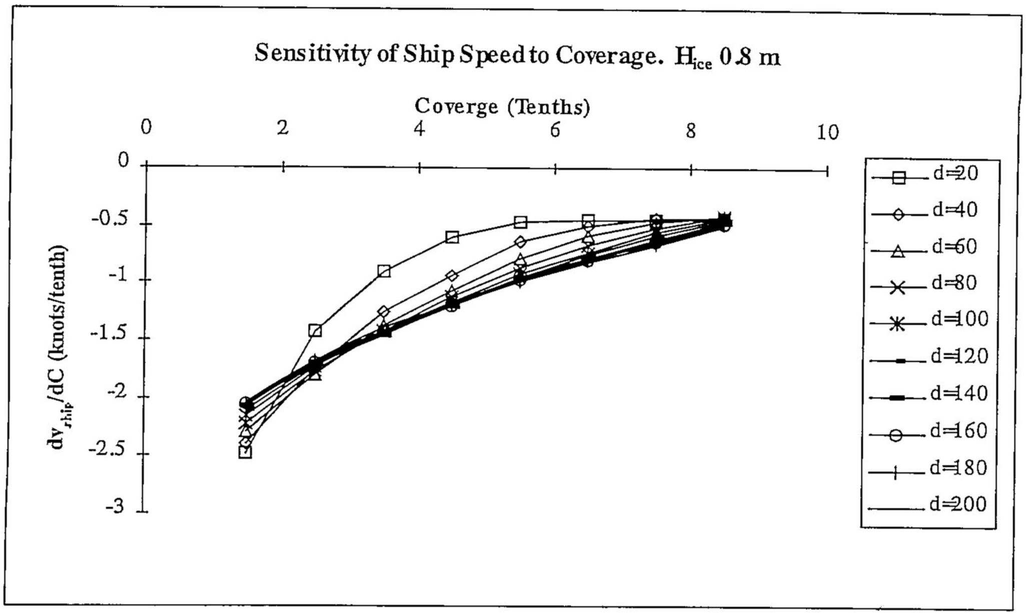


Figure 28 : Change in ship velocity with respect to coverage with average floe diameter as a parameter. Floe ice thickness 0.8 m .

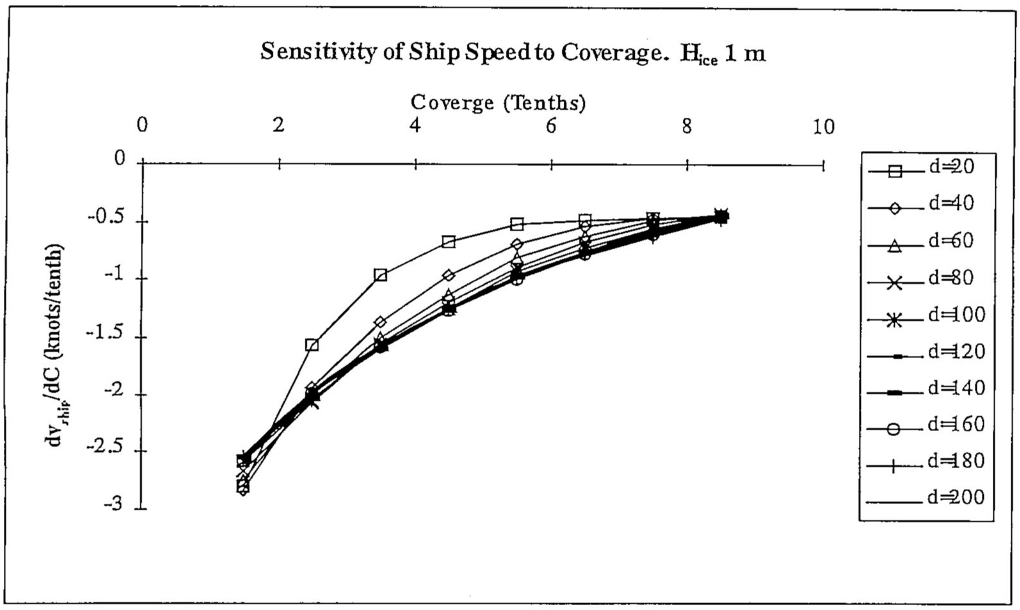


Figure 29 : Change in ship velocity with respect to coverage with average floe diameter as a parameter. Floe ice thickness 1 m .

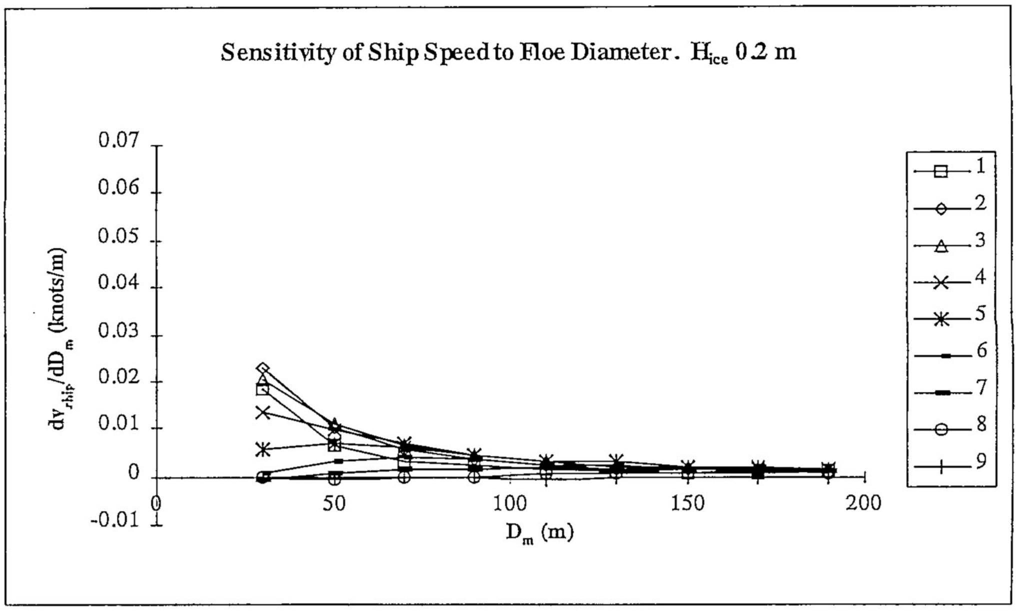


Figure 30 : Change in ship velocity with respect to average floe diameter with coverage as a parameter. Floe ice thickness 0.2 m. Legend entries refer to coverage in tenths.

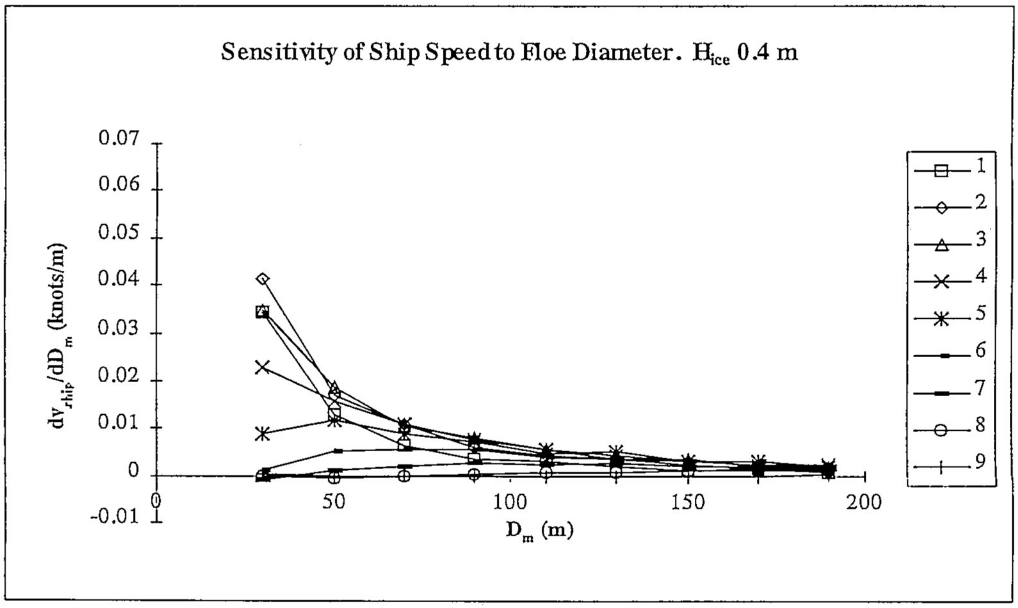


Figure 31 : Change in ship velocity with respect to average floe diameter with coverage as a parameter. Floe ice thickness 0.4 m. Legend entries refer to coverage in tenths.

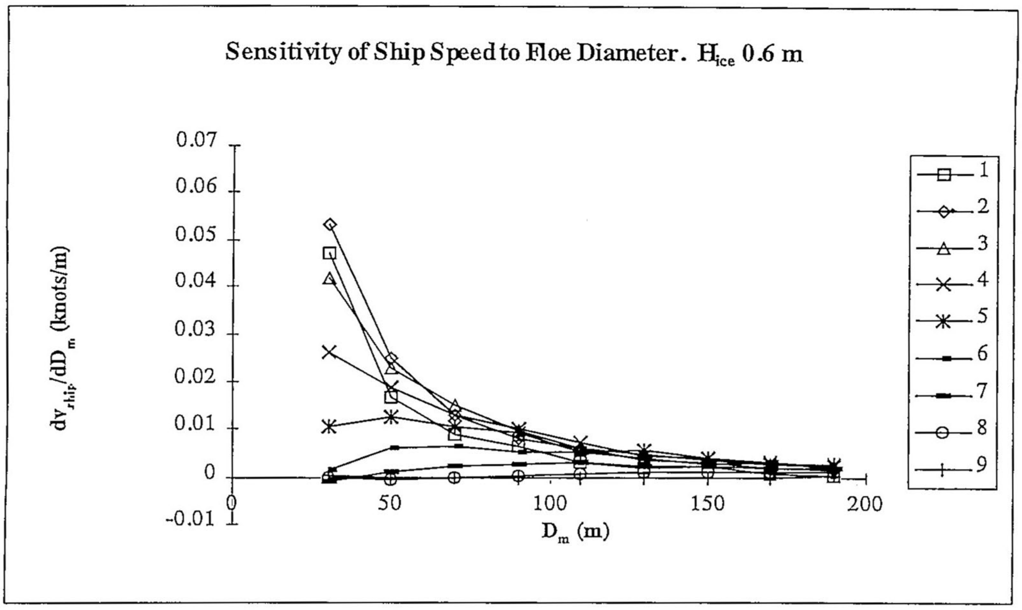


Figure 32 : Change in ship velocity with respect to average floe diameter with coverage as a parameter. Floe ice thickness 0.6 m. Legend entries refer to coverage in tenths.

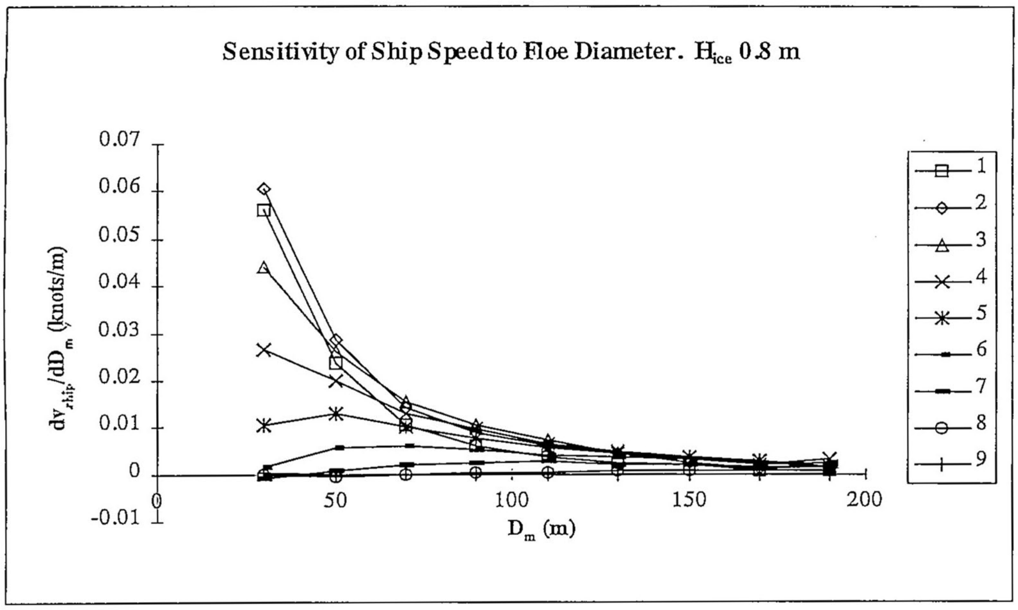


Figure 33 : Change in ship velocity with respect to average floe diameter with coverage as a parameter. Floe ice thickness 0.8 m. Legend entries refer to coverage in tenths.

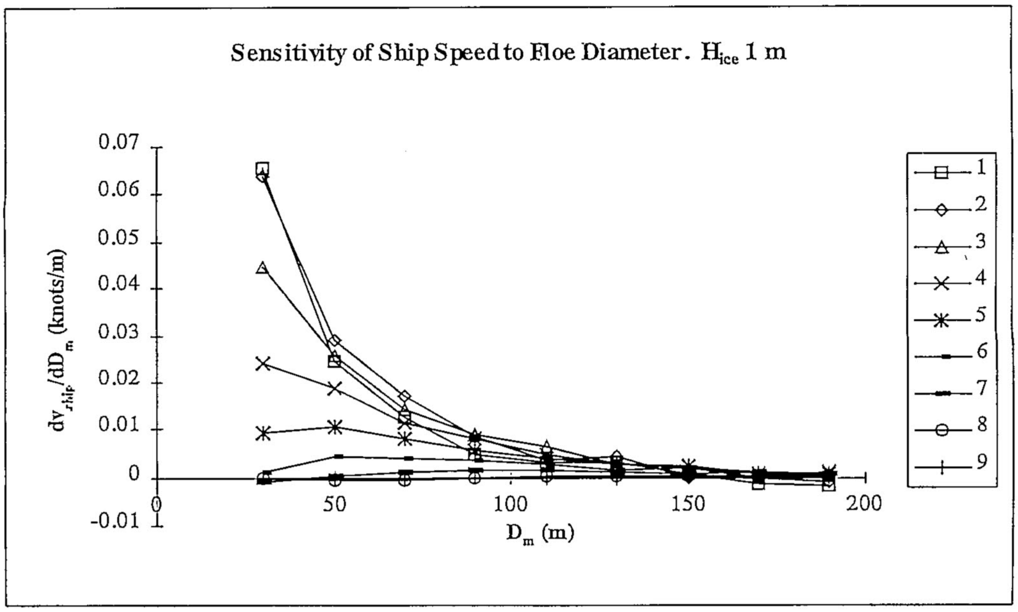


Figure 34 : Change in ship velocity with respect to average floe diameter with coverage as a parameter. Floe ice thickness 1 m. Legend entries refer to coverage in tenths.

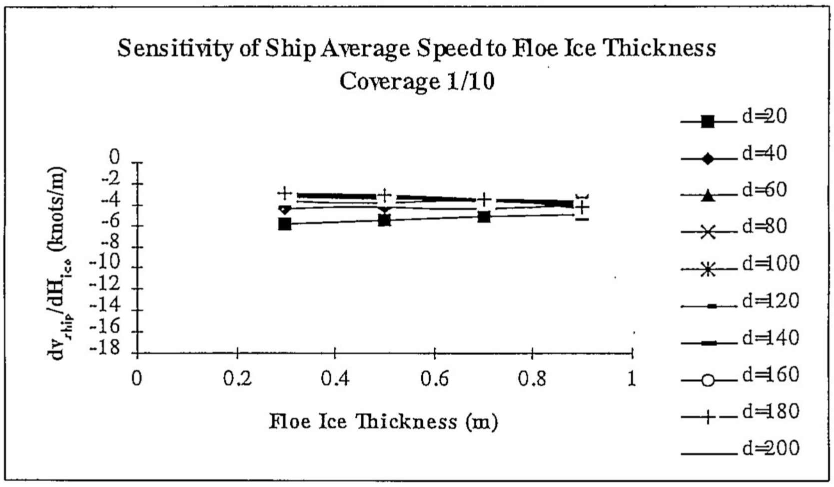


Figure 35 : Change in ship velocity with respect to average floe diameter with average floe diameter as a parameter. Coverage 1/10.

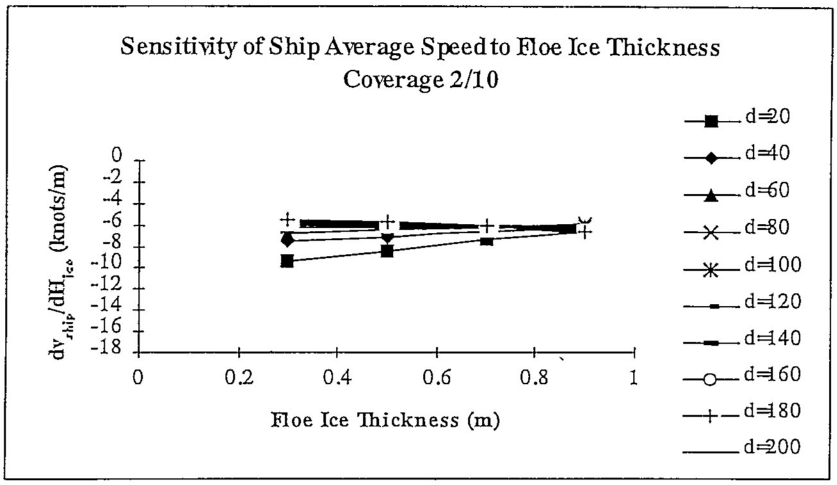


Figure 36 : Change in ship velocity with respect to average floe diameter with average floe diameter as a parameter. Coverage 2/10.

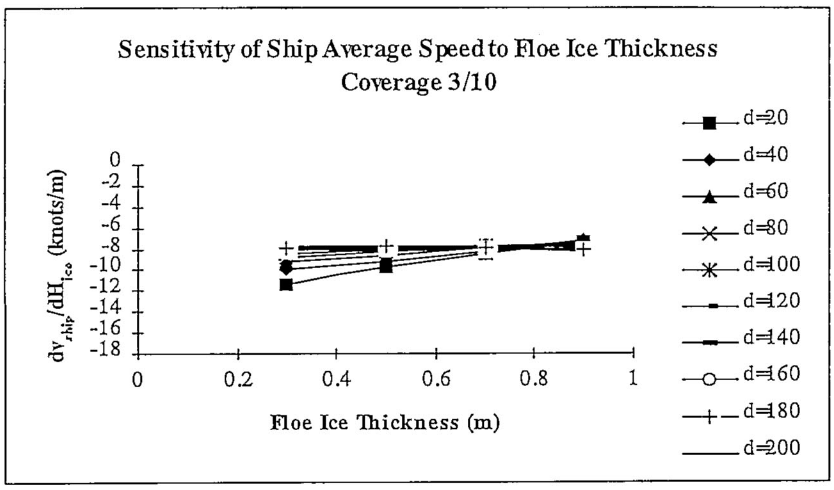


Figure 37 : Change in ship velocity with respect to average floe diameter with average floe diameter as a parameter. Coverage 3/10.

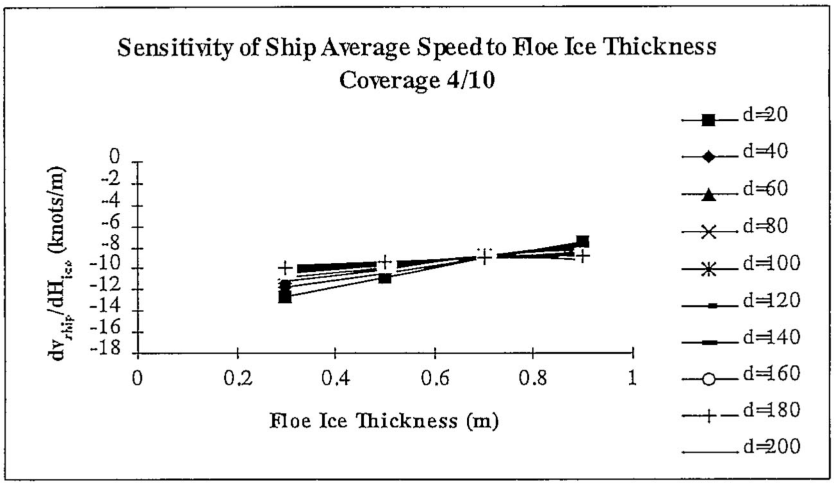


Figure 38 : Change in ship velocity with respect to average floe diameter with average floe diameter as a parameter. Coverage 4/10.

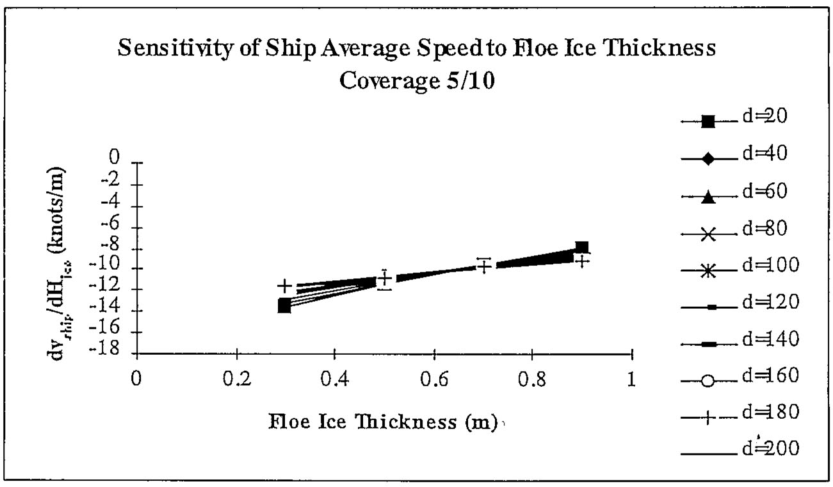


Figure 39 : Change in ship velocity with respect to average floe diameter with average floe diameter as a parameter. Coverage 5/10.

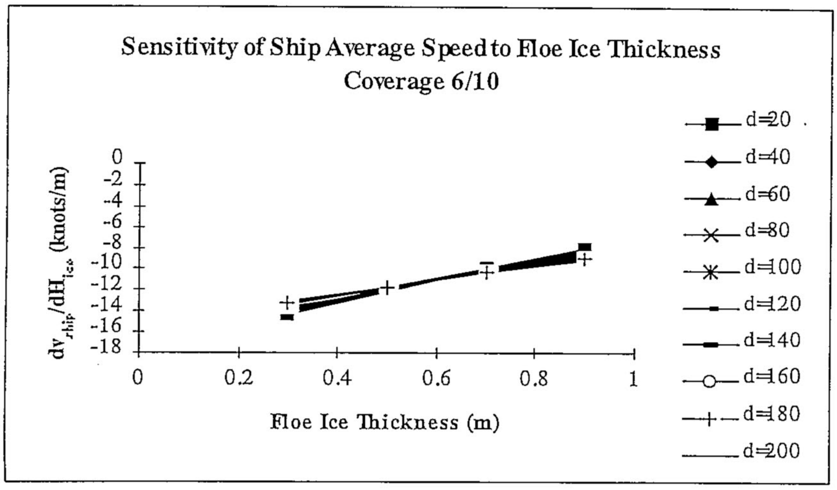


Figure 40 : Change in ship velocity with respect to average floe diameter with average floe diameter as a parameter. Coverage 6/10.

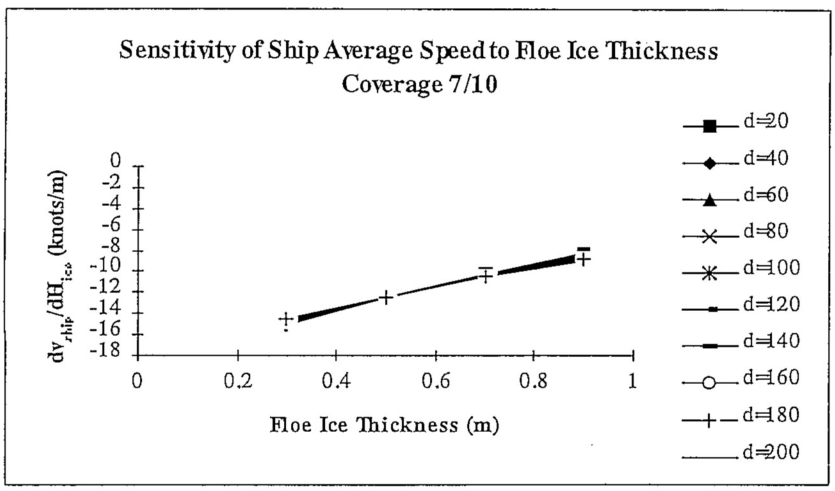


Figure 41 : Change in ship velocity with respect to average floe diameter with average floe diameter as a parameter. Coverage 7/10.

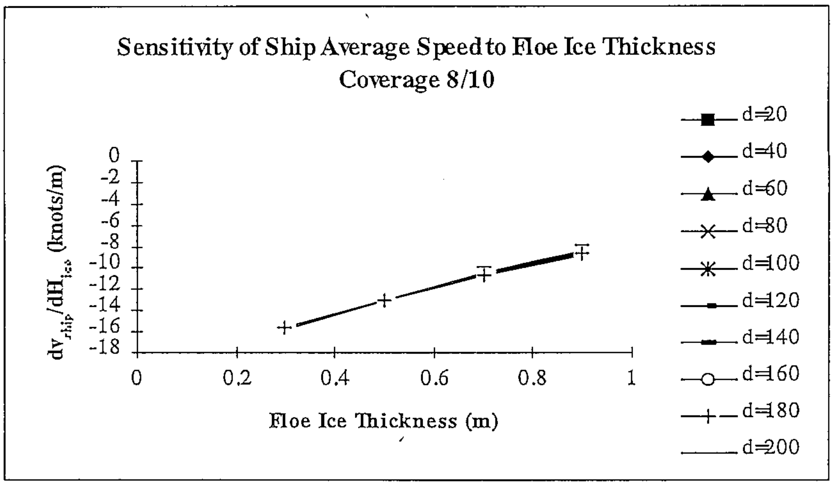


Figure 42 : Change in ship velocity with respect to average floe diameter with average floe diameter as a parameter. Coverage 8/10.

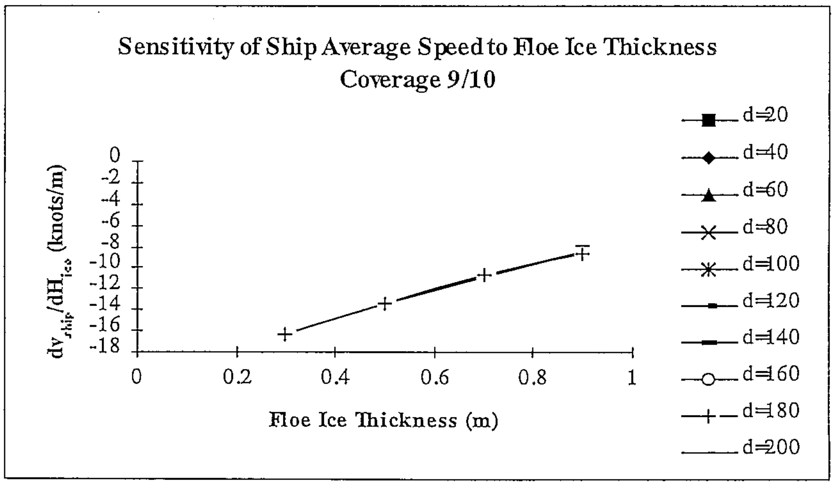


Figure 43 : Change in ship velocity with respect to floe thickness with average floe diameter as a parameter. Coverage 9/10.

Several observations can be made from these figures. First the effect of increasing diameter, coverage and floe thickness are different. Changes in ship speed with increasing floe diameter are positive but decline in value as floe size increases. Changes in ship speed with increasing coverage and ice thickness are negative and show similar trends - with increasing coverage and ice thickness the change in ship velocity becomes smaller. This is an interesting result as it shows that ship performance is more significantly influenced by changes in ice thickness when the ice is thin and by changes in coverage at low coverage.

4.3. Ridge Field Simulations

Simulations and analysis of the parameters describing ice conditions in ridge fields were conducted in the same way as for floe ice fields. A large number of test cases for ridge fields were run varying the length of the ridge field and the number of simulations required. All results in this section are for transits of 1000 km as this longer length would have a wider range of ridge heights and spacings than a shorter transit route. Five hundred simulations were conducted for each set of parameters describing the ridge field to get a good distribution of ship speeds. A large number of simulations was used because preliminary testing had indicated that the range of the average velocity distribution in the ridge field for a set of ice parameters could be up to 5 knots. The simulations were conducted with the view of avoiding conditions in which the ship would become stuck in the ridges. This meant the values of average sail height, level ice thickness and ridge density would be limited. The values used in the analysis were :

H_s	{1, 1.5, 2}	m
H_i	{0.2, 0.6, 1}	m
μ_m	{5, 10, 15, 20}/km	

For all simulations a keel-depth/sail-height ratio of 5 was used. **Figures 44-53** show the variation in vessel average speeds with each of these parameters.

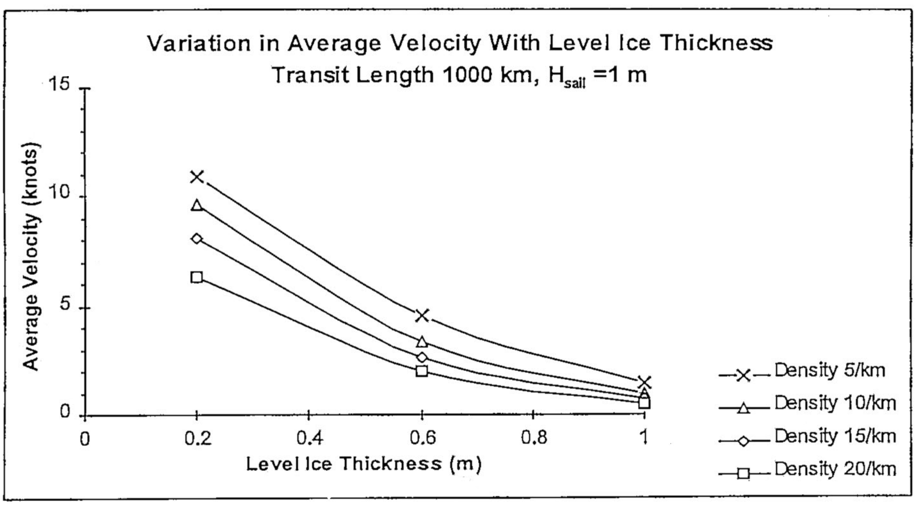


Figure 44 : Variation in vessel average speed as a function of level ice thickness with density as a parameter. Sail height 1 m.

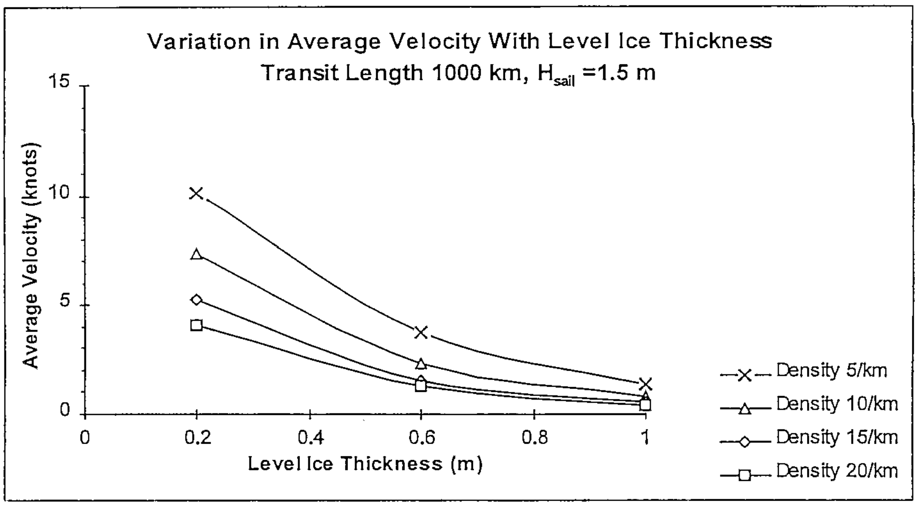


Figure 45 : Variation in vessel average speed as a function of level ice thickness with density as a parameter. Sail height 1.5 m.

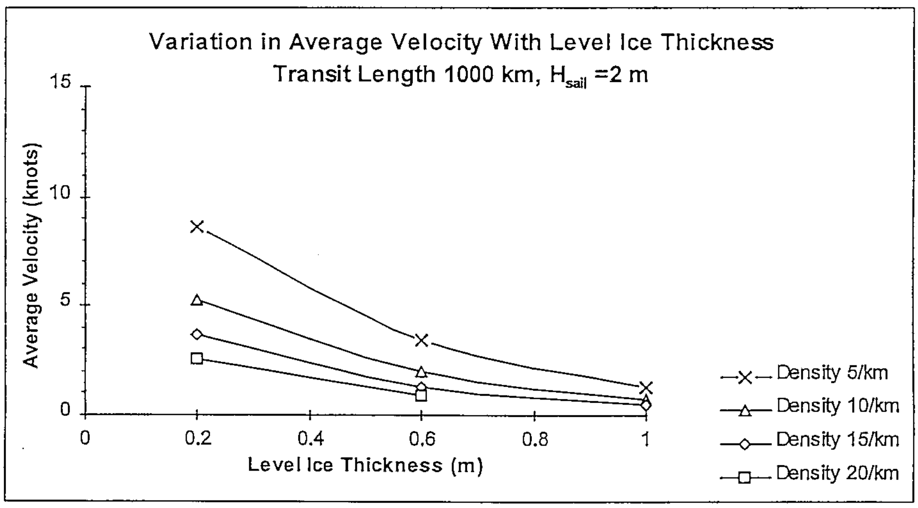


Figure 46 : Variation in vessel average speed as a function of level ice thickness with density as a parameter. Sail height 2 m.

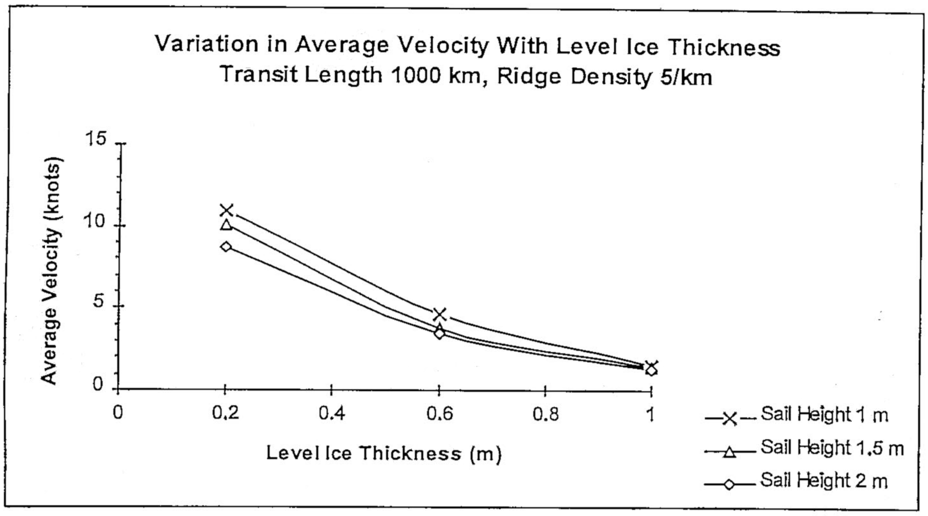


Figure 47 : Variation in vessel average speed as a function of level ice thickness with sail height as a parameter. Density 5/km.

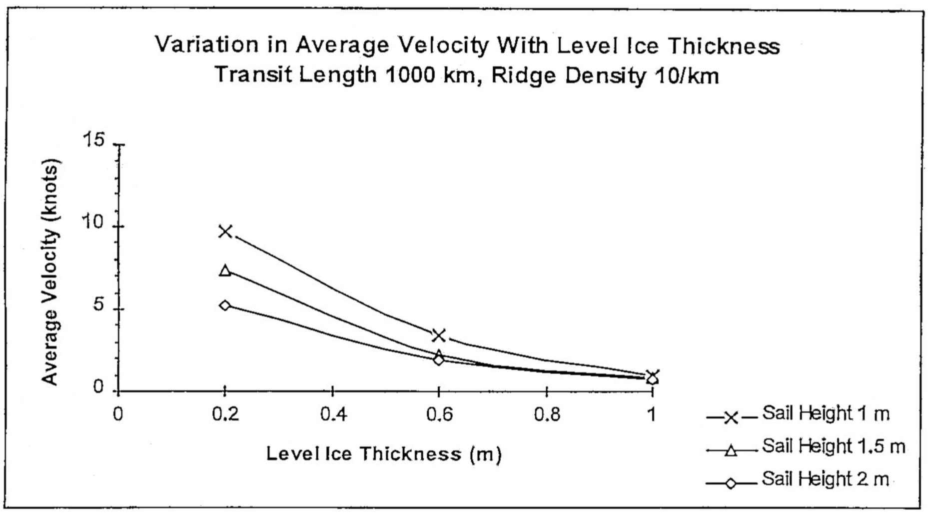


Figure 48 : Variation in vessel average speed as a function of level ice thickness with sail height as a parameter. Density 10/km.

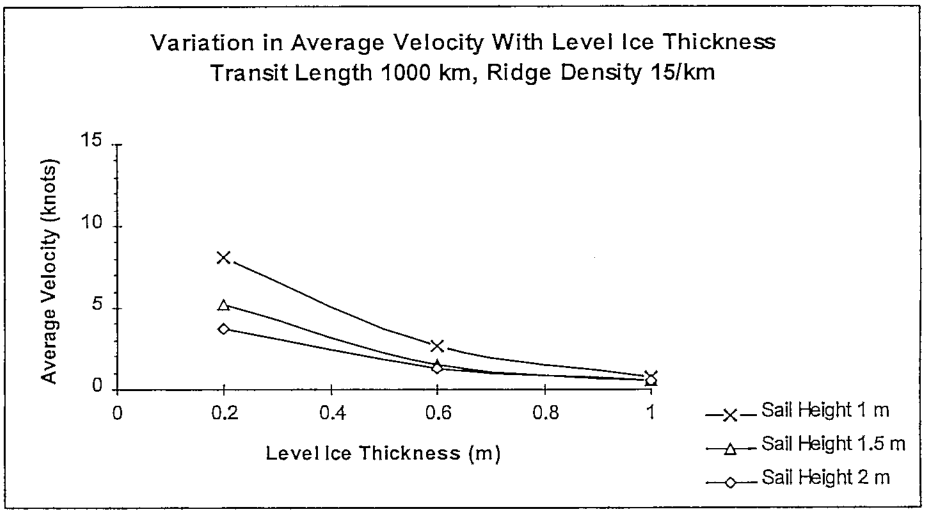


Figure 49 : Variation in vessel average speed as a function of level ice thickness with sail height as a parameter. Density 15/km:

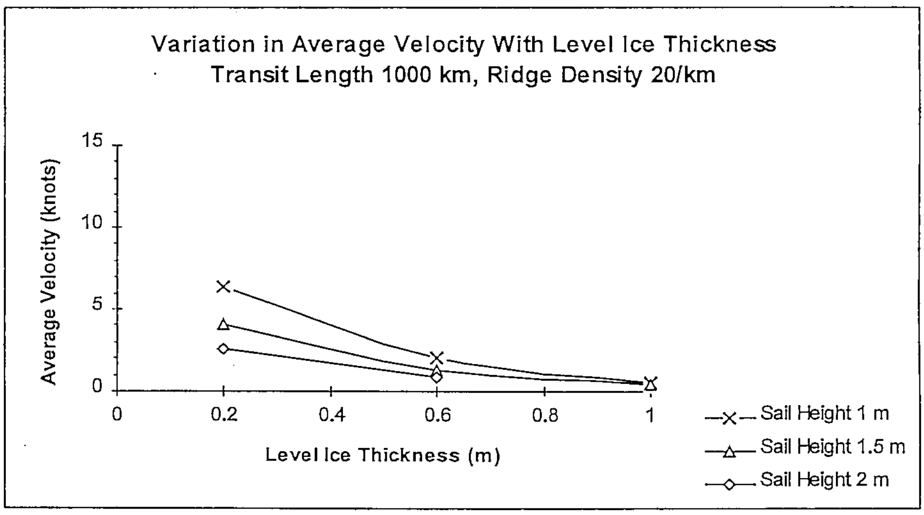


Figure 50 : Variation in vessel average speed as a function of level ice thickness with sail height as a parameter. Density 20/km.

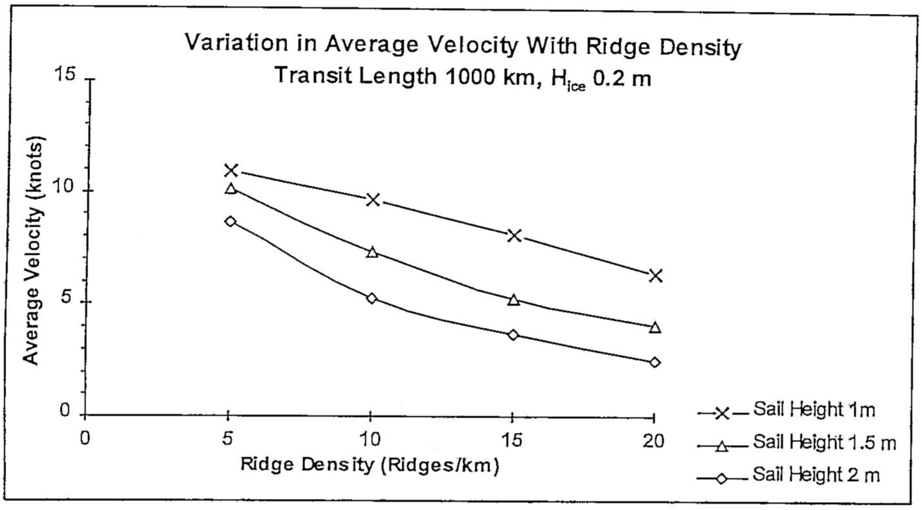


Figure 51 : Variation in vessel average speed as a function of ridge density with sail height as a parameter. Level ice thickness 0.2 m.

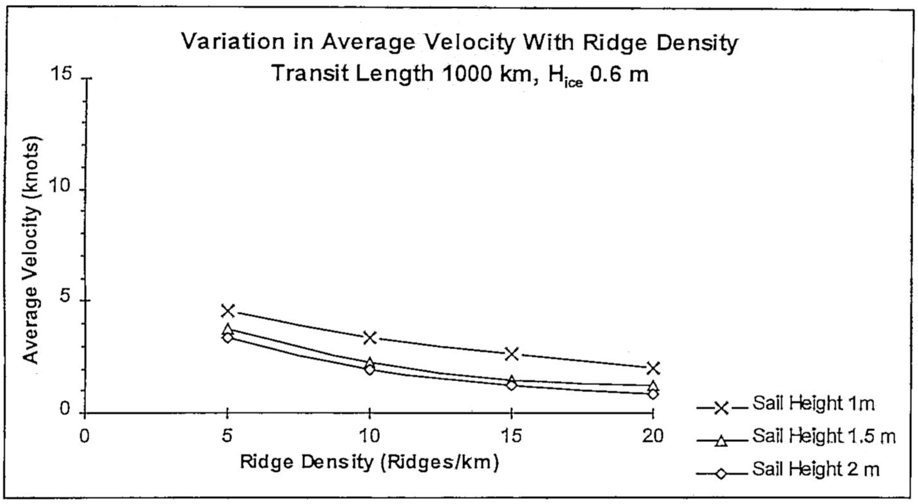


Figure 52 : Variation in vessel average speed as a function of ridge density with sail height as a parameter. Level ice thickness 0.6 m.

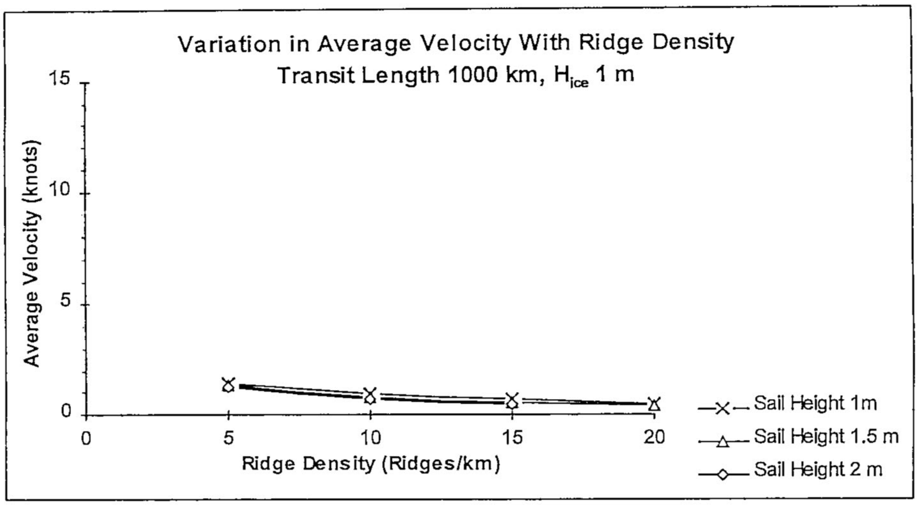


Figure 53 : Variation in vessel average speed as a function of ridge density with sail height as a parameter. Level ice thickness 1 m.

These figures show obvious trends with respect to level ice thickness, sail height and ridge density, namely decreasing ship speed with increases in these parameters. From these figures it appears that differences in sail height and ridge density are more significant at lower level ice thickness than at higher level ice thickness. In addition Figure 53 shows that at an ice thickness of 1 m the vessel speed is effectively independent of sail height, with the thickness of the level ice being the dominating factor in determining ship speed. The sensitivity of ship speed to each of the analysed parameters was examined in the same way as for the floe ice sensitivity analysis. **Figures 54-63** show the results of the sensitivity analysis.

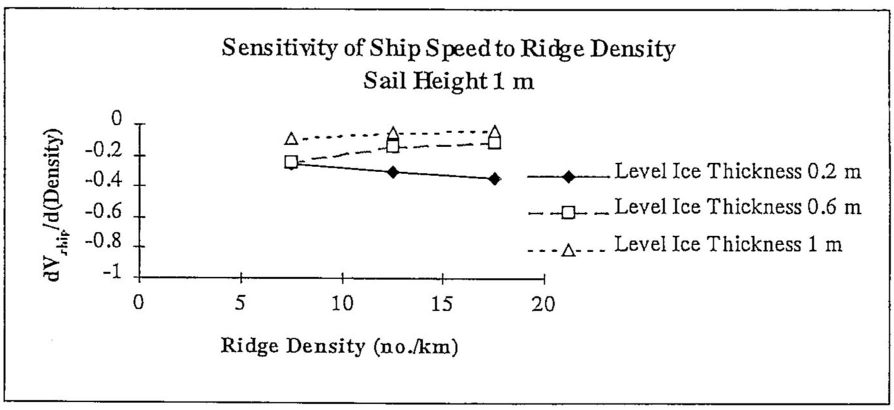


Figure 54 : Sensitivity of ship speed to ridge density with level ice thickness as a parameter. Sail height 1 m.

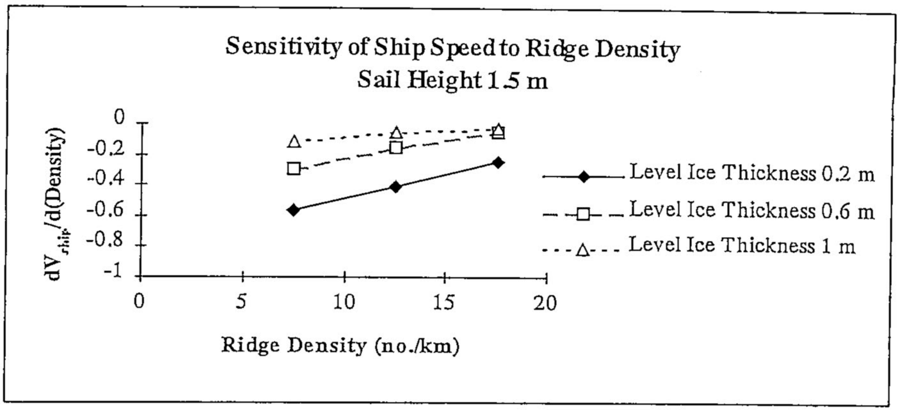


Figure 55 : Sensitivity of ship speed to ridge density with level ice thickness as a parameter. Sail height 1.5 m.

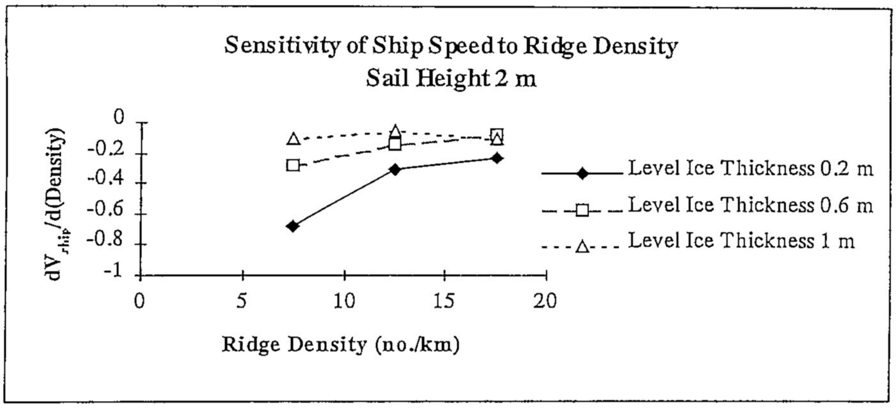


Figure 56 : Sensitivity of ship speed to ridge density with level ice thickness as a parameter. Sail height 2 m.

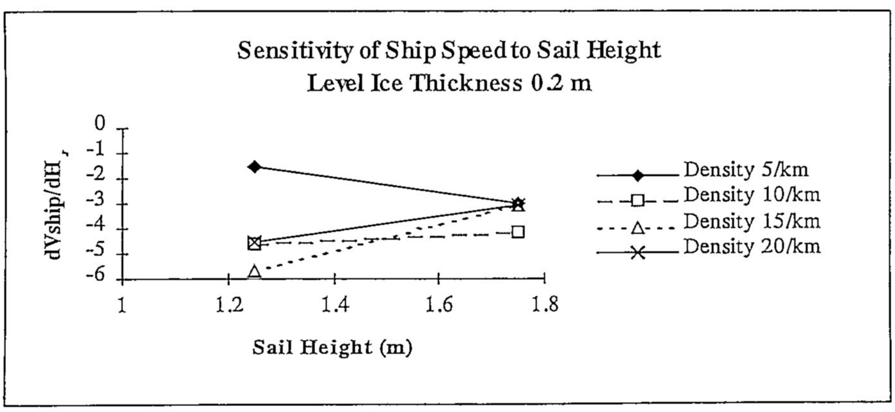


Figure 57 : Sensitivity of ship speed to sail height with ridge density as a parameter. Level ice thickness 0.2 m.

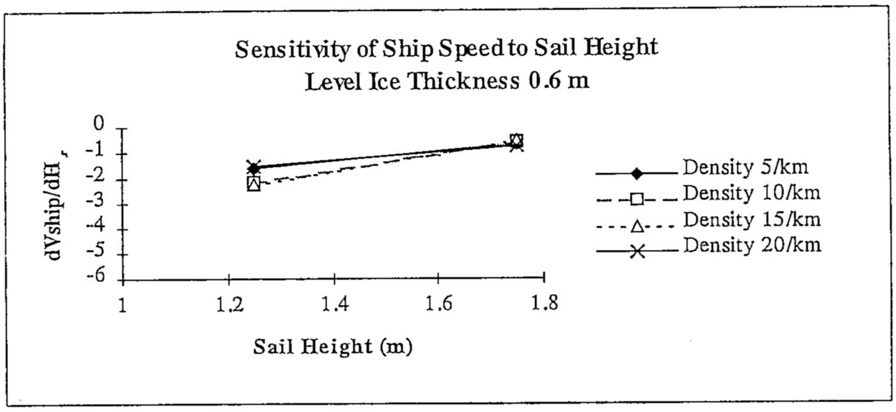


Figure 58 : Sensitivity of ship speed to sail height with ridge density as a parameter. Level ice thickness 0.6 m.

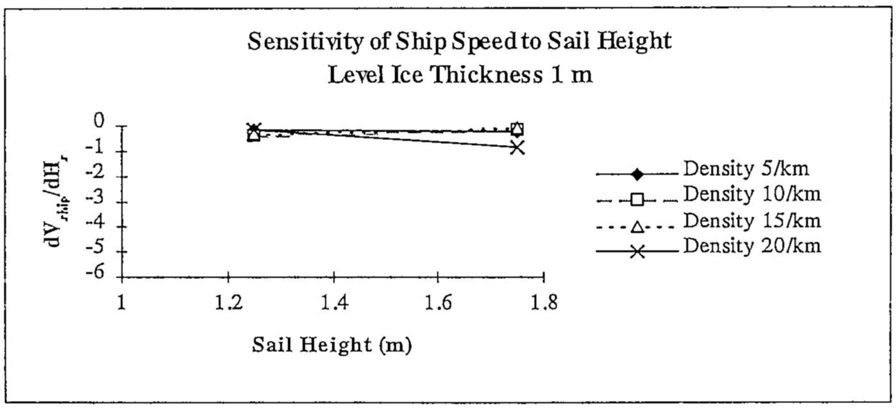


Figure 59 : Sensitivity of ship speed to sail height with ridge density as a parameter. Level ice thickness 1 m.

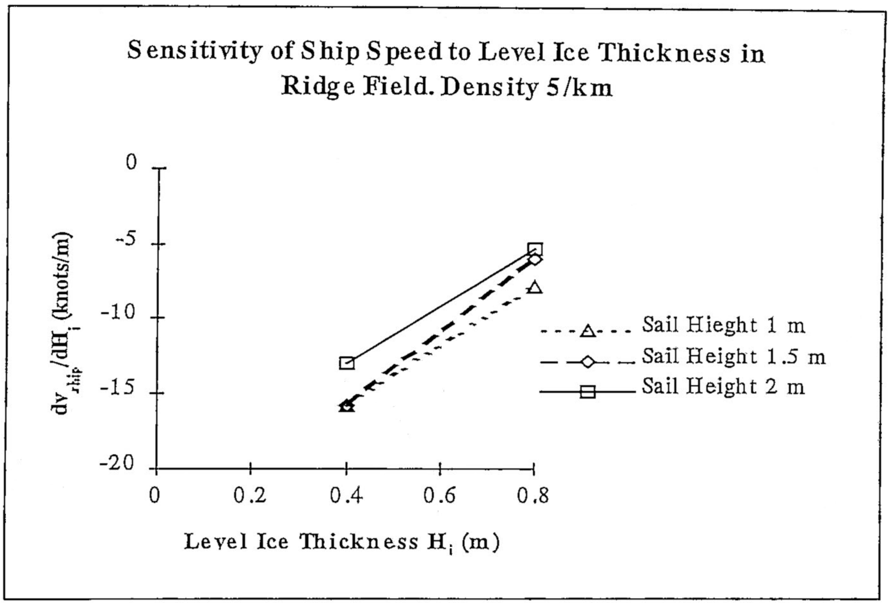


Figure 60 : Sensitivity of ship speed to level ice thickness with sail height as a parameter. Ridge density 5/km.

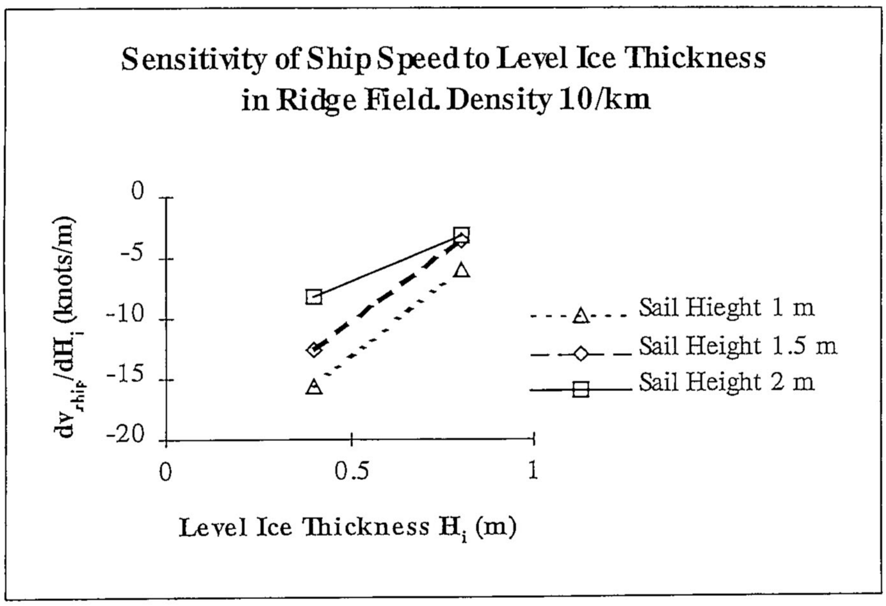


Figure 61: Sensitivity of ship speed to level ice thickness with sail height as a parameter. Ridge density 10/km.

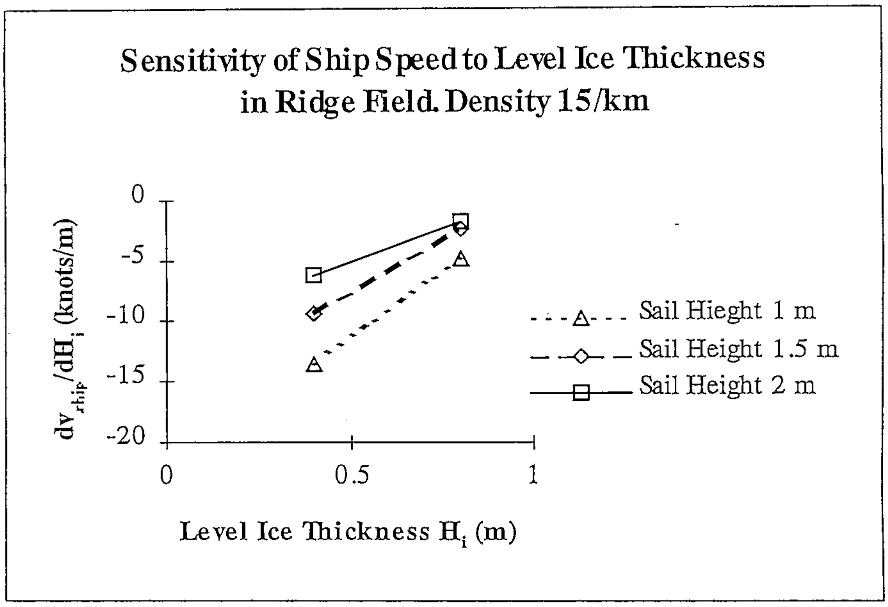


Figure 62 : Sensitivity of ship speed to level ice thickness with sail height as a parameter. Ridge density 15/km.

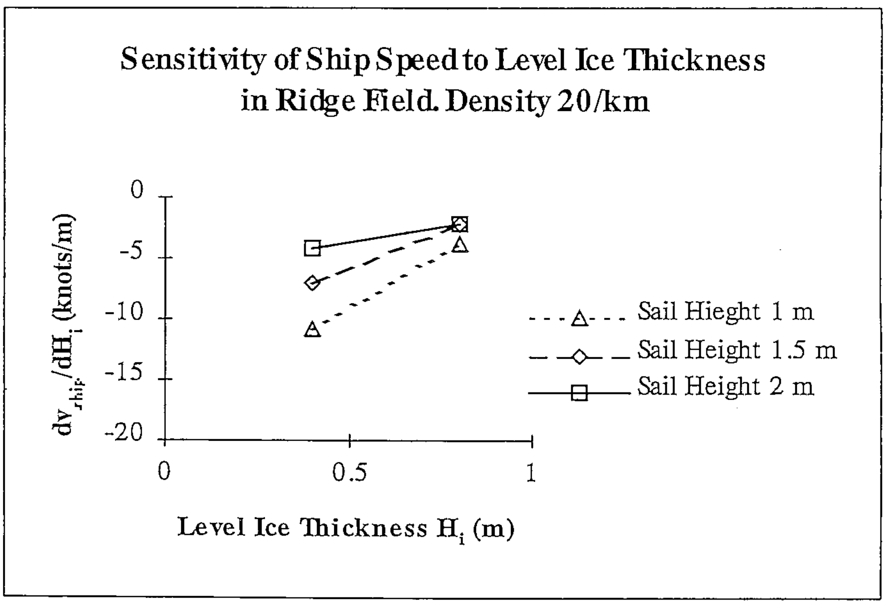


Figure 63 : Sensitivity of ship speed to level ice thickness with sail height as a parameter. Ridge density 20/km.

From these figures several points are apparent regarding the sensitivity of ship speed to ridge field conditions. In almost all cases the effect of increasing the value of the parameter decreases the change in ship speed. The only exception to this occurs for the combination of sail height 1 m, level ice thickness 0.2 m and ridge density 5/km. In this case the sensitivity of ship speed increases with ridge density. Increasing the ridge density results in a larger reduction in speed. This means small ridges in thin ice can significantly effect ship speed as their density increases.

4.4. Ridging Severity

The concept of ridging severity is introduced in an attempt to combine the sail height and ridge density into a single value which characterizes the severity of the ridge field i.e. the difficulty of navigating the ridge field. For this study ridging severity was defined to be the square of the sail height multiplied by the ridge density. This would be equivalent to defining an equivalent ice thickness for the ridge field. **Figure 64** shows a plot of the ship speed versus the ridging severity used here.

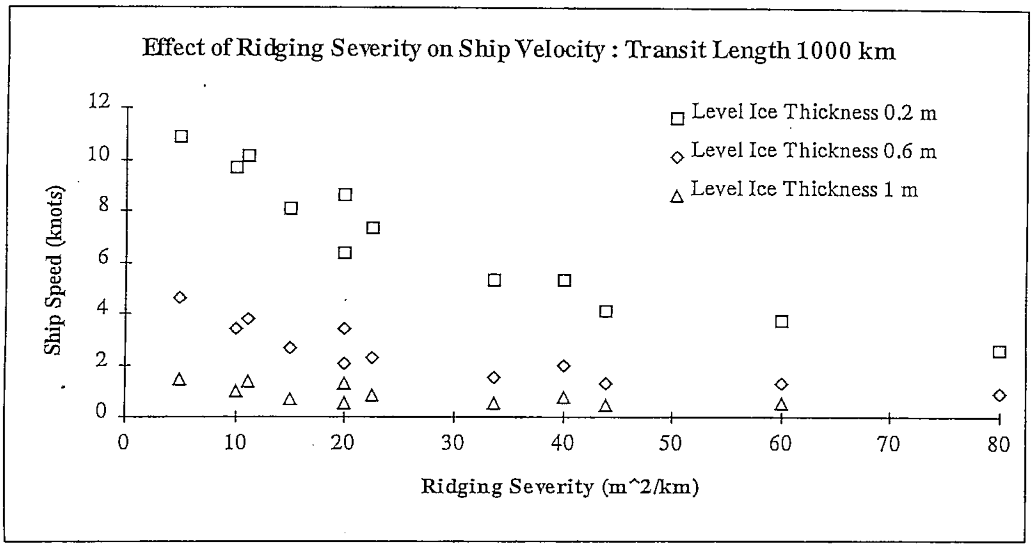


Figure 64 : Plot of ship speed versus ridging severity for the level ice thickness used.

It can be seen that for thick level ice ridging severity has little influence on speed, indicating that the ice thickness between ridges is the predominant factor in determining ship speed in thick ice. The rough nature of the curves implies that the definition of ridging severity must be refined. Nevertheless for thinner ice (0.2 and 0.6 m thickness) it is clear that a trend of decreasing ship speed with ridging severity occurs. This is a topic which should be investigated more completely as it can lead to the development of a single physically-based quantity describing the difficulty of navigation of a transit route.

5. VERIFICATION OF TRANSIT SIMULATIONS

As with any analytic method to predict ship performance the results of the analysis should be compared and verified with actual measurements of ship speeds in ice. The difficulty here is that a limited amount of data is available, particularly the lack of data regarding level ice thickness for reported transits for which average speeds have been reported. Some verification of SA-15 ship results from the program was able to be performed using data from Tsoy *et al.* In addition data from Kujala (1993) and Leiviskä (1998) regarding the velocity of *MS Kemira* as it penetrated a ridge was used to verify the form of the ridge resistance equations.

The comparison of Tsoy *et al*'s (1998) reported performance curves for an SA-15 ship in level ice, vast and giant floes (which can be considered level ice), and in its own channel to predictions from the present algorithm are shown in **Figure 65**. It can be seen that the results agree quite well, even on the basis of the limited data available. This indicates that the level ice and channel ice formulations are valid.

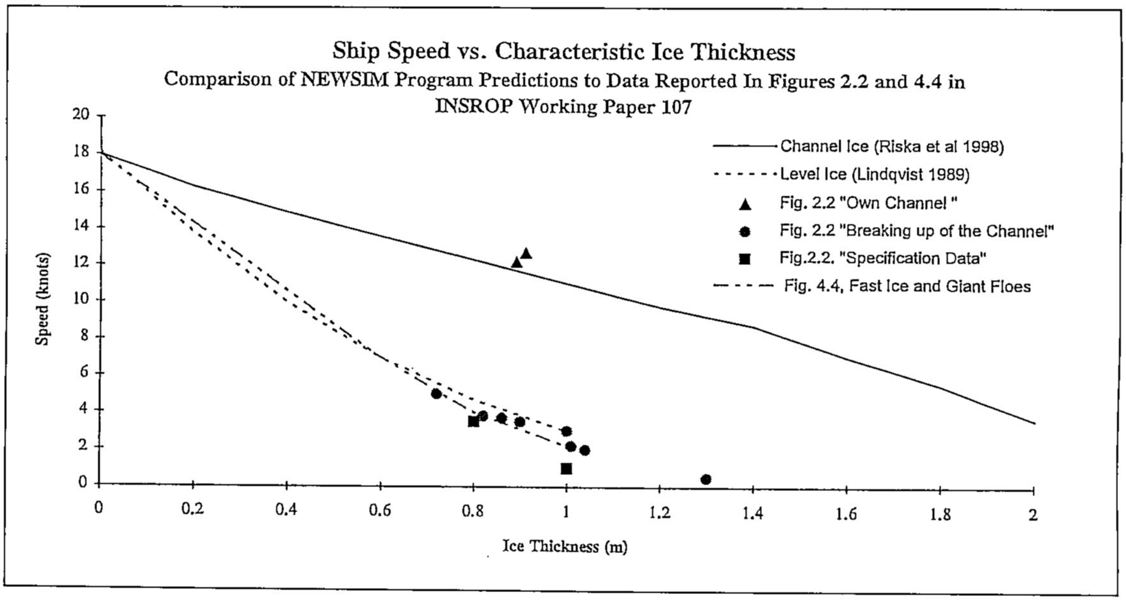


Figure 65 : Comparison of NEWSIM program predictions using Lindqvist's and Riska *et al*'s formulae to data from Tsoy *et al*, INSROP Working Paper 107, 1998, Figures 2.2 and 4.4.

Figure 66 shows the predictions for floe ice of 7/10 to 8/10 coverage in relation to Tsoy et al's (1998) data from Figure 4.4 of INSROP Working Report 107. It is clear that while the trend of decreasing ship speed with increasing ice thickness is similar (and obvious), the calculation underpredicts somewhat the actual possible speed of the vessel. This is a result of using level ice formulations for floe ice fields. This does not take into account the finite extent of such floes in the lateral direction and the divergence of broken floes that may occur as they are broken at the bow. Also the movement of the floes is not allowed. However, the underprediction seems to be of consistent value, making it possible to define a speed correction for this level of coverage. Here this speed correction is at maximum +2 knots.

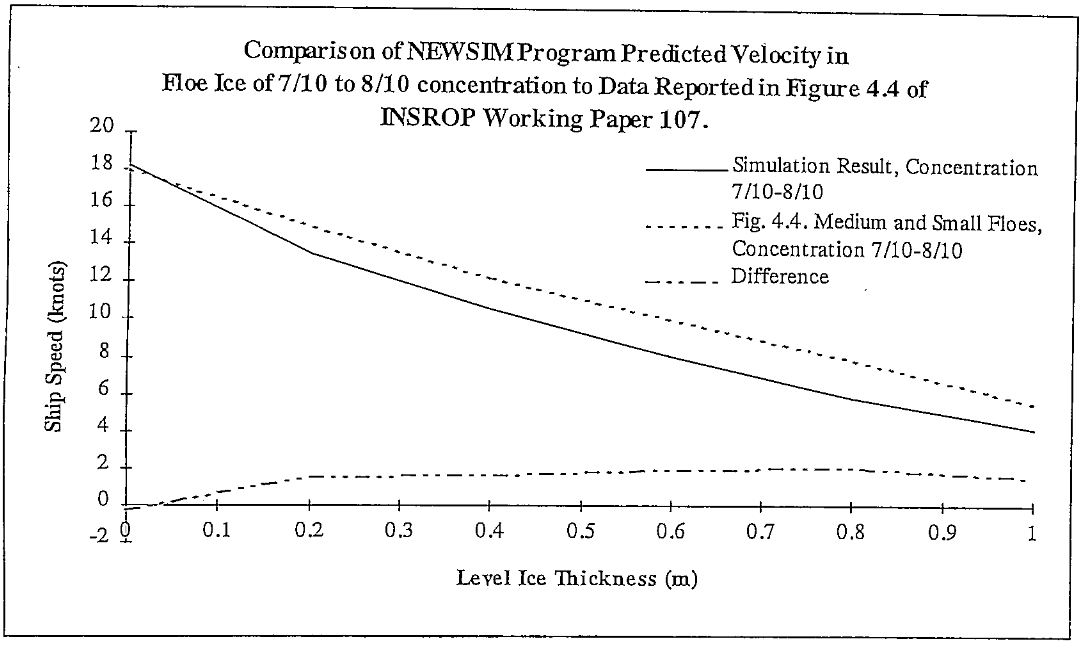


Figure 66 : Comparison of Tsoy *et al*'s data from INSROP Working Paper 107, Fig.4.4 to NEWSIM program predictions for ship speed in floe ice of 7/10-8/10 coverage.

Data from Kujala (1994) regarding MS Kemira and the speed versus time as this ship penetrated a ridge from Figure 2 in Leiviskä (1998) were used to verify the form of the ridge resistance equations. Only the form of the equations could be verified as the geometric details of the actual ridge were unknown (the sail size was estimated visually). **Figure 67** shows the comparison of the calculated prediction using an estimated ridge depth of 5 m and level ice thickness of 0.25 m with the measured data. It appears that the form of the ridge resistance equations is valid.

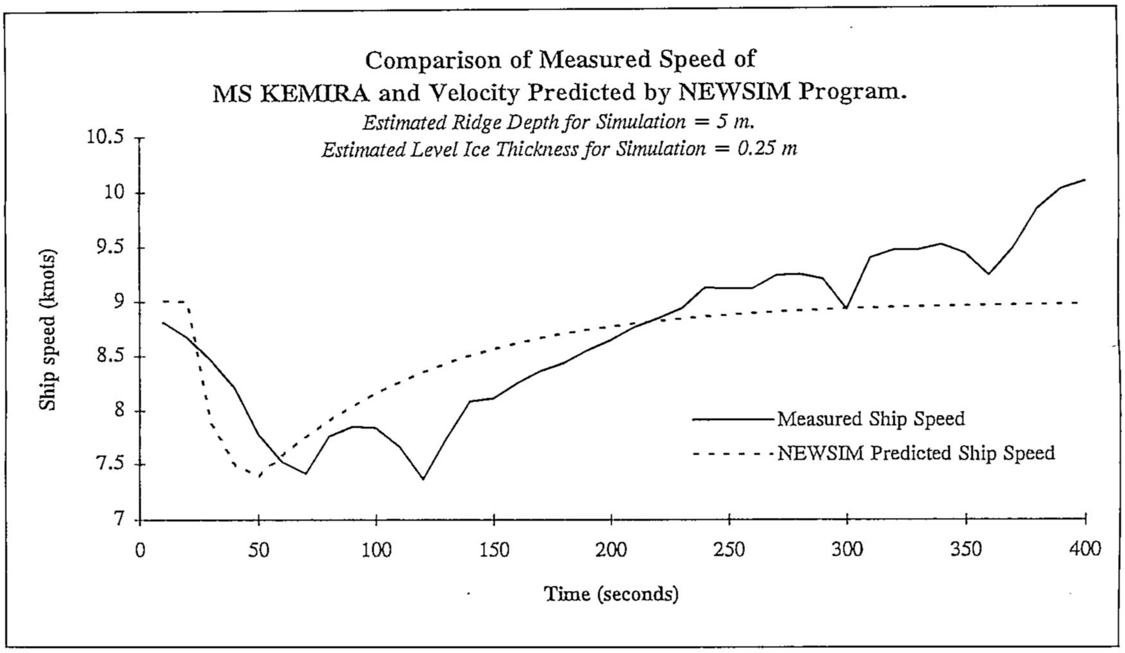


Figure 67 : Comparison of measured ship speed in a ridge and ship speed predicted by algorithm.

6. CONCLUSION

Helsinki University of Technology's Ship Laboratory has developed a ship transit simulation algorithm to predict ship performance in ice covered routes. This report has shown the application of this program to the performance of an SA-15 arctic cargo vessel for a variety of ice conditions. From the results it is clear that level ice results are valid while floe ice results tend to underpredict the ship speed. This is due to the lack of any applicable research into ship resistance in floe ice fields. The purpose of the study was not to predict the performance of SA-15 ships but rather to study the effect of ice conditions on ship performance. In this context the floe ice underpredictions are not significant as they appear from the validation data to be constant i.e. sensitivity of ship performance to ice condition's is not affected. Further validation of the results from the program should be conducted as new data is made available. Updating and verification of the resistance formulae used should be carried out continuously. At the current time the program is a good first attempt to examine ship performance with a view towards what the ship is capable of achieving, rather than to what it is currently limited. In addition the program is capable of being used as a design tool by examining how changes in the ship dimensions affect the ship performance.

Sensitivity analysis of floe ice and ridged ice fields indicate that a simple statement regarding the influence of the various parameters describing the ice conditions is not possible. The only generally applicable result is that the sensitivity of ship speed decreases with increases in the amount of ice present, as measured by the coverage, sail height and ice thickness. Even this statement has shown one exception - in ridge fields having 0.2 m level ice thickness, the sensitivity increased with increasing ridge density. Clearly the interaction of ice conditions is a complicated issue and makes the assessment of ship performance for a variety of ice conditions difficult.

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APPENDIX A : INPUT PARAMETERS FOR SA-15 SHIP AND CONSTANT ICE PARAMETERS USED IN SIMULATIONS

Values for ship parameters were taken from Tsoy *et al* , 1998.

Length Between Perpendiculars (m)	169.6
Length of Bow Region (m)	47
Length of Parallel Midbody (m)	57
Beam (m)	24.5
Draught (m)	9
Stem Angle (degrees)	30
Waterline Entrance Angle (degrees)	25
Maximum Open Water Speed (m/s)	9.35
Number of Propellers	1
Propellor Diameter (m)	5.6
Shaft Power (kW)	13900
Longitudinal Center of Buoyancy (m, positive forward of amidships)	0
Block Coefficient	.74
Midship Coefficient	.94
Density of Ice (kg/m^3)	880
Ice Bending Strength (Pa)	$0.45 \cdot 10^6$
Ice Compressive Strength (Pa)	$5 \cdot 10^6$
Ice Elastic Modulus (Pa)	$5 \cdot 10^9$
Ship-Ice Friction Coefficient	0.16
Ratio of thickness in Consolidated Layer to Level Ice Thickness	1.8
Speed of Converging Ice Between Ridges (m/s)	0

APPENDIX B : FLOE ICE AVERAGE SPEEDS USED IN SENSITIVITY ANALYSIS

Level Ice Thickness 0.2m

Coverage	d=20	d=40	d=60	d=80	d=100	d=120	d=140	d=160	d=180	d=200
1	15.69	16.06	16.19	16.25	16.3	16.33	16.35	16.36	16.37	16.39
2	14.9	15.36	15.56	15.67	15.74	15.79	15.82	15.85	15.88	15.89
3	14.38	14.79	15.01	15.14	15.23	15.29	15.33	15.37	15.4	15.42
4	14.06	14.33	14.52	14.66	14.75	14.81	14.87	14.91	14.94	14.97
5	13.85	13.96	14.1	14.22	14.31	14.37	14.43	14.47	14.51	14.54
6	13.72	13.73	13.79	13.87	13.94	13.99	14.04	14.07	14.11	14.13
7	13.57	13.56	13.57	13.6	13.63	13.67	13.69	13.72	13.75	13.77
8	13.41	13.41	13.4	13.4	13.4	13.41	13.42	13.43	13.45	13.46
9	13.24	13.24	13.24	13.24	13.24	13.23	13.23	13.23	13.23	13.23

Level Ice Thickness 0.4 m

Coverage	d=20	d=40	d=60	d=80	d=100	d=120	d=140	d=160	d=180	d=200
1	14.508	15.191	15.449	15.574	15.648	15.708	15.746	15.767	15.797	15.809
2	13.039	13.861	14.205	14.421	14.542	14.626	14.699	14.744	14.771	14.802
3	12.111	12.803	13.175	13.385	13.547	13.659	13.729	13.8	13.837	13.877
4	11.52	11.973	12.287	12.509	12.658	12.771	12.862	12.924	12.974	13.021
5	11.132	11.31	11.546	11.722	11.863	11.959	12.064	12.127	12.186	12.225
6	10.867	10.891	10.994	11.107	11.216	11.291	11.358	11.42	11.479	11.52
7	10.582	10.564	10.583	10.619	10.675	10.725	10.776	10.817	10.853	10.886
8	10.279	10.274	10.261	10.256	10.265	10.276	10.292	10.311	10.333	10.352
9	9.97	9.972	9.97	9.964	9.96	9.956	9.954	9.953	9.954	9.956

Level Ice Thickness 0.6 m

Coverage	d=20	d=40	d=60	d=80	d=100	d=120	d=140	d=160	d=180	d=200
1	13.411	14.354	14.691	14.868	14.993	15.052	15.094	15.14	15.156	15.164
2	11.367	12.427	12.923	13.179	13.339	13.456	13.527	13.586	13.625	13.652
3	10.148	10.979	11.439	11.741	11.936	12.06	12.152	12.22	12.277	12.325
4	9.364	9.885	10.263	10.52	10.718	10.86	10.949	11.031	11.093	11.137
5	8.838	9.048	9.302	9.509	9.693	9.799	9.907	9.982	10.035	10.088
6	8.457	8.486	8.603	8.735	8.838	8.941	9.021	9.078	9.139	9.177
7	8.07	8.051	8.069	8.112	8.169	8.23	8.277	8.321	8.358	8.399
8	7.67	7.664	7.652	7.648	7.655	7.668	7.688	7.708	7.729	7.748
9	7.271	7.275	7.271	7.266	7.262	7.259	7.257	7.257	7.255	7.261

Level Ice Thickness 0.8 m

Coverage	d=20'	d=40	d=60	d=80	d=100	d=120	d=140	d=160	d=180	d=200
1	12.366	13.485	13.954	14.167	14.285	14.354	14.401	14.435	14.449	14.461
2	9.886	11.094	11.662	11.948	12.124	12.244	12.328	12.377	12.401	12.427
3	8.46	9.344	9.865	10.174	10.382	10.525	10.612	10.671	10.715	10.741
4	7.553	8.084	8.484	8.744	8.941	9.067	9.164	9.236	9.277	9.336
5	6.939	7.146	7.405	7.607	7.759	7.87	7.958	8.028	8.083	8.115
6	6.473	6.506	6.617	6.734	6.838	6.915	6.989	7.048	7.083	7.127
7	6.02	6.003	6.019	6.06	6.103	6.155	6.194	6.234	6.267	6.298
8	5.565	5.56	5.547	5.544	5.551	5.56	5.574	5.59	5.606	5.62
9	5.124	5.126	5.123	5.119	5.115	5.111	5.109	5.108	5.109	5.108

Level Ice Thickness 1 m

	Floe Diameter									
Coverage	20	40	60	80	100	120	140	160	180	200
1	11.364	12.67	13.163	13.414	13.513	13.575	13.637	13.653	13.622	13.589
2	8.564	9.84	10.416	10.757	10.927	11	11.084	11.078	11.076	11.059
3	7.005	7.894	8.407	8.689	8.869	8.996	9.047	9.087	9.086	9.088
4	6.048	6.529	6.905	7.134	7.296	7.39	7.448	7.498	7.498	7.517
5	5.377	5.564	5.776	5.941	6.053	6.134	6.192	6.235	6.245	6.262
6	4.856	4.881	4.968	5.05	5.123	5.18	5.213	5.249	5.27	5.283
7	4.364	4.345	4.35	4.374	4.401	4.428	4.452	4.468	4.487	4.498
8	3.884	3.877	3.863	3.855	3.852	3.856	3.859	3.865	3.87	3.875
9	3.427	3.428	3.424	3.419	3.415	3.41	3.406	3.402	3.4	3.4

APPENDIX C : RIDGE FIELD AVERAGE SPEEDS USED IN SENSITIVITY ANALYSIS

Sail Height	1m			
Level Ice Thickness (m)	Density 5/km	Density 10/km	Density 15/km	Density 20/km
0.2	10.892	9.631	8.094	6.344
0.6	4.57	3.365	2.631	2.043
1	1.448	0.974	0.696	0.505

Sail Height	1.5 m			
Level Ice Thickness (m)	Density 5/km	Density 10/km	Density 15/km	Density 20/km
0.2	10.124	7.32	5.253	4.065
0.6	3.761	2.276	1.499	1.268
1	1.374	0.798	0.558	0.416

Sail Height	2m			
Level Ice Thickness (m)	Density 5/km	Density 10/km	Density 15/km	Density 20/km
0.2	8.626	5.257	3.708	2.529
0.6	3.407	1.968	1.247	0.889
1	1.25	0.727	0.501	

Review

of the report "Simulation of ship transit through ice" (Authors Matthew Patey and Kaj Riska)

The report under consideration is devoted to the problem of simulating ship motion in ice. The problem has been studied by different organisations and specialists both in Russia and abroad for quite a long time, but it still not lost its urgency. The problem is rather difficult because of many factors involved in its solution and, so, any contribution to it should be welcome. Development of a program for predicting the average speed of ice-breaking vessel operating on the route with the specified ice conditions will make it possible to solve two interrelated problems as follows:

- to asses the effects of ice conditions between the starting and final points of the route on the average speed depending on a propulsion power;
- to evaluate the influence of the characteristics of operating and/or ship to be designed on her technical and economic effectiveness on the route.

The most difficult problem is to determine ice parameters on the route between its starting and final points. The navigator makes his best to find the route with the easiest ice conditions, using ice data provided by satellites and air reconnaissance. For the short range reconnaissance the helicopters are used. Thus, the subjective factor is, sort of, superimposed on the objective character of ice conditions.

Consequently, simulation of ice conditions is an independent, rather difficult problem. The paper under consideration is devoted to the problem of determining ship speeds under the specified ice conditions and, thus, solves an independent task.

May be, we view this problem in a different light, since we bear in mind the problems facing our institute. In contrast to the organisations directly involved in operation of ships and icebreakers and for whom the principal merit of the model is its suitability for planning marine operations, we, as an organisation providing research support to ships and icebreaker construction, think the model's suitability for substantiating the principal characteristics of these ships to be a crucial factor in its evaluation.

We will consider the presented paper from this very point of view, basing on our Institute's studies in this area.

The paper under review deals with a problem of influence of two typical ice formations , viz. broken ice and level ice-ridges combination on ship speed. Dry-cargo ship of "Norilsk" type is taken as an example. The following parameters of these formations were investigated:

- for broken ice - concentration, dimensions and thickness;
- for level ice-ridges combination - level ice thickness, ice field dimensions, ridge sail height, ridge frequency per 1 km. These problems were studied by the authors rather thoroughly by varying the investigated parameters in a wide range.

However, when speaking about the ultimate aim that one should try to achieve in developing the speed prediction program, first of all, the importance of taking into account all the parameters having influence on speed should be stressed.

The thickness of snow cover both on level ice and in ridges has a great effect on speed. Compression is even more significant factor. There is no doubt that both these factors should be taken into account in the models to be developed.

At the same time, the authors of the reviewed paper were absolutely right in paying special attention to ship motion in broken ice, since this operation condition is crucial to the accuracy of simulation.

The program is based on the assumption that any ice field commensurable with the length of the ship is broken in the same pattern as a compact level ice field of the same thickness. When we have 9-10 concentration (90-100%) the resistance in broken ice proves to be equal to the resistance in level ice and independent of the ice floes diameter. These predictions contradict to both the mechanics of the process taking place during ship motion and earlier obtained test results. When running in broken ice the ship moves ice floes apart in the horizontal plane, while compact ice field is broken in vertical plane. If stem rake is 25-30^0 , the increase of the waterline entrance half angle results in resistance decrease in level ice, while the resistance in broken ice increases in this case.
The dependence of icebreaker resistance in 1.2m thick broken ice with 9-10 concentration is presented (Fig.1). The dependence is derived using full scale observations (V.I. Kashtelyan, I.I. Poznyak, A.Ya. Ryvlin "Ice resistance to ship motion", 1968).

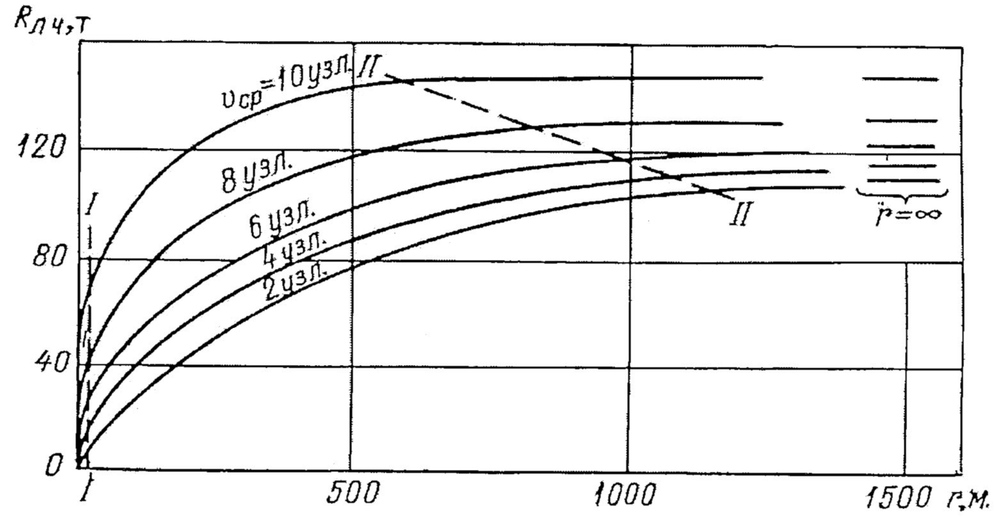

Fig.1. Dependence of resistance in ice - ($R_{л.ч.}$) on ice floe dimensions (r)
Obviously, the prediction results obtained by using the program under consideration and the presented full scale observations data contradict to each other. Even in vast ice fields (r>1000 m) if the ship runs in less than 100-250 m from the edge, resistance may be reduced 1.2-1.5 times depending on speed.
In conclusion, I think it should be stressed that the reviewed paper, certainly, contributes to solving the problem of simulating ship motion in ice. The present review offers some areas of future research that will make it possible to approach the task of the developed models practical application for solving both operational and design problems.

Reviewer

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the Chief Engineer
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Authors' Response to Reviewer's Comments

We thank the reviewer for his comments and insight regarding the report. All of his comments are, we feel, justified and we agree that there are difficulties with the current version of the program which should be dealt with in future research.

The reviewer has made several points to which attention must be drawn :

1. The thickness of snow cover on both level ice and in ridges is not taken into consideration in this program. This has a significant effect on the speed.
2. Compression is not taken into account, which has an even more significant influence on the speed.
3. The mechanics of the interaction between ice floes and the ship are not properly considered in the program and result in contradictory conclusions to those from earlier test results.

Each of these points will be addressed separately :

1. Effect of snow cover

The effect of snow cover was not taken into consideration in the program and clearly should be considered. One possible method of doing this would be to consider the snow cover as added ice thickness, i.e. 10 cm of snow could be considered as 5 cm of added ice thickness. However, more exact methods accounting for the physical properties of snow are desirable and should be researched.

2. Effect of Compression

Certainly compression has a very significant bearing on the average speed of a vessel in ice. Research conducted during the early 1990s (see references below) into the effect of compression on ship resistance in ice was incorporated into earlier versions of the program. Ice compression was factored into the resistance of the level ice between ridges through the use of a resistance multiplier dependent on ice velocity against the sides of the ship. This ice speed was an input variable, given in meters per second. However, ice compression observations in reality are typically given by visual observations on a qualititative scale of 0 to 3, i.e. a "ball" scale, 0 representing no compression, 3 representing very severe compression. The difficulty in realistically assessing ice compression is converting the qualitative observations given in balls to a meaningful physical unit. Furthermore the compression process is not well understood in terms of available driving forces and limiting values of ice loads. Especially in broken ice fields with various floes sizes and geometries the analytical treatment quickly becomes quite complicated. Some research has been conducted in the area of the effect of compression on ship resistance in broken or floe ice fields, but it is limited (e.g. Juurmaa *et al*, 1998). Further research and greater emphasis on the compression problem is necessary to properly evaluate and verify the effect of compression on the ice-going ability of ships.

3. Mechanics of the Interaction between the Ship and Floe Ice

The authors' are aware of the questionable nature of using level ice resistance formulations in evaluating ship speeds in floe ice fields, as mentioned in section 4.2 of the report. The problem of ship resistance in floe ice fields, as with compression, is inadequately understood at the moment. The heterogeneity of floe or broken ice fields on a scale comparable to that of the ship makes the problem complicated from the point of view of assessing forces on and the resistance of the ship. But more importantly the difference in the nature of the breaking of the ice field based on coverage is not captured by the use of level ice resistance equations. As pointed out by the reviewer, floes in a low or moderate coverage broken ice field move apart in the horizontal plane while in compact floe fields of higher coverage the field is broken in a vertical plane. It is this three dimensional aspect of the interaction which is lacking. The finite nature of the ice floes must be taken into consideration in the ship-ice interaction. This should be addressed more thoroughly in future research.

In conclusion, the authors agree with the reviewer's comments and hope to incorporate his suggestions into future versions of the ice transit simulation program.

Compressive Ice References

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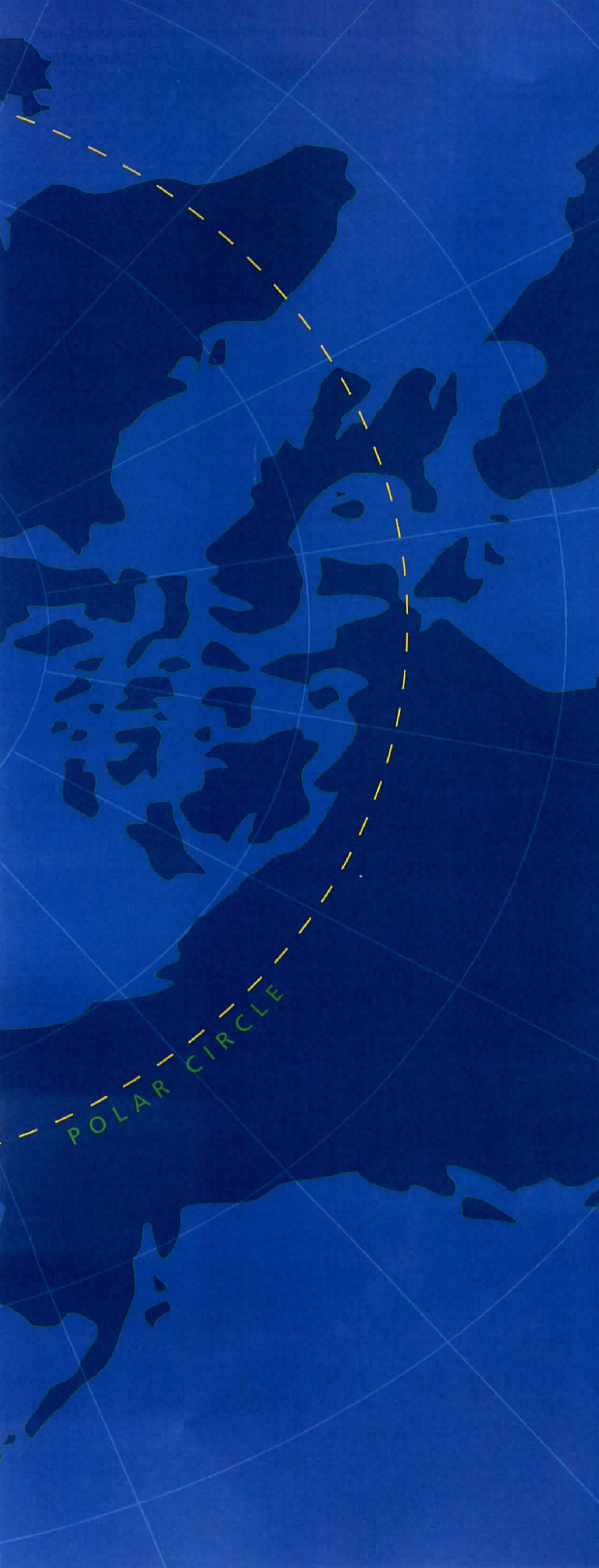
Ship resistance in compressive floe ice

Juurmaa, K. *et al.* "Influence of Ice Compression on Feasible Navigation on the NSR, Part II". INSROP WP-8.110-1998, I.1.8. 1998.



The three main cooperating institutions of INSROP

Ship & Ocean Foundation (SOF), Tokyo, Japan.

SOF was established in 1975 as a non-profit organization to advance modernization and rationalization of Japan's shipbuilding and related industries, and to give assistance to non-profit organizations associated with these industries. SOF is provided with operation funds by the Nippon Foundation, the world's largest foundation operated with revenue from motorboat racing. An integral part of SOF, the Tsukuba Institute, carries out experimental research into ocean environment protection and ocean development.

Central Marine Research & Design Institute (CNIIMF), St. Petersburg, Russia.

CNIIMF was founded in 1929. The institute's research focus is applied and technological with four main goals: the improvment of merchant fleet efficiency; shipping safety; technical development of the merchant fleet; and design support for future fleet development. CNIIMF was a Russian state institution up to 1993, when it was converted into a stockholding company.

The Fridtjof Nansen Institute (FNI), Lysaker, Norway.

FNI was founded in 1958 and is based at Polhøgda, the home of Fridtjof Nansen, famous Norwegian polar explorer, scientist, humanist and statesman. The institute spesializes in applied social science research, with special focus on international resource and environmental management. In addition to INSROP, the research is organized in six integrated programmes. Typical of FNI research is a multidisciplinary approach, entailing extensive cooperation with other research institutions both at home and abroad. The INSROP Secretariat is located at FNI.