**TP12814E**

# TANKER NAVIGATION SAFETY SYSTEM

# ARCTIC TANKER RISK ANALYSIS PROJECT PHASE III

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Transportation Development Centre
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16. Abstract

The final phase of the Arctic Tanker Risk Analysis project was the development of a prototype computer model called the Tanker Navigation Support System (TNSS). This model is intended as a shipboard risk management system capable of route planning based on assessing the risks of each track in a route plan by applying a predictive accident model patterned after study and definition of navigation and collision avoidance processes from the previous phases of ATRA. The model includes a historical database and risk analysis model and works on a PC platform. The prototype software was delivered to the Transportation Development Centre for the subsequent development of applications in the future.

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16. Résumé

La phase finale du projet d'analyse des risques inhérents à la navigation arctique (ATRA pour Arctic Tanker Risk Analysis) avait pour objet de mettre au point un prototype de logiciel embarqué d'aide à la navigation des pétroliers (TNSS pour Tanker Navigation Support System) capable de gérer les risques et de planifier l'itinéraire d'un pétrolier en fonction du calcul des risques inhérents à chaque route proposée par un plan de routage. Pour ce faire, le système fait appel à un modèle de prévision des accidents établi d'après l'étude et la définition des méthodes de navigation et d'évitement des collisions entreprises aux étapes précédentes du projet ATRA. Le logiciel comprend une base de données «historiques» et un modèle d'analyse des risques et tourne sur un ordinateur personnel. Le prototype de logiciel a été livré au Centre de développement des transports qui assurera le développement des applications connexes.

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EXECUTIVE SUMMARY

This report summarizes the methodology and findings related to the development of a prototype of the Tanker Navigation Safety System (TNSS). TNSS is a PC-based software application that utilizes the Commercial-Off-the-Shelf (COTS), GIS-based Windows software development platforms, Mapinfo and Visual Basic. The project consisted of the development and delivery of a working prototype, including source code. This report accompanies the delivery of the computer code to TDC.

The development of TNSS culminates a three phase project known as the Arctic Tanker Risk Assessment (ATRA) Project. ATRA Phase I identified the hazards most likely to produce an oil spill on the voyage route of an Arctic Tanker between the Bent Horn terminal and the Port of Montreal. ATRA Phase II focused efforts on issues with a particularly high risk component or a deficiency in documented information for risk management decision-making. The recommendation from Phase II was to proceed with the development of a formalized risk management system that would consist of a risk analysis model as well as an environmental and accident type data base to provide input data to the model. These modules were to be packaged into a software system with a Graphical User Interface (GUI) which was to be developed to the prototype stage in Phase III.

The remaining work to be done beyond Phase III is to populate the environmental data base to make it year round, and perhaps expand the geographic coverage to enable assessments of routes to other Arctic destinations. The prototype needs to be further developed into a fully robust system that is generalized to work with any ship type along with a complete environmental data base. Completion of this system development could be followed by the development of applications using the system for risk assessment of current and hindcast ship operations.

# SOMMAIRE

Ce rapport donne un aperçu de la méthode appliquée au développement d'un système prototype d'aide à la navigation des pétroliers (TNSS) ainsi que des résultats de ces travaux. Le TNSS est une application logicielle qui fait appel à Mapinfo et Visual Basic, des systèmes du commerce voués au développement de logiciels à base d'information SIG et qui fonctionne en environnement Windows. Le projet visait la mise au point et la livraison d'un prototype fonctionnel et de son code source. Le présent rapport est donc fourni au Centre de développement des transports en même temps que le code machine.

Les trois phases du projet d'analyse des risques inhérents à la navigation arctique (ATRA) ont abouti à la mise au point du TNSS. La phase I avait pour objet d'identifier les dangers les plus susceptibles d'occasionner des déversements accidentels d'hydrocarbures le long de la route entre le terminal de Bent Horn et le Port de Montréal. Dans la phase II, il s'agissait d'approfondir diverses questions caractérisées par un facteur de risque élevé et pour lesquelles la base de connaissances n'est pas suffisante pour autoriser la gestion du risque qu'elles comportent. Au terme de la phase II, il a été recommandé d'élaborer un système formalisé de gestion du risque fondé sur un modèle d'analyse du risque ainsi que sur une base de données environnementales et les types d'accidents éventuels. Au cours de la phase III, ces modules devaient être réunis en un prototype de progiciel intégrant une interface utilisateur graphique (IUG).

Dans le cadre de la phase III, il reste à enrichir la base de données environnementales de manière à ce qu'elle fournisse des informations à l'année et, éventuellement, à étendre la couverture géographique aux fins de l'évaluation des risques sur d'autres routes arctiques. Le prototype doit être perfectionné au point de constituer un système entièrement fonctionnel assorti d'une base complète de données environnementales et s'appliquant à tous les types de navires. Une fois le système au point, on pourrait élaborer de nouvelles applications en implémentant le système pour l'évaluation du risque associé à des opérations maritimes en cours et antérieures.

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# 1. Introduction

## 1.1. Scope

In Phase 3 of the Arctic Tanker Risk Analysis (ATRA) project, the original scope of the project was revisited to consider the implications of including all tankers carrying petroleum products in the risk analysis. One of the original objectives was to analyze the causes most likely to produce an oil spill from the MV *Arctic* enroute from Bent Horn in the high Arctic to Montreal. This objective was broadened in Phase 2 with the inclusion of *Type* ships in the analysis of historical casualty and spill frequencies[1]. In Phase 3, international literature was examined, and further analysis of Canadian marine accident data was conducted to provide causal statistics and performance data in the design and implementation of a navigation risk model. The navigation risk model was intended to form an integral component of a Tanker Navigation Safety System (TNSS) described below. *Type* ship operations and constraints were also an important consideration in the risk model design; therefore, a comparison of the physical differences in manning, experience, equipment fit, and hull and propulsion configuration was conducted. Consequence data gathered in Phase 2 were also integrated.

Expert systems to monitor a vessel's internal and external situation have been designed either to assist with a real-time course of action to minimize risk to the ship or to model the navigation process[2]. This project has attempted to pattern the marine navigation risk model after this type of system and replace real-time data with historical data and other parameters from a risk information database. The navigation risk model was intended to highlight the most probable courses of action, situations, and outcomes through linkages between a top event such as a grounding, collision, or striking and the range of most likely basic events that could lead to these accidents.

Once the navigation risk model was developed, the next step was its integration with a prototype Tanker Navigation Safety System or TNSS utilizing the *off-the-shelf* benefits of MapInfo and other development tools and database products. It was intended that this development consolidate the work to date in a more communicable format, to assist mariners and other decision-makers.

# 2. Study Area

The study area for the Arctic Tanker Risk Analysis project included the waters of the St. Lawrence River from the port of Montreal eastward, the northern extent of the Gulf of St. Lawrence, and the coastal waters of the Labrador Sea, Davis Strait, Hudson Bay, Lancaster Sound, and Barrow Strait. In the early stages of the risk analysis, a typical voyage route was identified and generalized into eleven route segments from Montreal to Bent Horn in the high Arctic. The need for geographic data covering a wider area than that collected earlier for the eleven route segments was addressed in this study.

# 3. Methodology

## 3.1. Tanker Navigation Safety System

The TNSS prototype was designed to evaluate the feasibility of providing navigators and decision-makers with a marine risk information system based on historical data and operator-selected routes. Two approaches to data access were implemented; both used a map interface. One required an operator to define a navigation route and the other enabled direct access to historical navigation safety information. The prototype system was designed and developed by integrating rapid application development tools, including MapBasic, Visual Basic, and Access[3]. Its components included: a deterministic navigation risk model, a routing and information system interface, historical data, accident cause frequency estimates, consequence estimates, and a desktop Geographic Information System (GIS) and database management system, Fig. 1.

## 3.2. Navigation Risk Model

A deterministic navigation risk model was developed in cooperation with the Institute for Risk Research[4]. The model structure was based on critical watchkeeping tasks, operational preparedness, and the risk situation. This included: navigation, collision avoidance, and shiphandling tasks; ship systems capabilities; proximity to hazards (ships, shoals, ice, and obstructions), and shoreline sensitivity. It performed as follows: failure in a critical task or ship system only results in an accident or a top level event when the ship is unable to avoid a hazard, i.e., if a ship is off track and standing into danger, the ship will only ground if there is insufficient time to stop, turn, anchor, or otherwise avoid the danger. Therefore, risk of collision, grounding, striking, or ice damage along any navigation track depends on many geo-specific variables, such as distance to shoals, wind, visibility, currents in addition to human and ship-specific variables (see Fig. 2. representing the collision probability fault tree). The risk of consequences resulting from a casualty depends on the type of accident and the environment in which the casualty occurs. This was modelled using a simple event tree incorporating the use of cost ranges for each event. Navigation risk model data were accessed from TNSS via a routing system interface. The model was integrated such that it is executed for each track in a voyage to determine accident risks, costs, and sensitivity information.

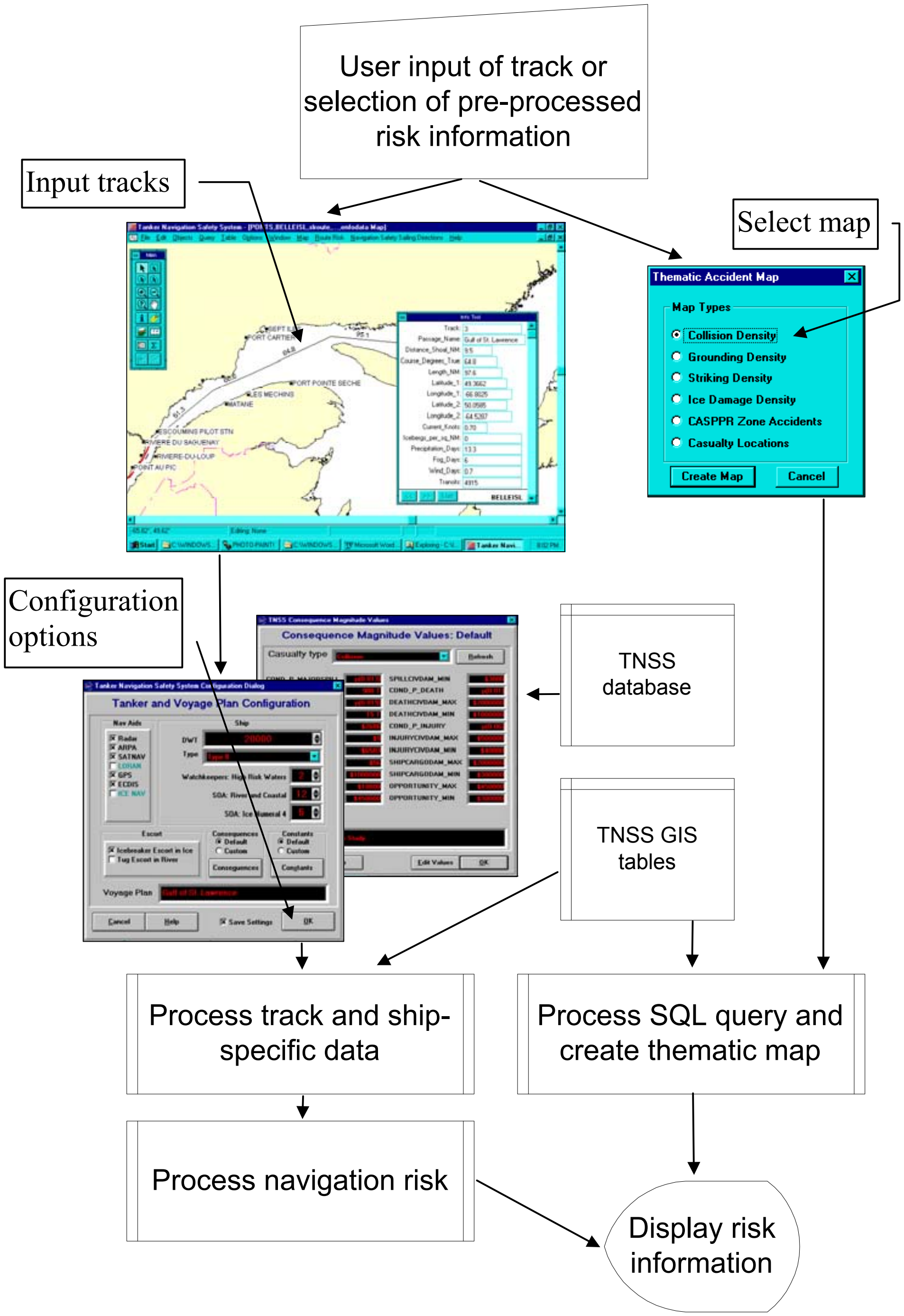


**Fig. 1. Tanker navigation safety system**

## 3.3. Routing System

The first approach to providing risk information was through the use of a routing system interface. In order to gather track-specific historical data for input into the risk model, data gathering routines were programmed in MapBasic to respond to the input by an operator of a voyage plan and return track-specific environmental data, as well as course and track length data. The prototype made use of a 1:1,000,000 scale base map, but nautical charts could also be implemented. Ship configuration information, consequence estimates, and constants used in the model were stored in an Access database for retrieval by a fully integrated Visual Basic interface.

## 3.4. Information System—Sailing Directions

The second method of accessing navigation risk information was through the use of interactive thematic maps illustrating the location of *high risk* areas for different accident types. These accident maps, as well as custom user-generated maps are produced in real time for the operator. They also enable an operator to click on a screen object, such as a portion of a waterway, to retrieve its associated data.

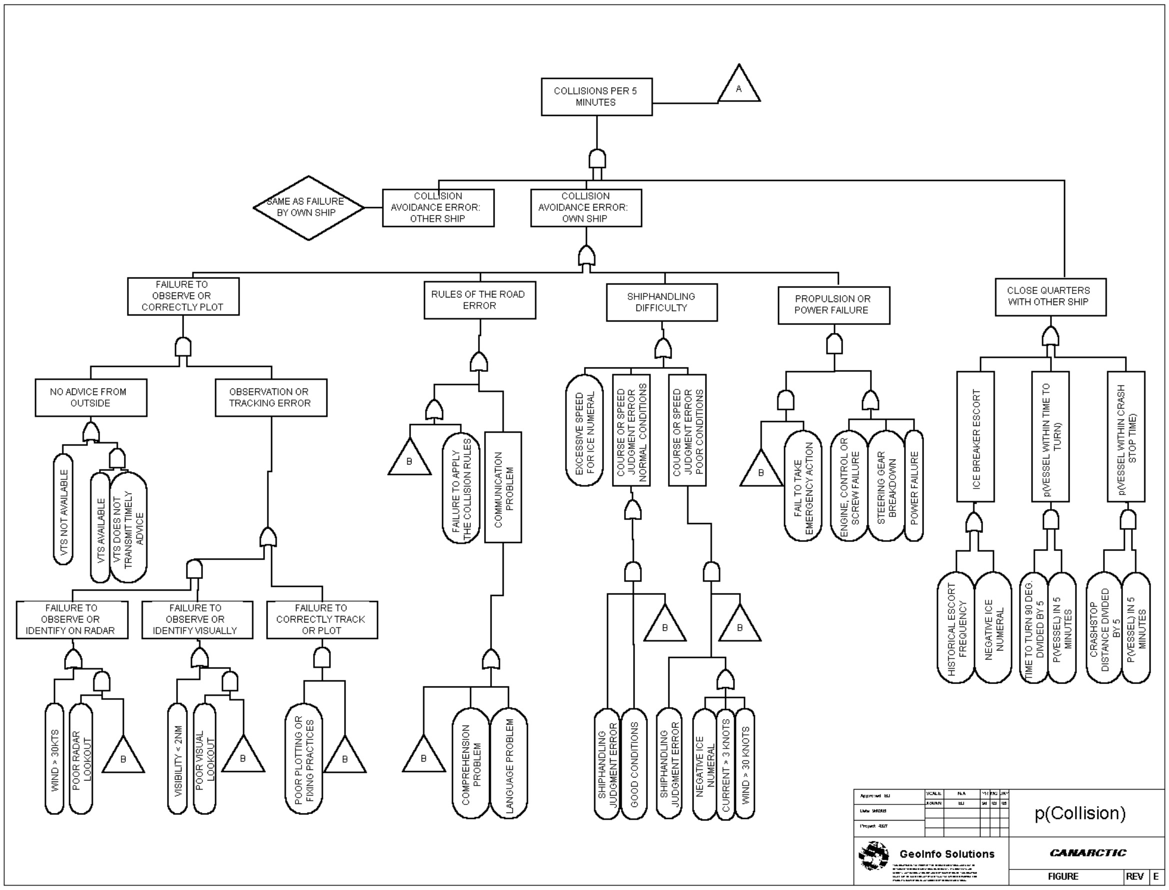


**Fig. 2. Collision probability fault tree**

## 3.5. Casualty Rates and Consequences

Historical casualty rates formed part of the risk mapping component of TNSS and were estimated for model validation work. Casualty rates were estimated by aggregating marine casualty records of the Canadian Transportation Safety Board, and determining exposure measures including: arrivals and departures in Arctic ports from Transport Canada and Statistics Canada records and ship-miles calculated from Transport Canada movement records.

Conditional probabilities for consequences to casualties were estimated using spill records of the United States Minerals Management Service, the International Oil Pollution Compensation Fund, the Canadian Ship-source Oil Pollution Fund, and statistics from the annual reports of the United States Coast Guard. These estimates included oil spill frequency and size, as well as death and injury rates which were applied in the accident cost estimation process of the navigation risk model.

## 3.6. Model Data

Casualty cause data were obtained from a literature search and from a classification (conducted by the author) of the Canadian Transportation Safety Board marine casualty records. Other factors were estimated through theoretical relationships using historical data. For example, a *safe speed* in ice given the ice regime and ship type was generated from vessel transit data used in the IDIADS Trafficability Data Reports[5] as part of validation trials of the Canadian Ice Regime system. These reports included ship speed and sea-ice concentrations, in tenths coverage, from which the corresponding *ice numeral* was calculated. Altogether, data from fifteen voyages were used, all for *Type B* ships. Only the unescorted parts of the voyages were used since under escort the ship's speed is dependent on the ice breaker and the ice numeral in the track is different from that of the surrounding ice regime.

Climatological, hydrographic, and ice data were gathered from a number of sources and entered into the TNSS geographic information system. The process employed geocoding, digitizing, and other techniques to give full geographic coverage from the St. Lawrence River, along the Canadian east coast to the eastern Arctic including Hudson Bay. After processing, these data were automatically entered for eight parameters into 4307, twenty NM square grid cells.

Informal telephone inquiries to large shipping companies operating in the St. Lawrence River, the East Cost and the Arctic were conducted to characterize the level of manning in restricted and open waters. While the results were anecdotal, the exercise confirmed that under restricted conditions, one would probably find two officers on the bridge. One of these officers would usually be the Master; however, a pilot or ice pilot might also double up with the Officer-of-the-Watch. Six of the companies reported their watch rotation and all reported a four hours on and eight hours off schedule. One could conclude that since the normal practice of watchkeeping is to 'double-up' in restrictive conditions, the workload would be excessive for a single officer.

## 3.7. Marine Risk Database

A literature search was conducted to create a concise annotated bibliography of research findings in the field of human error at sea. Data from about 40 reports were entered into a risk information database. This database was intended to provide supporting documentation on the frequencies of a range of navigation and shiphandling errors; however, it was found that in most cases, the results were less than precise. Statistical techniques of hypothesis testing were not followed in most of the studies and it proved difficult to apply the research by creating conditional probabilities. Nevertheless, the database documented the types of analyses conducted internationally and provided some useful parameters.

# 4. Findings

4.1. Tanker Navigation Safety System Development

Fig. 3 illustrates an example risk analysis output of the TNSS prototype. In this example, the *risk browser* table lists the probability of ice damage, the accident cost range in Canadian dollars, and the probability of a spill greater than 136 t. When an operator selects a track, a window displays a list with track geometry and geographic data. The environmental data include mean climatic conditions over a twenty-year collection period, the minimum distance to shoals calculated by a parallel-index technique, and the expected traffic volume per month.

The system also provides cartographic quality thematic maps representing high risk areas through the use of a colourized grid or enhanced symbology. The built-in GIS technology is used to plot the spatial distribution of accidents by type, count the number of occurrences within either a grid cell or other boundary region, and then aggregate the result by ranges. The map is then updated and high risk areas are highlighted. Environmental sensitivity data gathered earlier in the project were also entered into the system for viewing by an operator. All in all, this information is designed to replace perceived risk with factual risk for safer passage planning or decision-making.

4.2. Navigation Risk Model

Through discussions with the Institute for Risk Research and the Transportation Development Centre, it was decided that the need to develop a route planning risk analysis functionality in TNSS necessitated a re-allocation of resources. Thus an original task of the ATRA III project was modified 'from a calibration exercise to one of evaluating and extending the model components developed to date'[6]. Although the navigation risk model was neither calibrated nor validated, it was independently examined by the Institute for Risk Research, where it was recommended that the on-going improvements with each revision of the fault trees continue for at least ‘one further revision before presenting the model to the marine community’[6]. This suggests that further input by the academic community is desirable prior to further sensitivity testing and evaluation of what has turned out to be a very difficult problem. As a basis for further development, the model was founded on navigation practice and provides risk estimates with direction and magnitude. Moreover, accident rates estimated from the model were inspected for the St. Lawrence River and Davis Strait and found to be within an order of magnitude when compared to the frequencies determined from historical traffic and accident data, Table 1.

## 4.3. Route Planning

In order to control entry into a zone in the Arctic, the Canadian government has established vessel performance measures in ice based upon the vessel's ice strength and the expected ice conditions. TNSS calculates these measures termed *ice numerals* or *ice decision numerals*, using historic mean ice conditions for a sample period of June 11 to 17 digitized from the *Passage Planning Manual*[7]. This provided a measure of the risk of ice damage to a vessel in any given area for passage planning purposes. In order to determine whether there was a significant relationship between mean speed and ice numeral, a small sample of vessel transits was examined.

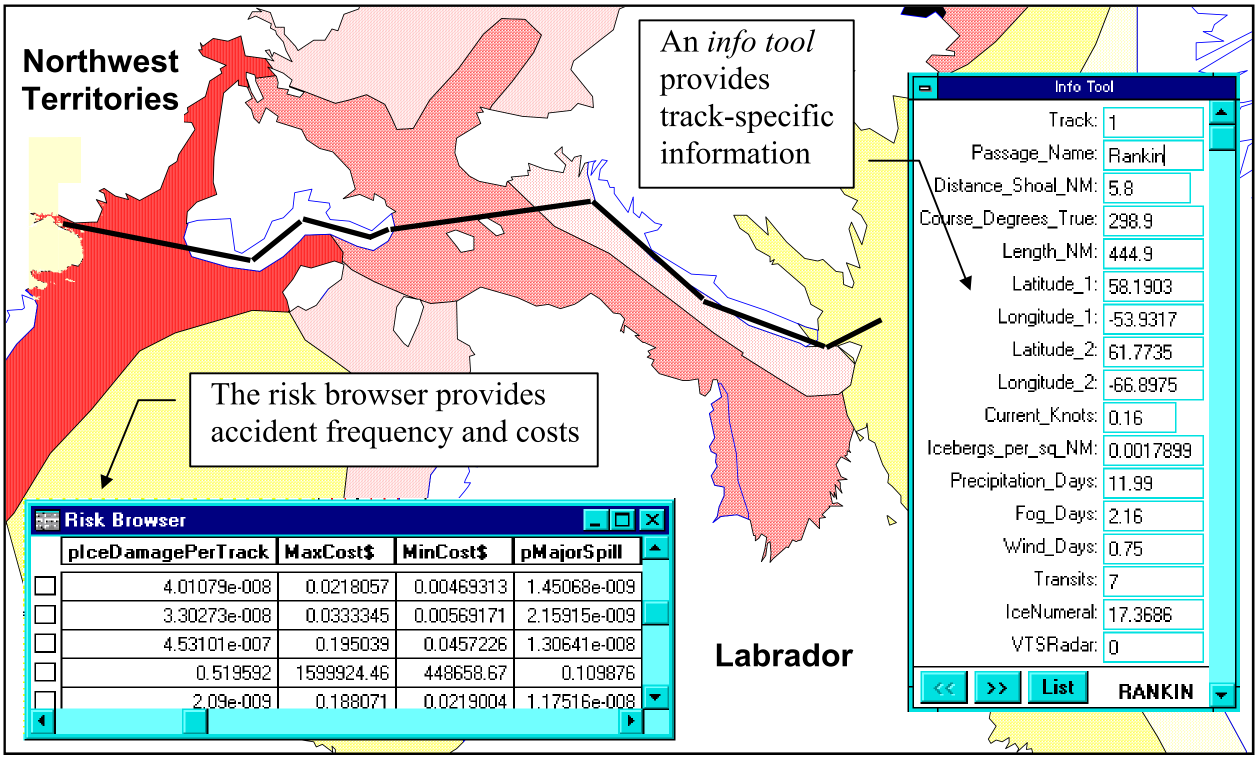


**Fig. 3. TNSS risk analysis output**

### TABLE 1. ACCIDENT RATES PER MILE AND MOVEMENTS BY REGION AND CASUALTY TYPE, JUNE TO OCTOBER, 1977 - 1991

| Region | Unit mean annual | Exposure | Grounding Total | Grounding Frequency | Ice Damage Total | Ice Damage Frequency | Collision Total | Collision Frequency | Striking Total | Striking Frequency |
|---|---|---|---|---|---|---|---|---|---|---|
| Eastern Arctic Ports: Cargo | Total Arrivals & Departures | 296 | 0.3 | 1.14E-03 | 0.1 | 4.37E-04 | 0.0 | 0.00E+00 | 0.1 | 2.32E-04 |
| Eastern Arctic Ports: CCG | Total Arrivals & Departures | 42 | 0.0 | 0.00E+00 | 0.1 | 1.52E-03 | 0.0 | 0.00E+00 | 0.0 | 0.00E+00 |
| Eastern Arctic: CCG | Shipmiles | 57857 | 0.3 | 4.58E-06 | 0.8 | 1.40E-05 | 0.0 | 0.00E+00 | 0.0 | 0.00E+00 |
| Lancaster - Barrow | Shipmiles | 10993 | 0.1 | 1.23E-05 | 1.5 | 1.39E-04 | 0.0 | 0.00E+00 | 0.0 | 0.00E+00 |
| Davis Strait - Labrador | Shipmiles | 89301 | 0.0 | 0.00E+00 | 1.8 | 2.00E-05 | 0.2 | 2.30E-06 | 0.1 | 1.52E.06 |
| St. Lawrence R. Approach | Shipmiles | 6709970 | 0.5 | 6.95E-08 | 0.0 | 0.00E+00 | 0.5 | 6.95E-08 | 0.0 | 0.00E+00 |
| St. Lawrence R. Montreal - Sagenay R. | Shipmiles | 5892381 | 3.2 | 5.43E-07 | 0.0 | 0.00E+00 | 0.5 | 7.92E-08 | 0.2 | 3.39E-08 |
| St. Lawrence R. Ports | Total Arrivals & Departures | 5898 | 6.1 | 1.05E-03 | 0.0 | 0.00E+00 | 4.4 | 7.53E-04 | 8.9 | 1.50E-03 |

A 3rd order regression was performed on the sample mean speeds with the decision numerals such that,

$$Y = 0.0025x^3 - 0.0398\, x^2 + 0.2489\, x + 3.6985$$

where $Y$ is the estimated mean safe speed in ice per ice decision numeral. This relationship indicated an $r^2$ value of 0.70 where 70 percent of the total variation was explained by the regression, Fig. 4. Since the calculation of the ice decision numeral depends upon ice type and concentration as well as ship type, the function was used to predict a safe speed given these data. This safe speed can be used to predict performance, i.e., the speed of advance (SOA), and the risk of ice damage, as it can be assumed that excessive speed beyond that normally set by an ice navigator will likely result in damage to the hull and/or propulsion and steering systems.

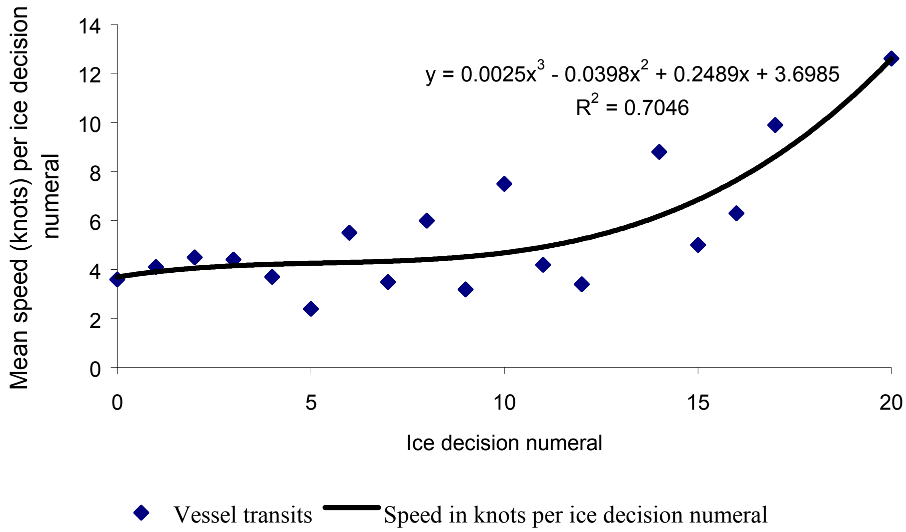


**Fig. 4. Mean vessel speeds in positive ice, 1976 - 1992**

The geographic information system also provided built-in functions to return great circle distances. This simplified the processing required to return track information to the operator of TNSS. A short distance sailing algorithm was programmed to utilize these distances in the calculation of the course and length for each track drawn by the navigator. Waypoint information was also included as part of the data returned so that the prototype is ready to be integrated with an electronic chart display information system (ECDIS).

### 4.4. Model Data and Parameters

The navigation risk model requires human error data in addition to its strong dependence upon geographic data. A small bibliographic database of human factors studies which included marine accident cause statistics from 38 sources was created. In general, the available statistics resulted from the quantitative study of accident records, however, the statistics were not conducted with the objective of creating conditional probabilities. For example, one of the most comprehensive studies was undertaken by Karlsen & Kristiansen[8]. They counted the occurrence of many factors, such as poor manning in good and poor visibility, rules violation in fog, etc. However, it proved difficult to apply the results to determine, for example, either the conditional probability that a rules violation alone results in a collision or the conditional probability that a rules violation in conjunction with poor manning results in a collision. The complexities of causal factor interaction are also an inherent problem in casualty database design. In a recent report to the International Maritime Organization submitted by the Correspondence Group on the Casualty Database Construction, several countries and organizations provided some insightful comments on casualty database design[9]. Canada's perspective on the proposed checklist was as follows:

> Canada believes that a standardized investigative/analytic approach supported by a flexible database design holds more promise than any other approach, such as the application of checklists. Databases of checklists of human factors have deficiencies:

- they cannot communicate the relationship between the factors and the occurrence
- the application of checklists is not reliable
- checklists try to be comprehensive, but it is impossible to specify all contributing factors and conditions
- checklist items may be value laden rather than descriptive
- checklist items often reflect different points on a single continuum rather than different factors[10].

In order to address the problems with the current databases, each record should be examined by a qualified mariner who can appreciate the tasks at hand on a bridge. The mariner will be able to annotate each record and provide qualitative data to make the record useful. The causal factors in some records might be re-organized to better represent the accident situation. Problems such as citing visibility as the cause for a collision rather than as a contributing factor to the cause of unsafe speed for the prevailing conditions would be overcome. This approach was applied in this study to classify Canadian accident records into several large groups.

Table 2 lists the distribution of accident cause by type for: the St. Lawrence River, its ports of call and approaches; Davis Strait and Labrador Sea; Barrow Strait and Lancaster Sound; Arctic harbours. This table was one of several sources used to create a set of human error parameters, and it was the only source created specifically to cover the marine accident record of eastern Canada. Quite a different characterization than that presented in Table 2 would have resulted had the type of waterway not been isolated in the analysis. Southern ports in summer have accidents of all types, whereas the river is the scene for frequent groundings. Quite repetitive reference is made in the literature to the predominance of human error as the cause of accidents; this would also be true for accidents in the St. Lawrence waterway. However, an inspection of accident cause for groundings in the St. Lawrence River suggests that propulsion, power or steering failure plays the most important role. It is shiphandling errors causing strikings, collisions and groundings in ports that might sway the results to support the more commonly accepted notion. Shiphandling errors and failure to observe or determine ice type is the principal cause of accidents in the Arctic.

Table 3 and Table 4 identify the data parameters used to estimate the cost of an accident in the navigation risk model. The source for these estimates is logged in the TNSS database and an operator has the opportunity to modify any value and input a new source justification for the change. These data parameters are incorporated into TNSS as follows: for each track, the probability determined for each accident type is multiplied by each consequence probability and its associated costs. The process is repeated from track to track for the entire voyage plan.

## TABLE 2. ACCIDENT CAUSE BY REGION AND CASUALTY TYPE, 1977-1991, JUNE TO OCTOBER

| Region and casualty type | Total accident count | Position fixing | Collision rules | Fail to observe vessel in close quarters | Failure to observe or determine Ice Type | Ship handling | Engine or screw failure | Steering failure | Total power failure | Unsure |
|---|---|---|---|---|---|---|---|---|---|---|
| St. Lawrence R. (SLR) | | | | | | | | | | |
| Grounding | 48 | 8 | - | - | - | 6 | 2 | 18 | 13 | 1 |
| Collision | 7 | | 1 | 4 | - | 1 | - | 1 | - | - |
| Striking | 3 | 1 | - | - | - | 1 | 1 | - | - | - |
| Ice Damage | - | - | - | - | - | - | - | - | - | - |
| SLR Ports | | | | | | | | | | |
| Grounding | 93 | 21 | - | - | - | 35 | 18 | 13 | 4 | 2 |
| Collision | 66 | - | - | 9 | - | 49 | 3 | - | 1 | 4 |
| Striking | 132 | 5 | - | - | - | 197 | 13 | 3 | - | 4 |
| Ice Damage | - | - | - | - | - | - | - | - | - | - |
| SLR Approaches | | | | | | | | | | |
| Grounding | 7 | 3 | - | - | - | 2 | - | - | - | 2 |
| Collision | 7 | - | - | 3 | - | 3 | - | - | - | 1 |
| Striking | - | - | - | - | - | - | - | - | - | - |
| Ice Damage | - | - | - | - | - | - | - | - | - | - |
| Davis -Labrador | | | | | | | | | | |
| Grounding | - | - | - | - | - | - | - | - | - | - |
| Collision | 3 | - | - | - | - | 2 | - | - | 1 | - |
| Striking | 2 | 1 | - | - | - | 1 | - | - | - | - |
| Ice Damage | 27 | - | - | - | 8 | 8 | - | - | - | 1 |
| Lancaster - Barrow | | | | | | | | | | |
| Grounding | 2 | - | - | - | - | - | 2 | - | - | - |
| Collision | - | - | - | - | - | - | - | - | - | - |
| Striking | - | - | - | - | - | - | - | - | - | - |
| Ice Damage | 23 | - | - | - | 3 | 11 | - | - | - | 1 |
| Arctic harbours | | | | | | | | | | |
| Grounding | 5 | 2 | - | - | - | 1 | 1 | - | - | 1 |
| Collision | - | - | - | - | - | - | - | - | - | - |
| Striking | 1 | - | - | - | - | 1 | - | - | - | - |
| Ice Damage | 3 | - | - | - | - | 1 | - | - | - | - |

**Table 3. Consequence Probabilities**

| Consequence probabilities | Unit | Collision | Grounding | Striking | IceDamage |
|---|---|---|---|---|---|
| p(spill >136 tonnes \| accident) | conditional | 0.013 | 0.029 | 0.007 | 0.021 |
| Major spill size | tonnes | 900 | 900 | 900 | 900 |
| p(spill <136 tonnes \| accident) | conditional | 0.019 | 0.065 | 0.04 | 0.12 |
| Minor spill size | tonnes | 15 | 15 | 15 | 15 |
| p(death \| accident) | conditional | 0.01 | 0.01 | 0.01 | 0.01 |
| p(injury spill \| accident) | conditional | 0.06 | 0.06 | 0.06 | 0.06 |

**Table 4. Accident Costs, CAN$**

| Consequence | Cost in CAN$ |
|---|---|
| Spill clean-up at sea per tonne | 9 - 2,686 |
| Spill clean-up ashore per tonne | 56 - 6,503 |
| Natural resource damage fines | 10,000 - 1,000,000 |
| Physical damage, civil | 3,000 - 450,000 |
| Death | 1,000,000 - 2,000,000 |
| Injury | 40,000 - 500,000 |
| Ship and cargo damage | 300,000 - 2,000,000 |
| Opportunity cost | 30,000 - 450,000 |

## 5. Discussion

Unlike a routing optimization algorithm which iterates until a desired optimum is reached, TNSS relies on the expertise of the navigator to provide one or more passages to be examined. The operator has the benefit of overlaying appropriate maps of information, such as iceberg and sea ice concentrations, to minimize the interaction with both hazards. Similarly, a plan might route a vessel clear of a fishing vessel fleet, thus enabling the vessel to maintain a higher and safer speed.

Simple passage can be analyzed in a few minutes using the expert judgment approach; a passage plan of the St. Lawrence River with 97 tracks can be processed in 20 minutes on a 486 computer. Most of this time is consumed by the parallel index module, which determines a track's minimum distance to the nearest shoal (the shoreline is used in the prototype). To reduce run-time computations, the distance to shoals was pre-processed for each grid cell in the study area and the parallel index routine is only run for tracks with a minimum distance to shoals of less than 20 NM.

The system replicates some of the planning functions traditionally performed using *Sailing Directions* to augment a passage plan and avoid some of the surprises that may befall a navigator in unfamiliar waters. While not a replacement for local knowledge, an informed navigator is more likely to be aware of the real, rather than perceived, risks in a waterway. This function is especially critical in the ports and tight passages of the St. Lawrence River, as well as the ice-covered waters of the Canadian Arctic.

The marine risk model was intended to highlight the most probable courses of action, situations, and outcomes through linkages between a top event such as a grounding, collision or striking and the range of most likely basic events that could lead to these accidents. The Institute for Risk Research has described this model design as a *feed forward feed backward* relationship. For example, the basic events that cause fatigue on one track cause the fatigue to be carried forward, perhaps diminishing human performance on the next track. In the first stage of model development, courses of action were drafted and the model soon became unwieldy, requiring too many parameters with unknown values. Subsequent revisions and discussions led to a simpler model design, but its structure still requires revision to avoid problems with some poorly defined overly sensitive input parameters. As the Institute put it, 'marine safety analysis is very complex compared to road, air and rail safety, mainly because ship's tracks are not fixed like rail tracks'.

## 6. Conclusions

TNSS may prove to be very successful as a tool to assist marine experts with decision-making. The development of a geographic interface to historical marine risk data was achieved, as was a method of aggregating the data to provide a spatial display of marine risk. The navigation risk model proved to be more difficult than was originally anticipated, but the groundwork is laid.

The examination of safe speed in ice could be an important inclusion in the development of a ice routing optimization tool or simply an ice analysis tool. A pre-processed ice analysis chart in vector format with attached frequencies of each ice type can quickly be sent to a ship at sea, where ice decision numerals can be processed for the entire Arctic in seconds. Safe speeds returned for each track would assist with the revision of ETAs; unsafe ice regions would indicate the need for higher resolution ice data. Moreover, a navigator would be better equipped to anticipate problems.

The application of *off-the-shelf* desktop GIS and object-oriented rapid application development tools proved much less time consuming than developing the same prototype using C++ would have been. Moreover, the robustness of the prototype is attributed to the robustness of the development platforms: MapInfo and Visual Basic.

# 7. References

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