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SAFETY DISTANCE DURING ESCORT AND CONVOY BASED ON CHANNEL BREAKOUT SIMULATION AND MODEL TESTS

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ABSTRACT

Escort and convoy are typical operations when a merchant ship navigates in ice beyond its own ice-going capability. In such scenarios, a safety distance between the front ship and the following ship is maintained. The leading vessel may suddenly decelerate or even come to a halt if it encounters a heavy ridge or thick ice floe. When this happens, the following ship needs to take actions to avoid collision with the leading vessel. An evasive operation for such collision avoidance is to break out of the channel. The safety distance can be defined as the minimum distance which is needed for successful collision avoidance. This depends on various parameters such as ice thickness, ship speed, channel width, the ship's icebreaking capability and its manoeuvrability in ice. This paper investigates safety distance during escort and convoy by model-scale experiments and numerical simulation of a ship breaking out of ice channel. The experiments are carried out at Aalto Ice Tank and the numerical simulations are conducted via the in-house simulation software package of Aalto University Marine Technology group. The dependencies of the safety distance on ice thickness, channel width and initial speed are identified via multiple experimental and simulation runs. The simulation proves to provide accurate estimation on breakout distance through comparison with model test results, and reveals the influence of ice thickness, channel width and initial speed on the breakout distance.

Keywords: Safety distance; Escort; Ice channel; Ice navigation; Ship performance in ice; Numerical simulation.

1. INTRODUCTION

Escort and convoy operations with icebreaker assistance are often used and even required when a ship enters ice-covered sea areas beyond its own icebreaking capability [1]. In such scenarios, the assisted ship aims to follow the leading vessel at a distance long enough for safety, but short enough so that the channel behind the leading vessel does not close much if the ice field is dynamic [2]. In case of an emergency, e.g. when the leading vessel comes to a halt due to a heavy ridge, the following ship needs to take immediate action to avoid collision. Such actions can be braking the vessel by reversing the propulsor thrust or evasively breaking out of the channel with rudder or pod action [3]. Accidents may happen if the following ship cannot stop or leave the channel before reaching the front ship [4]. For instance, a bow-stern collision in an ice convoy operation in the Gulf of Finland in 2006 led to the release of oil in the sea ice environment, with large impacts to the marine and coastal areas near Tallinn, Estonia [5].

A key parameter for escort and convoy safety is the distance needed for the following ship to avoid collision through stopping or breakout. Previous authors have investigated the operational distance at which vessels follow a leading vessel in escort and convoy operations based on data from the Automatic Identification System and sea ice data [6], while others have proposed a statistical model to determine the safety distance [7].

This paper deploys an in-house simulation tool developed at Aalto University Marine Technology group [8] to simulate a ship breaking out of ice channel. The tool is applied to a 92-metre double-acting general cargo ship to estimate the breakout distance and investigate its dependence on various parameters. This paper also reports model tests carried out in Aalto Ice Tank with a 1:16.8 scale model to validate the simulation.

2. Definitions

The breakout distance in a channel can be defined from the location of manoeuvring started to the location where the ship reaches furthest in the channel. This is sketched in Figure 1. This distance depends only on ice conditions and the manoeuvrability of the following ship. Additionally, we here define the safety distance as the minimum escort or convoy distance to avoid collision, considering also the time needed to initiate evasive action, namely the reaction distance, and the distance that the

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front ship has travelled before it becomes stationary, namely the *deceleration distance*. This is illustrated in Figure 1. Following these definitions, the safe convoy/escort distance is the distance between the leading and following ship which leads to

$$d_{convoy} + d_{deceleration} \geq d_{reaction} + d_{breakout/stop} \quad (1)$$

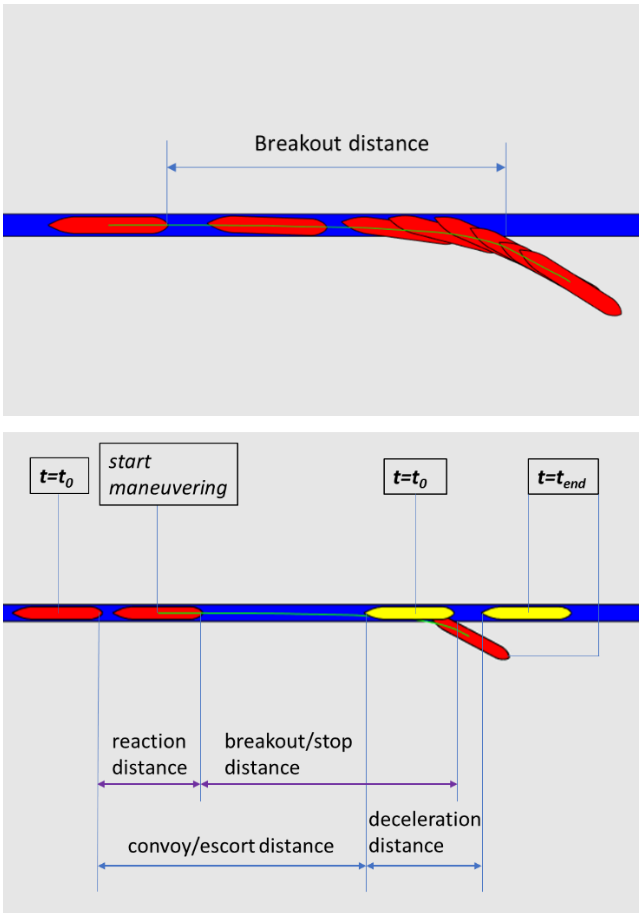

Figure 1. Illustration of channel breakout and definition of breakout distance and safety distance.

3. SIMULATION METHOD

The Aalto Ship-Operation-in-Ice Simulator (ASOIS) was developed as a ship-scale simulation tool combining various submodels to compute different icebreaking processes. It is developed primarily as a manoeuvring simulator which estimates ship manoeuvrability in level ice [8]. The simulator essentially solves the ship motion equations subject to the instantaneous ice and hydrodynamic forces in four degrees of freedom, i.e.

$$\begin{bmatrix} M_{ship} & 0 & 0 & 0 \\ 0 & M_{ship} & 0 & 0 \\ 0 & 0 & I_{xx} & 0 \\ 0 & 0 & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} \dot{v}_x - \omega_z v_y \\ \dot{v}_y + \omega_z v_x \\ \dot{\omega}_x \\ \dot{\omega}_z \end{bmatrix} = \mathbf{F_{ice}} + \mathbf{T_{net}} + \mathbf{F_{rud}} + \mathbf{F_{hyd}} \quad (2)$$

where the left-hand side of the equation represents the mass and acceleration matrix in the ship coordinate system, while on the right-hand side of the equation the terms denote ice force, propeller thrust, rudder force and hydrodynamic force. Hydrodynamic forces are calculated with linear coefficients estimated empirically. The contact between the ship and the ice sheet is solved stepwise numerically, with the ice sheet being updated each time a bending failure occurs. The simulation is carried out in ship-scale without the need to resolve material level details so that it runs fast.

The simulator has been applied to simulate ship turning in level ice [8] and ship going through narrow ice channel [9]. In this paper, the simulator is applied to simulate a ship breaking out of channel to estimate breakout distance. The ship starts at an initial velocity v_0 in an ice-free channel in the beginning of the simulation, and turns the azimuth thruster to a high angle to break out. The simulation stops once the ship is completely out of the channel or when the speed drops to zero. The furthest position of the ship in the channel is then extracted for the calculation of breakout distance.

A double-acting ship *Infuture* is used as the sample ship in this paper. *Infuture* is a river-sea going general cargo ship with Finnish-Swedish Ice Class IA Super, which operates astern when independently navigating in ice. The ship is designed to break 60 cm river ice at 2 knots. It has an icebreaking stern combined with long parallel midbody and an azimuth thruster installed at the stern. The main parameters are listed in Table 1.

Table 1. Ship particulars

	Full-	Model-scale	Unit
Length overall	92.5	5.50	m
Breadth	12.6	0.75	m
Depth	8	0.48	m
Draught	4.45	0.26	m
Displacement	4053	0.852	t
Open water service speed	11.5	2.80	m/s
Full engine power	1678	0.09	kW

Two sets of simulations were conducted:

1. **The validation set** simulates the experiments to validate the model predictions. The input parameters (initial speed, propeller force and ice properties) are set the same as those measured in the experiments, presented later in Section 3, so that $\mathbf{T_{net}}$ and $\mathbf{F_{rud}}$ in Eq. (2) are predefined**.** The ship is set free to run and turn. The simulated ship trajectories are compared with the measured ones to check consistency.

2. **The investigation set** simulates the ship in full scale with different ice thicknesses, channel widths and initial speeds to identify the influence on breakout distance. The assumed scenario starts with the ship being convoyed or escorted by a leading vessel with a certain speed. Then, when the leading vessel comes to a halt, the following ship turns the pod to 90 degrees and power to the maximum which maximizes the breakout capability thereby minimizing the breakout distance. A constant 80% of full engine power is set throughout the simulation. Three convoy speeds are set as the initial speed of

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channel breakout. Table 2 summarizes the test setups of the simulation runs in the investigation simulation set.

Table 2. Parameters of the investigation simulation set

Parameters	Value
Flexural strength	500 kPa
Compressive strength	1.5 MPa
Young's modulus	2 GPa
Ice thickness	40, 60, 80 cm
Propulsion	1342 kW
Pod angle	90 deg
Initial Speed	8, 10, 12 knots
Channel width	1.1, 1.3 ,1.5, 2 ship breadth

4. MODEL TESTS

Experiments were carried out at Aalto Ice Tank with a self-propelled remote-controlled 1:16.8 scale model of the *Infuture* vessel in fine-grained model ice [10]. Two breakout tests were conducted with pod angles of 45 and 60 degrees. The reason that smaller pod angles than 90 degrees are chosen is that for validation purpose, it is preferred that the ship can break out completely. With 90 degrees pod angle the ship has no propulsion forward, therefore may stop already before it leaves channel. The target ice thickness and flexural strength are 40 cm and 500 kPa in full scale, which correspond to 29.8 kPa and 24 mm in model scale. The test parameters including measured model ice properties are summarized in Table 3. A remote control and data acquisition station is placed on the bridge at one side of the tank (see Figure 2). Before the breakout tests, the model ship was used to create two ice channels. The breakout tests were then carried out in the self-made ice channels (this procedure was also implemented in the simulation runs). The channels are almost ice-free as shown in Figure 2, which is also often the case in escort scenarios with modern icebreakers being able to clear most of the ice in the channel [11].

In each test run, the model accelerated in the channel to cruising speed. The azimuth thruster was then turned to the target angle to initiate breakout. The propeller speed was kept constant through the runs for ease of comparison with simulations. The realized delivered powers were 115% to 130% of the scaled engine nominal power, with the excess due to intentional emergency overloading, powerline inertia and compensating for lower model propeller efficiency. The test run was stopped when the ship was completely out of the channel. Figure 3 presents a photo of the ship breaking out of a channel.

The control commands and measured propulsion data were transmitted through radio communication. The model ship was instrumented to record propulsor thrust in longitudinal and transversal direction, propeller speed, propulsion power and thruster angle. The thrust deduction coefficient was measured in open water channel. The position of the ship in 6D was tracked with a motion tracking system using video cameras, based on which ship speed and position relative to the channel can be calculated.

Figure 2. Model ship and ice channel before breakout test starts

Figure 3. Model ship Infuture breaking out of channel

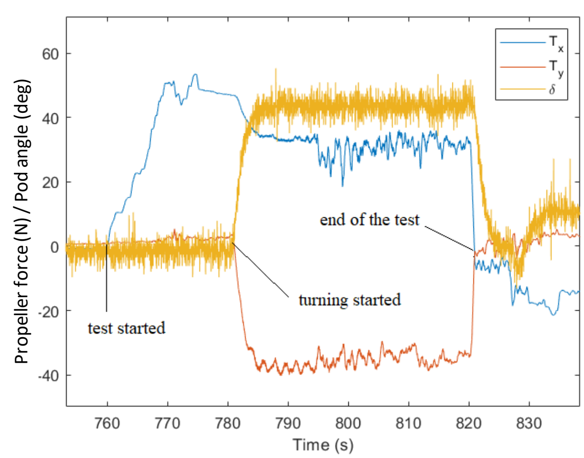

Figure 4. Example of propeller force and pod angle signals during channel breakout test (refer to Table 3 for test condition parameters, pod angle 45 deg)

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In the simulation runs, the measured force signals are fed to the simulation to keep consistency. Figure 4 gives an example of the measured propeller force in longitudinal and transversal direction as well as the pod angle. The initial condition of the simulations is set to correspond to the conditions in the model test when the pod starts to turn (see Figure 4). All the input parameters are measured so no assumptions on the inputs or empirical coefficients need to be made in the simulations.

Table 3. Parameters of model test runs

Parameters	Value
Flexural strength	30.7 kPa
Compressive strength	25.1 kPa
Young's modulus	62.8 MPa
Ice thickness	23 mm
Propulsion	~100 W
Pod angle	45, 60 deg
Speed when pod starts to turn	0.617, 0.545m/s
Ice channel	Self-made

5. RESULTS AND DISCUSSION

5.1. Comparison between simulation and measurement

In the validation set of simulations, the two model test scenarios were simulated with the input parameters obtained from the test measurement. Figure 5 compares the simulated and experimental vessel trajectories. The ending point is the location where the ship gets completely out of the channel. It can be observed that the distances from the starting point to the ending point between simulation and measurement are very similar, which is shown in Table 4 as breakout distance. The exit angles, however, differed: the simulation ship turns less than the model ship. The time needed to break out of the channel is shown in Table 4, whereas the time histories of the ship speed are plotted in Figure 5. These show that with a 45-degree thruster angle, the simulation predicts substantially higher vessel speed and shorter breakout time than those realized in the experiments. Better agreement is achieved with the 60-degree pod angle case.

Overall, the simulation model provided accurate estimates of the breakout distance despite differences in speeds and exit angles. This supports the applicability of the simulation model for analysis of channel breakout and safety distance evaluation in escort and convoy operations.

5.2. Dependence of breakout distance on ice thickness, channel width and speed

In the investigation set of the simulation runs, the dependencies of breakout distance on ice thickness, channel width and speed of the following vessel are investigated. Figure 7 presents the simulated trajectories with channel width being 1.1 times of the ship breadth, initial speed of 12 knots and ice thickness 0.4 m, 0.6 m and 0.8 m. The ending points are either the locations where the ship gets completely out of the channel, or the location where the ship completely stops. The breakout/stopping distances along the channel are 235 m, 268 m and 393 m. It can be observed that it gets more difficult for the

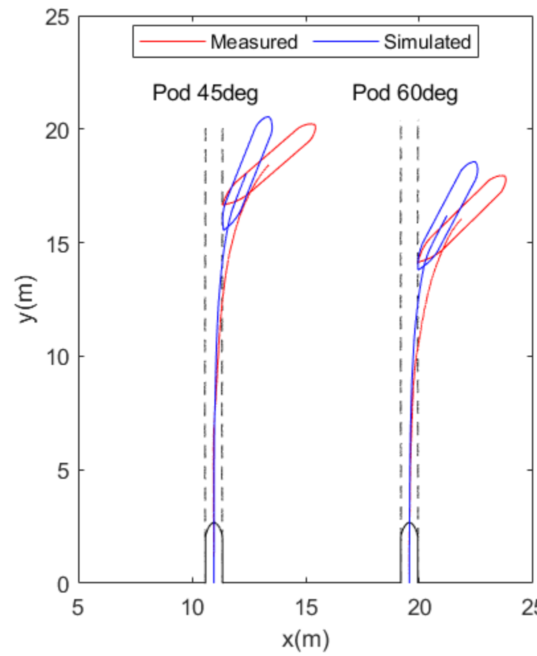

Figure 5. Comparison of ship trajectories during breakout between measurement and simulation (refer to Table 3 for test condition parameters)

Table 4. Comparison of breakout distance and time

	Pod angle 45deg		Pod angle 60deg	
	Breakout distance	Time to breakout	Breakout distance	Time to breakout
Measurement	13.93m	29.7s	11.67m	30.2s
Simulation	13.66m	24.4s	11.81m	27.4s

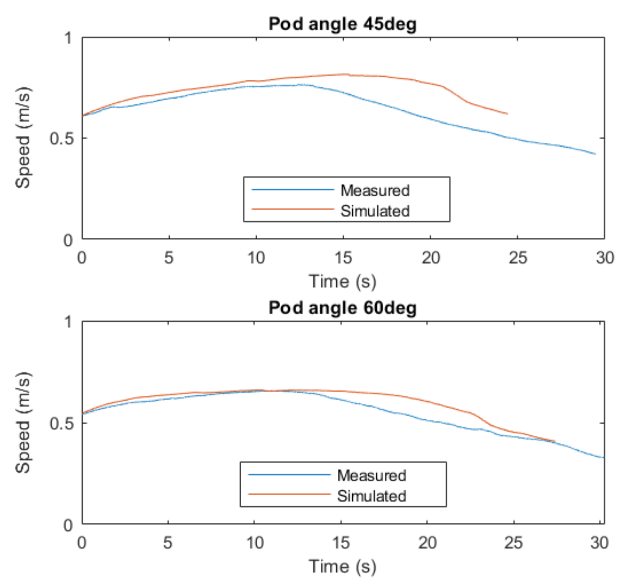

Figure 6. Time history of ship speed during breakout (refer to Table 3 for test condition parameters)

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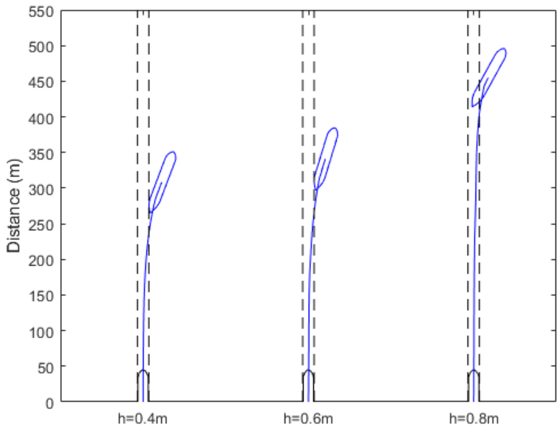

Figure 7. Simulated ship trajectories with various ice thickness (initial speed 12knots, channel width 1.1B)

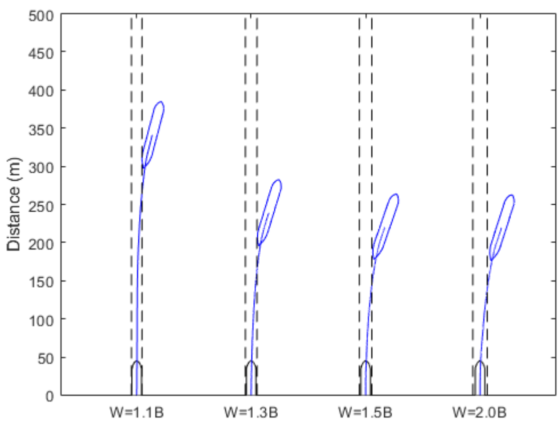

Figure 8. Simulated ship trajectories with various channel width (initial speed 12knots, ice thickness 0.6m)

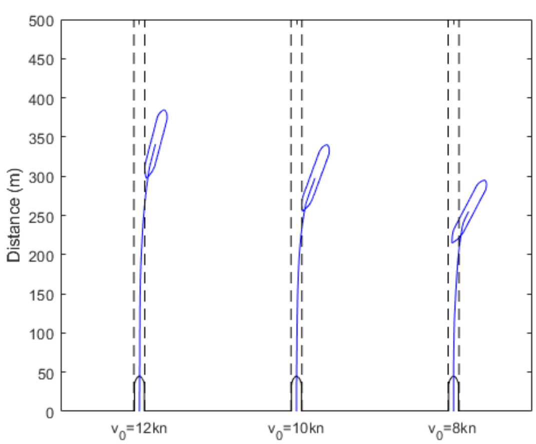

Figure 9. Simulated ship trajectories with various initial speed (ice thickness 0.6m, channel width 1.1B)

ship to break out of the channel when thickness increases, which is what would intuitively be expected. The increase is moderate from 0.4 m to 0.6 m ice when the ship can break out completely while it becomes significant from 0.6 m to 0.8 m when the ship cannot complete the breakout.

Figure 8 presents the simulated trajectories with various channel widths, an ice thickness of 0.6 m and initial speed 12 knots. The breakout distances are 268 m, 166 m, 148 m and 146 m for channel widths 1.1, 1.3, 1.5 and 2.0 times the ship breadth, respectively. As expected, wider channels are easier to break out of. The decrease in breakout distance from 1.1B to 1.3B is significant, while further increase of channel width to 1.5B is much less influential. The breakout distance remains almost unchanged with channel width further increased to 2.0B. It can be summarized that the influence of channel width on breakout distance decreases dramatically with wider channel.

Figure 9 presents the simulated trajectories with various initial speeds, an ice thickness of 0.6 m and a channel width of 1.1 times ship breadth. The breakout/stop distances are 268 m, 232 m and 199 m for initial speed 12knots, 10knots and 8knots, respectively. The ship stops before it breaks out with initial speed 8 knots while with higher speeds it can complete the breakout operation. The overall trend seems linear.

5.3. Estimation of safety distance

As illustrated in Figure 1, the safety distance is the minimum escort/convoy distance needed to avoid collision. The above simulations have given the breakout distance as the results. With an estimation of the reaction distance and deceleration distance, it is possible to provide an estimate the safety distance, i.e. the distance at which a following vessel is still able to avoid a collision by breaking out of the channel when the leading vessel experiences a sudden deceleration or gets beset. In this subsection, an illustrative case study is presented to provide a possible approach to determine the safety distance.

Suppose the ship *Infuture* is being escorted by icebreaker *Sisu* on the Baltic Sea in 0.6-metre ice at 12 knots. The breadth of Sisu is 23.8 m so the channel it made is nearly twice the width of Infuture. The breakout distance obtained with 2.0B in Figure 8, which is 146m, can be used as channel width has little influence when it is sufficiently large. Assuming the reaction time which the crew in the following ship need to start collision-avoidance is 20 s, the reaction distance will be about 123 m. Further, assuming the time needed for the pod to turn 90 deg is 10 s, an additional distance of maximum 62 m should be added to the breakout distance. The total advancing distance of the following ship before it breaks out completely is then 123+62+146=331m.

To calculate the deceleration distance, assuming the icebreaker encounters a heavy ridge, which generates a constant resistance of 2000 kN onto the ship. With the net thrust curve of Sisu, it can be calculated that the ship will stop in 54 s after moving forward 149 m. Therefore, the safety distance in this case should be 331-149=182 m.

The above is merely a rough calculation for the purpose of demonstration of the concept. More precise calculation can be made if more detailed information of ship and human factors,

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especially related to the reaction time in different conditions are known. Approaches based on vessel movement data from the Automatic Identification System, in combination with kinematic models from the vehicle following modelling literature, as presented in [6] can provide a fruitful path to refine the here presented analysis. More detailed models of ship deceleration in complex ice fields, such the model reported in [12] for ridged ice, could also provide more accurate estimates of the lead vessel's dynamics and how that relates to the safety distance.

6. CONCLUSIONS AND FUTURE WORK

This paper investigates the capability of a ship to break out of ice channels with various ice thickness, channel width and initial speed, through simulations with a simulation program for estimating ship performance in ice, as well as a series of model tests. The simulation method is shown accurate to estimate the breakout distance compared to the investigated model test cases.

It is found that for the sample ship, the breakout distance is dependent on ice thickness, channel width and initial speed. The dependence is significant when ice becomes too thick for the ship to breakout or the channel width becomes close to ship width. It should be noted that the findings here apply to ships equipped with an azimuth thruster. Care should be taken to interpret these results for vessels equipped with conventional propeller and rudder, and follow-up research is recommended to ascertain whether the observed relations are similar.

It should also be noted that the sample ship used in this paper has good icebreaking capability when going forward but relatively poor manoeuvrability in ice due to the long parallel midbody. For future work, other hull forms, e.g. with better manoeuvrability or with less icebreaking capability, should be investigated to see the influence of hull form. More model tests with different thicknesses and channel widths are also needed to provide a more comprehensive validation of the simulation model.

Finally, while the insights in the safety distance in escort and convoy operations provided based on a first-principle based simulation model are unprecedented, in future work it should also be investigated if the resulting safe distance under different ice conditions is operationally feasible. Especially in dynamic and compressive ice conditions, it is possible that the recommended safety distance from a perspective of being able to break out of the channel to avoid collision with a decelerated or stopped leading vessel, leads to such large distances between leading and following and vessel that the channel closes before the following vessel has traversed this distance. In such cases, this would lead to assisted vessels becoming beset in ice conditions, which is also undesirable from operational and safety perspectives. Work to better understand the balance between these two requirements related to a safe and operationally feasible following distance in dynamic, compressive ice conditions, is left for future research.

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