A Tanker Navigation Safety System

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This paper summarizes the results of Phase 3 of the Arctic Tanker Risk Analysis Project (ATRA) which provided a prototype Tanker Navigation Safety System (TNSS). TNSS is a ship-board risk management system capable of route planning and decision support based upon a knowledge database. The objective of the project was to provide timely risk assessment information to a mariner or decision maker in a system capable of integration with existing ECDIS or shipboard PC systems. The historical information was to include: accident location, frequency and type, ice, wind, visibility, environmental sensitivity and other factors. The specifications of the TNSS prototype were expanded so that risk could be assessed for each track in a route plan by applying a predictive accident model patterned after the navigation and collision avoidance process.

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]. *Type* ships are ice-strengthen vessels classified as Type A, B, C, D, or E according to the extent of ice strengthing as described in the Canadian Arctic Ship Safety Pollution Prevention Regulations or CASPPR. 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, hull and propulsion configuration was conducted. Consequence data gathered in Phase 2 was also integrated.

Expert systems to monitor a vessel's internal and external situation have been designed to either assist with a real-time course of action to minimize risk to the ship, or 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 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 which may 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 which was 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 approached in this study.

3. Methodology

3.1. Tanker navigation safety system.

The TNSS prototype was designed to evaluate the feasibility of providing a marine risk information system to navigators and decision-makers based on historical data and operator-selected routes. Two approaches to data access were implemented and 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 conjunction with the Institute for Risk Research[4]. The model structure was based upon 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 resulted in an accident or a top level event when the ship was 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 was dependent upon 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 was dependent upon the type of accident and the environment in which the casualty occurred. This was modelled using a simple event tree which incorporated 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.

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 : 1000000 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.

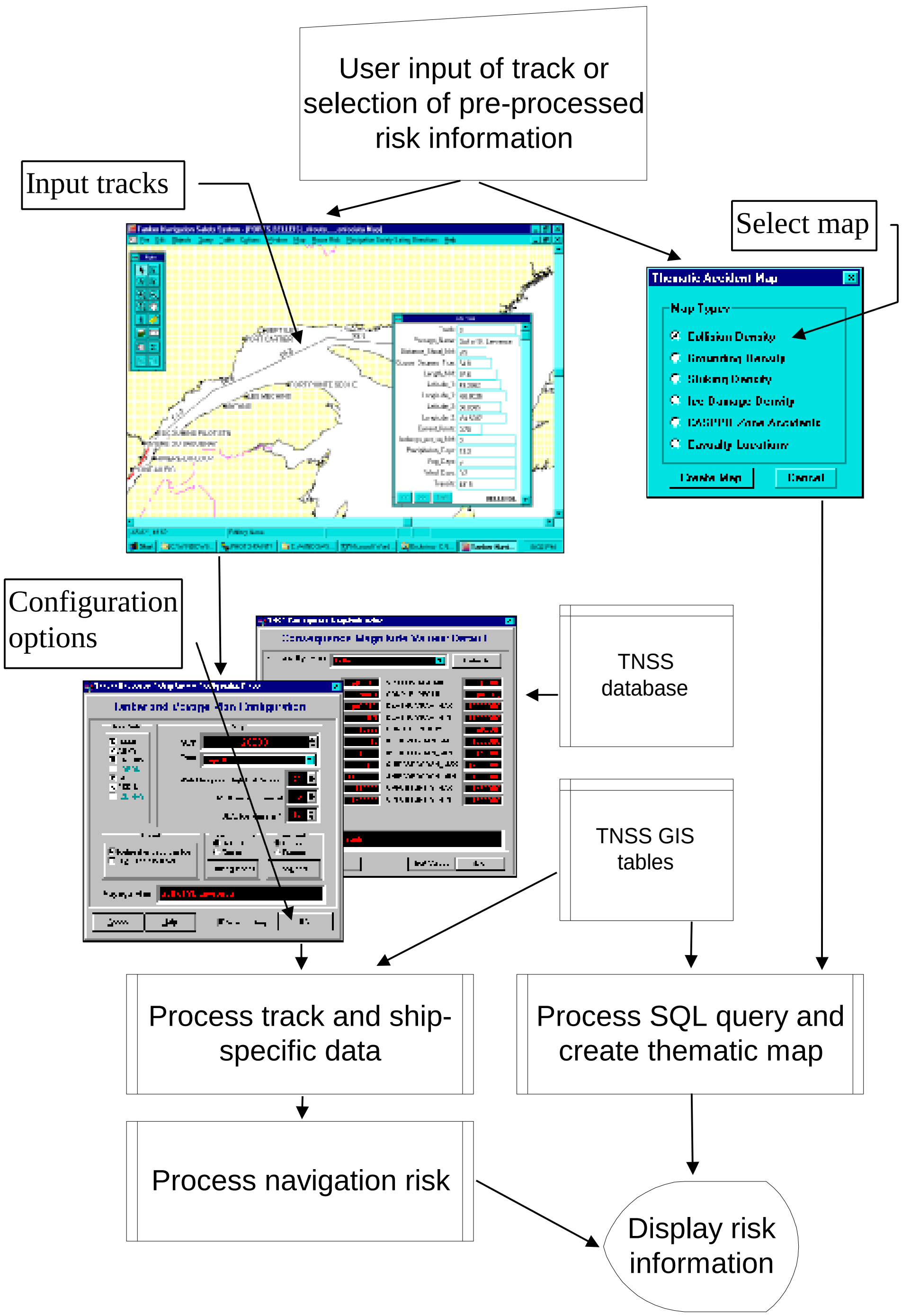

Fig. 1. Tanker navigation safety system

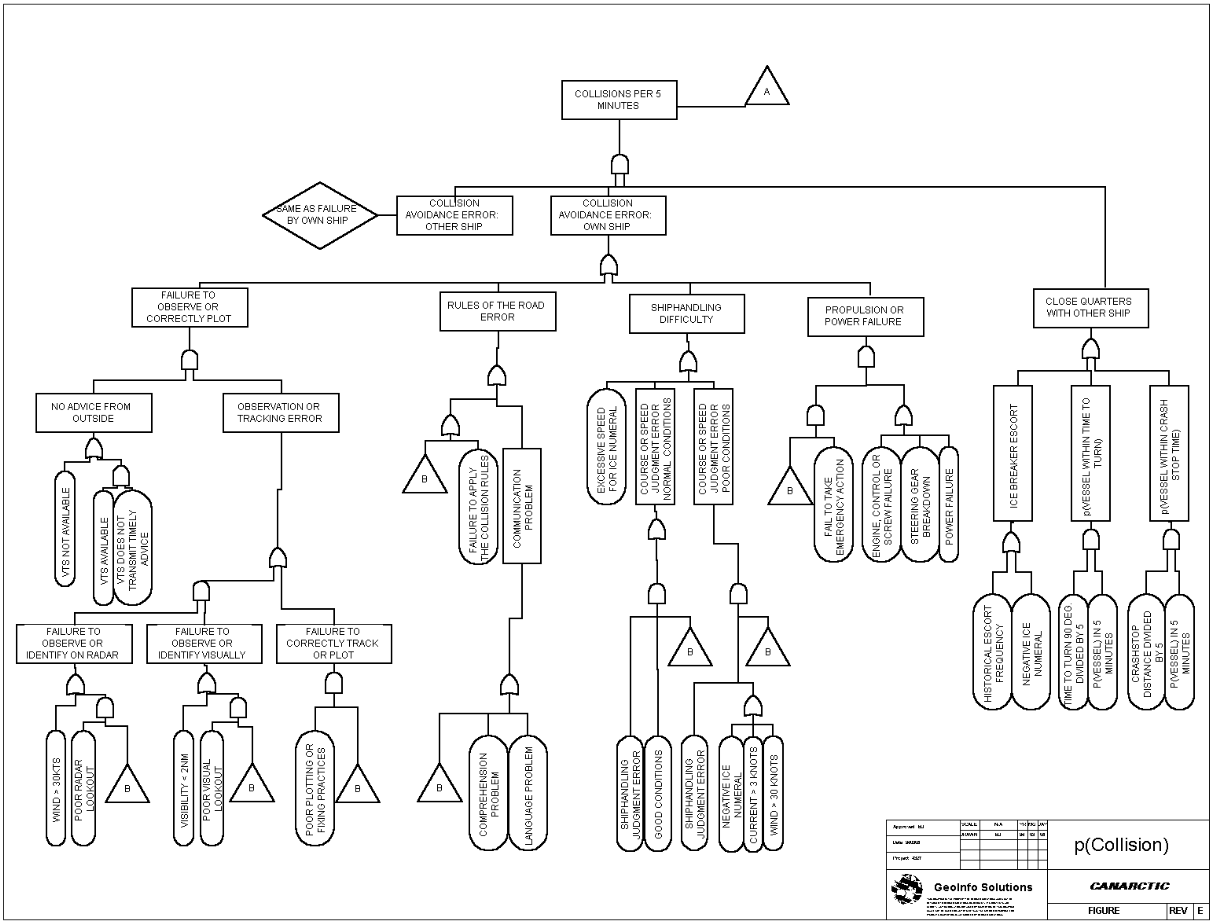

Fig. 2. Collision probability fault tree

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 of the Canadian Transportation Safety Board marine casualty records conducted by the author. 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 was used, all of which was for *Type B* ships (the most commonly occurring vessel and CASPPR ice strength classification in the Eastern Arctic). 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.

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 tonnes. When an operator selects a track, a window displays a list with track geometry and geographic data. The environmental data includes 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

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 provided risk estimates with direction and magnitude and was founded on navigation practice. 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 I.

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 if there was a significant relationship between mean speed and ice numeral, a small sample of vessel transits was examined.

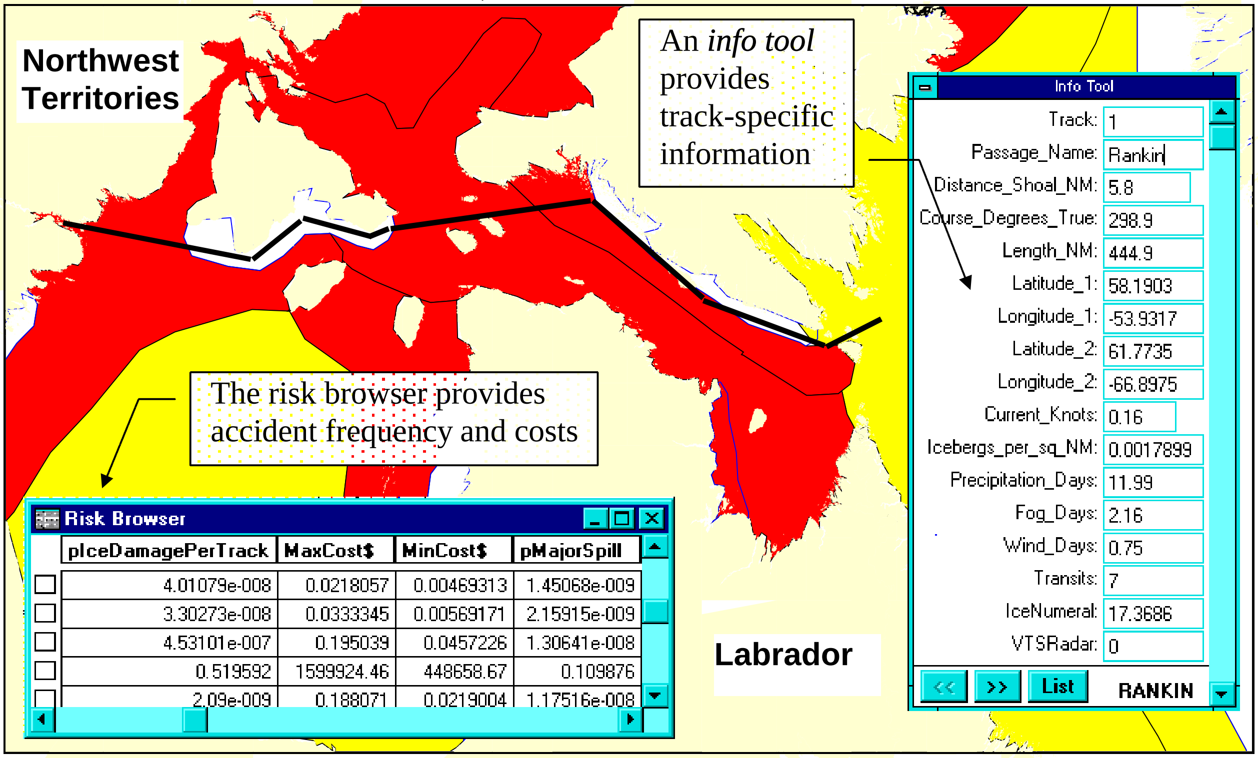

Fig. 3. TNSS risk analysis output

...DENT RATES PER M... ...Y REGION AND CASUALTY TYPE,

JUNE TO ... 1977 - 1991

Region	...nual	Exposure	Grounding Total	Frequency	Ice Damage Total	Frequency	Collision Total	Frequency	Striking Total	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	57 857	0.3	4.58E-06	0.8	1.40E-05	0.0	0.00E+00	0.0	0.00E+00
Lancaster - Barrow	Shipmiles	10 993	0.1	1.23E-05	1.5	1.39E-04	0.0	0.00E+00	0.0	0.00E+00
Davis Strait - Labrador	Shipmiles	89 301	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	6 709 970	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	5 892 381	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 &	5 898	6.1	1.05E-03	0.0	0.00E+00	4.4	7.53E-04	8.9	1.50E-03

Departures

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

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

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.

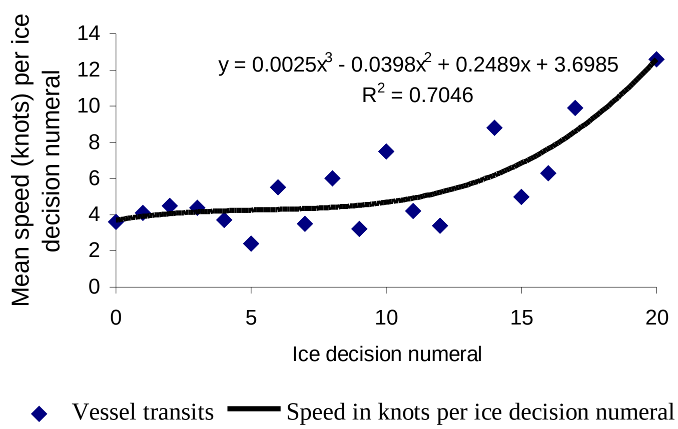

Fig. 4. Mean vessel speeds in positive ice, 1976 - 1992

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 a 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, J. & S. 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 is also a problem inherent 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].

These problems with current casualty databases can be approached by a qualitative record by record examination by mariners who can appreciate with depth the tasks at hand on a bridge. 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 the bounty of 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 play the most important role. It is shiphandling errors causing strikings, collisions and groundings in ports that might sway the results to provide 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	-	-	-	107	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	300 000 - 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 fishing vessel fleet that would enable the vessel to maintain a higher and safer speed.

A simple passage can be analyzed using the expert judgment approach in a few minutes; 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 tracks 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 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 the marine experts with decision-making. The development of a geographic interface to historical marine risk data was achieved, as was the 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.

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