REDUCING RISK – WITH THE MARINE NAVIGATION SAFETY SYSTEM

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Introduction

Recent marine casualty events in North America and abroad have riveted the attention of maritime administrations on waterway safety. Canadian authorities, who were particularly concerned by the Valdez super-tanker casualty, launched a research initiative entitled Arctic Tanker Risk Analysis (ATRA) [1] with the objectives of advancing marine risk analysis techniques and developing quantitative means of estimating risk. This five-year program dealt with an icebreaking oil-bulk-ore carrier's trade route from an oil terminal in the high Arctic islands (Bent Horn, NWT) to Montreal, Quebec.

These preliminary investigations produced a toolset for marine risk analysts made up of georeferenced marine casualty databases, environmental info-sets, route planning and analysis tools, fault tree representations for various classes of marine accidents, and accident consequence models to facilitate risk estimation [2].

The Canadian Coast Guard, having explored the ATRA deliverables, expressed a requirement to estimate waterway risk under varying levels of short range aids-to-navigation services, in a way that would be judged satisfactory by staff level of service officers, commercial mariners, and pilots. Thus the Marine Navigation Safety System (MNSS) project was initiated. This paper describes the various aspects of the project: the attributes that allow the 99.9% pre-processor to compute track width(s) surrounding a vessel to ensure safe passage; the marine consequence analysis techniques deployed; the risk estimates obtained from the analysis of a specific waterway; and the validation of the MNSS results against the USCG waterway analysis and management system (WAMS).

The challenges for any new, proposed technology are credibility, ease of application, and return on investment. New marine risk analysis technology will only be adopted if it is seen as producing reasonable risk estimates and if the analysis techniques are understood by waterway users. Return on investment in this case is measured by the safety benefits accrued: lives and property saved, and environmental casualties averted.

Requirements in Aids-to-Navigation Assessment

The Canadian Coast Guard is committed to taking advantage of the latest developments in marine navigation technologies and to positioning Canada as a world leader in the application of new marine technology. With the many recent advances in electronic navigation technology, commercial mariners are relying more heavily on on-board aids such as electronic chart displays, ECDIS, and DGPS. Coast Guard continues to promote the use of new technology as part of its commitment to provide more equitable, safe, cost effective, and environmentally friendly service across Canada. In light of the Marine Services Fee, and with the compensatory support of modern on-board navigation systems, commercial users are also encouraging the reduction and removal of conventional aids to navigation.

The assumption underlying the current Aids Modernization project is that DGPS and ECDIS will significantly change the future requirements for conventional aids to navigation in confined commercial channels. The MNSS project is viewed as part of the validation of this assumption.

The standards and design for the provision of conventional aids to navigation are contained in the Levels of Service (LOS) Standards. Adjustment of the standards to reflect the future benefits of using DGPS and ECDIS is under consideration, recognizing that safe navigation in modern times relies on a mix of on-board electronic aids and conventional aids such as buoys and beacons.

The LOS Standards identify risk elements in terms of specific hazards, while designing a safe navigation passage. The MNSS has given Coast Guard an opportunity to investigate changes to the risk base related to striking, grounding, and collision.

The MNSS model LOS pre-processor incorporates many of the basic components of the existing LOS Standards. The LOS pre-processor, however, is not considered a replacement for the current Standards for the provision of aids to navigation.

The concept generated by the MNSS model for the Canso Strait test site proved to be a promising first look at evaluating change to the risk base resulting from proposed changes to existing aids to navigation systems under the Aids Modernization project.

Basic Tool Set

The basic tool set of the MNSS is a Geographic Information System (GIS) used to store geographic data and to provide a marine risk analysis interface to manage risk estimation for a particular waterway route segment, combined with external pre- and post-processors used to modify predicted casualty rates and consequence magnitudes.

MNSS design

Figure 1 illustrates the process of assessing marine navigation risk within the MNSS. This example is oriented to LOS analysis or Aids to Navigation requirements. The system is run for each vessel category, environmental navigation condition, track segment, and traffic volume.

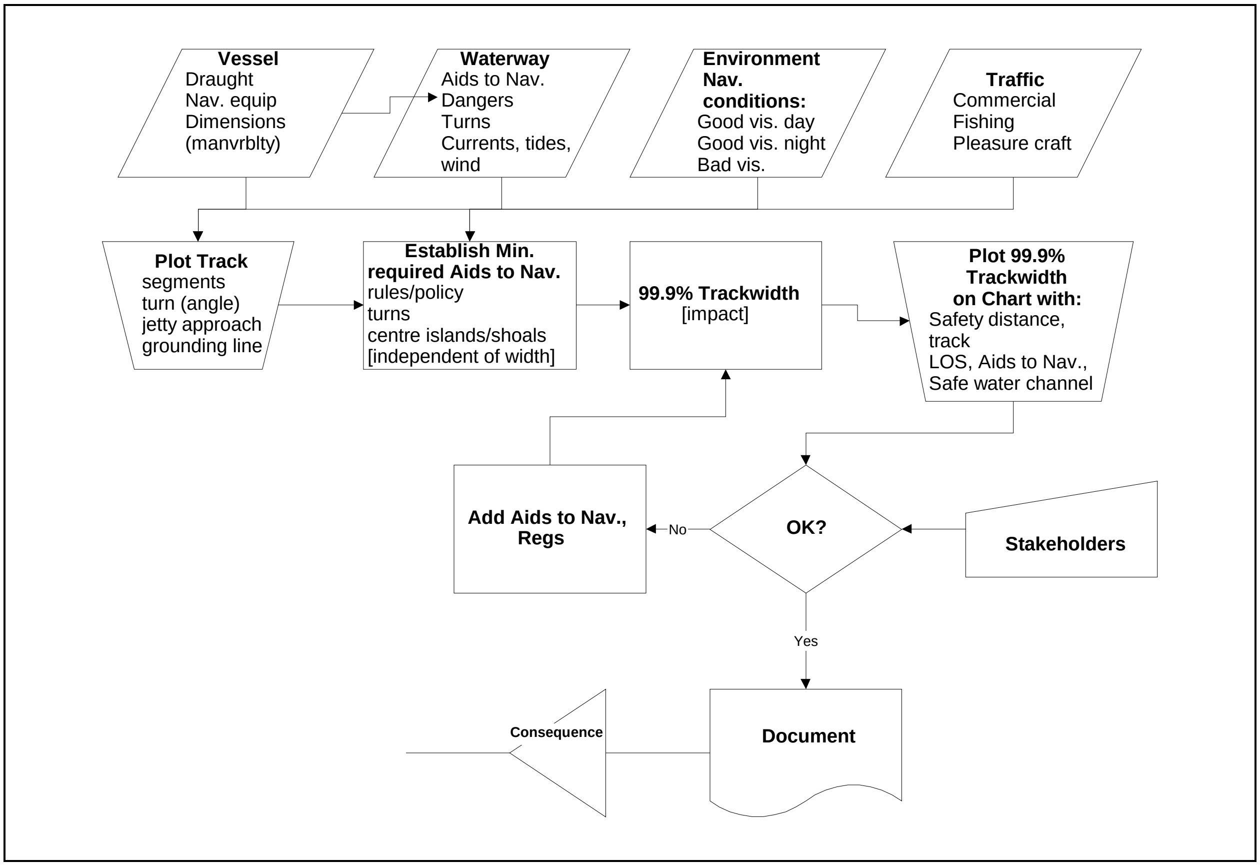

Figure 1 MNSS design

From the experience with developing complex fault trees for grounding, collision, striking, and ice damage risk in the Arctic Tanker Risk Analysis project - ATRA phase III, TP 12814E [2] - it was clear that further work to develop and calibrate a predictive marine risk model would require visual modelling software that allowed risk managers, mariners, and decision-makers to participate in its development and use. This led to the use of Excel and MapInfo GIS. The 99.9% pre-processor was modelled in Excel, using Crystal Ball for Monte Carlo simulation.

MNSS data

The MNSS uses the most detailed environmental, navigation chart, traffic, and marine casualty data available, thus enhancing risk communication by providing both decision-makers and stakeholders with organized and relevant information. This risk information data base is designed to grow as other marine risk issues are examined. Data tables in the MNSS were created from government sources and ATRA phase III.

Casualty data from the Canadian Transportation Accident Investigation and Safety Board (TSB) were converted into MapInfo format and categorized by GeoInfo Solutions into the Vessel Traffic Services (VTS) ship type and TSB casualty type groups. The MNSS casualty table contains 20-year averages from 1975 to 1995, as well as over 27,000 records.

Traffic data were converted from summary VTS Lotus tables into an Excel spreadsheet format. Both accident and traffic data were pre-processed into frequency counts by casualty type, VTS region, vessel type, and month. The traffic table produced for the MNSS contains four-year averages from 1990 to 1993.

Cause, conditional probability, and cost data provided in the MNSS as default tables are primarily from the final reports of ATRA II, TP 12325E [3] and ATRA III. ATRA II details how these parameters were determined. A user may choose to temporarily replace these default tables with those from other studies.

Biophysical, social, and environmental data were obtained from Statistics Canada and Environment Canada. Wind, current, and visibility statistics for Canso Strait were used as input tables to the 99.9% pre-processor in the MNSS, and receptor data were used to help identify the resources at risk and the associated stakeholders. Biological resources and human activity maps detail the extent of receptors that could be affected by an oil, chemical, or LNG spill. These maps are used to document and modify the process of estimating consequences in the MNSS.

Digital navigation charts were converted to MapInfo format from DXF files. This included the creation of a minimum navigation symbol set to overlay the landform and depth contour polygons.

Pre-Processor

Risk measurement

Once the prototyping software was chosen, the next consideration was the unit of measure to describe the casualty risk. In the ATRA project, both relative risk indices and absolute probabilities were estimated. While the causal relationships were developed to the extent necessary to predict a change in risk level from a change in risk policy, the model lacked a complete set of estimates for event failures in the fault trees. A literature search revealed many useful parameter estimates, but measurement problems in these studies remain unresolved.

The solution to marine risk modelling became apparent when the Canadian Coast Guard's method of measuring waterway risk or LOS of aids to navigation was examined. Risk was measured by testing to see whether or not a threat threshold was met or exceeded. Threats were vessel specific and included such parameters as distance to shoals, currents, and wind. This relative risk index methodology was similar to that employed in ATRA I [4], but it suggested that a common unit of measure for each threat was possible if the parameters were organized by tasks performed by a watchkeeper. Furthermore, since grounding risk depends most on distance to shoals, distance was the key.

The establishment of a safe buffer width

It was not difficult to imagine a variable safe buffer width about a ship as it transits a unique track in a passage plan. Ships at anchor are marked on charts with uniquely estimated "safety swinging circles" representing the furthest extent of the bridge, the stern, and the safety margin. This safety buffer takes into account such parameters as the scope of cable payed out, the fixing accuracy and frequency, the prevailing weather, holding conditions, and the notice for power.

Similarly, a "ship domain radius" has been used to describe a safe buffer about a ship with respect to collision avoidance. Therefore, it was decided to re-work and simplify the fault tree relationships of the Tanker Navigation Safety System and develop independent and additive components that collectively measure the minimum distance to shoals required for safe navigation 99.9% of the time. This Excel spreadsheet was termed the 99.9% pre-processor.

Contributing factors to zone width calculation

The 99.9% buffer width is the distance required over a segment of a waterway for the minimum safe operation of a vessel. Safe is defined as the distance that would ensure that 999 out of 1000 transits, operating with normal care and attention, would not go aground, or that only.1% of transits would experience any difficulty. It is expected that even the one out of 1000 would usually be lucky and would not result in a casualty. In risk terms, the 99.9% distance would likely result in a risk of 10E-4 to 10E-6 per nautical mile.

The 99.9% distance is measured perpendicular to the Channel Track and has up to six independent components, each of which contributes to the safe distance in a separable way. These components are defined as follows:

- Beam and Crab - The physical distance across the channel of the vessel at a nominal three degrees to the track. This is the overall lateral distance covered by the vessel as it proceeds down the channel at an angle to the track (part width, part length). The Weather factor includes a factor to increase the crab angle in response to environmental conditions.

- Shiphandling - The maximum range of distance of the centre line of the vessel about the intended track of the vessel in calm conditions, on a straight segment of the waterway, with a given level of visibility. This distance depends on the physical characteristics of the vessel (e.g., inertia, rudder response time) and the course-keeping skill of the bridge team.

- Positioning Quality - The maximum range of the centre line of the vessel about the intended track of the vessel due to the estimation of the location or position of the vessel in the channel or relative to the track on the chart. This distance varies with the aids to navigation of the waterway, the navigational aids on the vessel, the visibility, the shoreline topography and landmarks, and the variation of the clearing contour line. This distance is estimated as the "maximum probable error" in the determination of the position of the vessel in the channel segment. The position distance varies with the skill of the bridge team.

- Turn Paths - The maximum range of the centre line of the vessel about the Chart Track in a turn. Each vessel will choose a different start location, turn radius, and end location for a turn. This will trace out a defined path for vessels making the turn. The cross track width of the locus of all paths defines the turn path distance. Increases in the 99.9% distance due to the radius of the curve and the length of the vessel are accounted for in the Beam and Crab factor. Environmental conditions are accounted for in the Weather factor.

- Weather Distance - The increase in the 99.9% distance due to the effects of wind, waves, visibility, tides, and cross currents in the waterway segment. The distance is estimated based on experience with the impact of these factors as defined by the current CCG design method. The Weather factor includes distance components for the ship Crab angle, for Shiphandling and for Positioning. The Weather distance varies with the skill of the bridge team.

- Passing, overtaking, or crossing distance - If passing is not permitted, then the 99.9% distance is found from the sum of the previous components. If passing is permitted, then the 99.9% distance is found from the combination of two specified vessels passing (1 and 2) as the sum A1+A2+B1+B2+((C1+C2)/2)+((D1+D2)/2)+ ((E1+E2)/2)+F1-2, where F1-2 is the maximum probable (i.e., the 99.9% extreme) least clearance distance between vessel 1 and vessel 2.

A segmented approach to risk measurement

Referring to Figure 2, one can see that the output values of the independent navigation components are grouped in the top right of the pre-processor form. These values vary with the Monte Carlo simulation and the maximum value is then entered in the 99% width cell. This value represents the width of channel required for safe navigation for a particular track segment. This process is repeated by creating a spreadsheet for each straight track and turn segment comprising a navigation passage plan.

Modification of accident rates

The next step was theorized as a new means of measuring the LOS and of estimating changes to casualty probability, which account for the risk mitigation benefits of ECDIS and other fitted navigation aids. Since the threat of grounding increases as a ship approaches a shoal, a relationship between the calculated safe buffer width and the channel width probably exists. This ratio was used to provide a new measure of the LOS. A preliminary trend curve was fitted to historical grounding frequencies and buffer width/channel width data for a small sample in the St. Lawrence River. The sample proved to be too small to be significant, but with further development of the 99.9% pre-processor to increase its sensitivity to the threats of narrow channels, it is expected that the means of measuring changes in grounding risk from changes in navigation buoy deployment, vessel speed, the presence of vessel traffic management, etc., will be available, understandable, and utilized. In the meantime, a simple LOS ratio can be used as a multiplier to modify historical casualty rates.

Study Area:

General Inputs	
Category	I
Vessel Beam (feet)	100
Vessel Length (feet)	1000
Displacement (GRT)	100000
Speed (Knots)	7
Bridge Experience Multiplier	1

Output (feet)	
Beam and Crab	152
Shiphandling	160
Position	333
Turn	0
Weather	166
Passing	0
"99.9%" (average)	**811**

Format

Reset multipliers to default

LOS	
Track/Turn Length (NM)	0.7
Channel Width (min)	1800
99.9% Width (max)	1500
LOS C	**0.83**

A	**Beam and Crab**	
	Crab Angle (degrees)	3

B	**Shiphandling**	
	Course keeping Width (feet)	160

C	**Positioning Quality**	**Day**	**Night**	**Poor Visibility**	**Conventional Aids to Nav.**
	Conventional: Visual/Radar	75	150	330	Med-High (emphasis on ranges)
	Conventional & GPS	150	200	330	
	Conv. & ECDIS w. DGPS	60	90	210	
	Chart Accuracy	120	120	120	
	Best Position Accuracy	75	150	330	
	Next Best Position Accuracy	150	200	330	
	Positioning Quality (feet)	220	291	450	
	Navigation Conditions	Weighted by Visibility Frequency			
	Sig. Visibility Hazard (NM)	<5.4			
	Poor Visibility Frequency (%)	40			

D	**Turn Paths**	
	Degree of Turn	0
	Turn Path Factor	1

E	**Weather**	Manual Input from Weather Table and WX Data			
	Reset to Default WX Freq.	1	**A**	**B**	**C**
	Level II Frequency (%)	40	49	11	7
	Level III Frequency (%)	30	73	16	10
	Environmental Sum	166	122	27	17
	Multiplier	1			

F	**Passing, overtaking or crossing Traffic**	No	This control affects all worksheets	From	To
	Passing Distance	300		201	399

Figure 2 99.9% Pre-processor

Consequence Modelling - Post-Processing

The base MNSS system includes a wide range of categories of marine tanker consequence costs, based on worldwide tanker spill data (i.e., International Oil Pollution Compensation Fund, IOPCF, and U.S. Mineral Management Service, MMS), spill clean-up costs, and civil fines/penalties levied, among other consequence costs. Under a more complex scope of consequence analysis, these inherent data sets, combined with casualty frequency information, could provide a first-cut risk estimate.

In keeping with the modular nature of the toolset, detailed consequence analysis requirements (perhaps in support of quantitative investigation of a known "hot spot" in the waterway) are fulfilled through post-processing techniques. The sole requirement of the post-processor(s) is that the resultant affected zones be readily handled by the MNSS, that is, the data format must be compatible with the native GIS.

We have deployed off-the-shelf consequence modelling tools to investigate the extent of the impacted zone arising from hypothetical chemship releases and have imported and overlaid this data on electronic charts to determine the risk receptors at stake. Under a pool-fire scenario, heat radiation zones have been established, and toxic cloud and vapour cloud explosions, as well as explosion over-pressure effects, have been examined. Figure 3 illustrates the hypothetical results of a collision involving a product tanker, where a chemical release event leads to the consequences just discussed. the affected zones and the waterway and shore-based resources at stake can then be identified. This type of analysis enhances the stakeholders' understanding of the extent of damage and consequence costs that could arise from a marine release of significant magnitude.

Marine administrations are sometimes loath to consider the effects of a tanker release in such detail; however, if they are to develop a meaningful dialogue about waterway risk with waterway stakeholders, including shipping associations, pilots and masters, and petrochemical manufacturers, these scenarios must be examined. An improved understanding of human health, environmental impact, property loss, and business interruption in monetary terms would help to sharpen decision-making regarding investment in waterway safety.

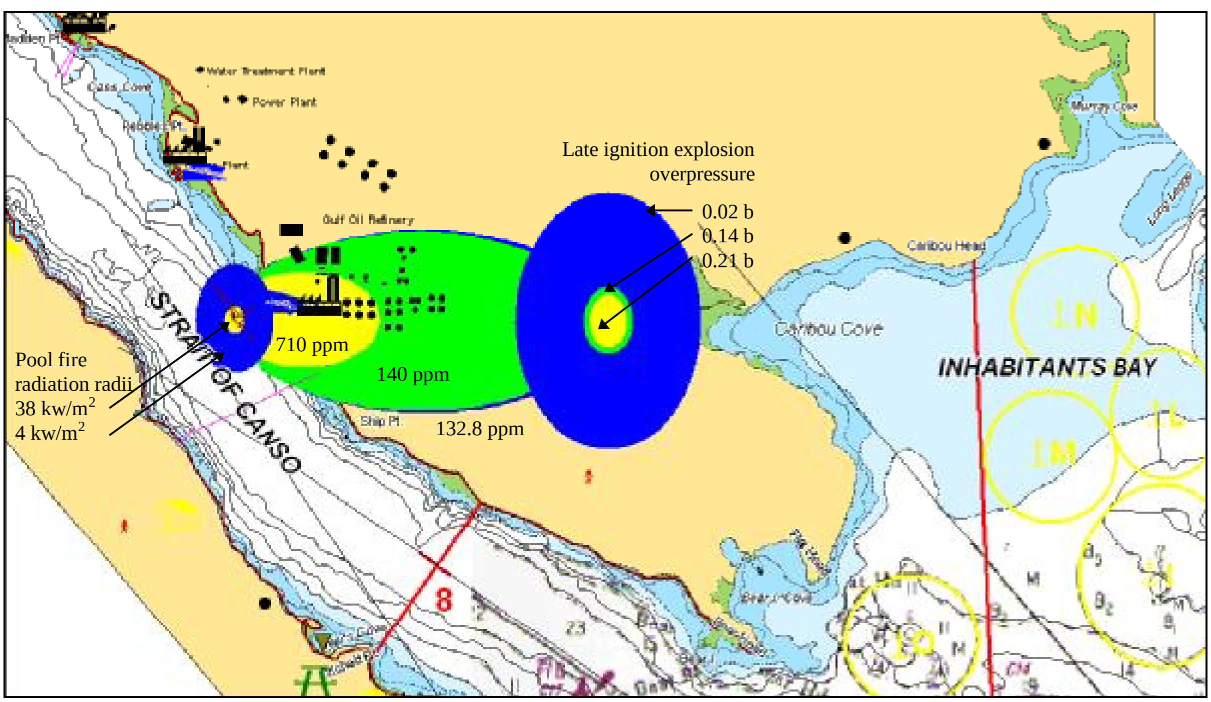

Figure 3 Risk Consequence Map

Risk Results - the Canso Strait Experience

Risk estimates have been produced for the Canso Strait waterway to demonstrate MNSS capabilities.

Specifically, the probability of groundings caused by navigation or ship-handling error can be changed within the MNSS by multiplying the grounding frequencies caused by fixing or shiphandling error by the proposed LOS measure. Accident rates were calculated for the status quo and various options, and output as maps (see Figure 4) and tabular reports of grounding rates and total costs (see Table 1).

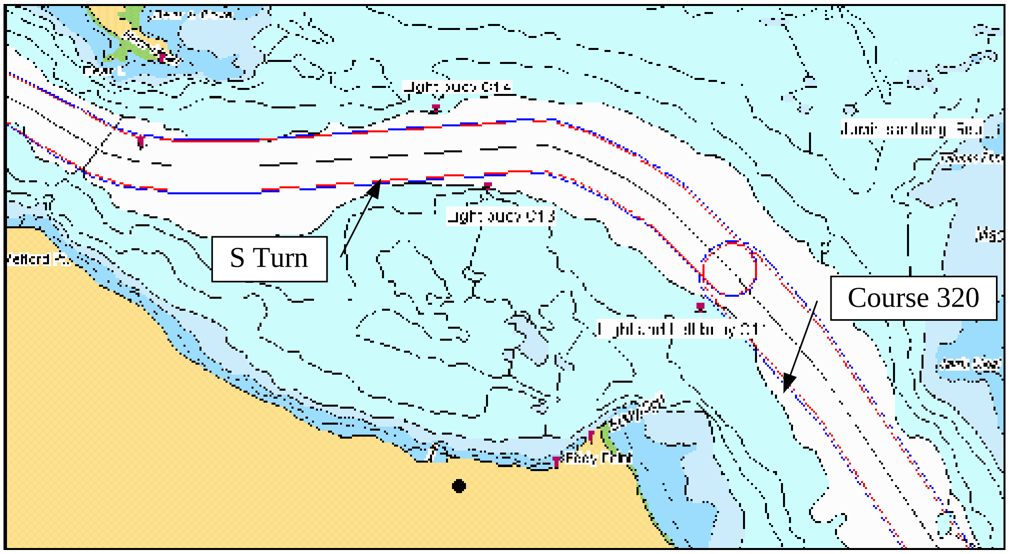

Figure 4　　Canso Strait approaches

Depicted in Figure 4 are two track segments studied using the MNSS tool set: the “s” turn and course 320°. Each track segment is surrounded by two buffer zones, representing the variation in the 99.9% buffer widths resulting from different navigation aid scenarios; however, all the scenarios illustrated include ECDIS.

- The “s” turn buffers are smaller than the 320º approach track because a no-passing rule was voluntarily adopted as a standard procedure.
- The “s” turn outside buffer represents the hypothetical removal of Janvrin Range and the addition of ECDIS; the tighter inside buffer results from the addition of ECDIS to the status quo conventional aids.
- The 320º approach track outside buffer represents the hypothetical removal of Durell Pt. Range and the addition of ECDIS; the tighter inside buffer results from the addition of ECDIS to the status quo conventional aids.

The overlaying of these safe navigation buffer zones on a navigation chart reveals that passage can occur without the buffer zone intersecting a “no-go” line, i.e., a depth contour equal to the design vessel's draught. The greater the manoeuvring room in excess of the buffer width, the safer the channel and the higher the LOS.

Tables 1 and 2 are typical reports resulting from an MNSS analysis. Both show grounding frequency ranges (min and max), total cost, and consequence frequency ranges for environmental and human effects categories.

Table 1 depicts total annual costs for groundings, considering the "s" turn segment with status quo aids to navigation. Note the minor reduction in annual costs indicated in Table 2, where ECDIS carriage is assumed, in addition to the conventional aids.

Table 1 Level 2 tanker grounding report for the "s" turn status quo

Cause Factor	Statistic	Grounding Frequency	Total Cost	Oil Spill Frequency	Death Frequency	Injury Frequency
Grounding	**Annual**	**Annual**	**Annual**	**Annual**	**Annual**	**Annual**
Position Fixing	Min	0.0028	$1 735	0.0003	0.0000	0.0002
Position Fixing	Max	0.0084	$27 004	0.0008	0.0001	0.0005
Shiphandling	Min	0.0046	$2 863	0.0004	0.0000	0.0003
Shiphandling	Max	0.0139	$44 615	0.0013	0.0001	0.0008
Engine, power or prop failure	Min	0.0029	$1 808	0.0003	0.0000	0.0002
Engine, power or prop failure	Max	0.0088	$28 179	0.0008	0.0001	0.0005
Steering gear breakdown	Min	0.0017	$1 054	0.0002	0.0000	0.0001
Steering gear breakdown	Max	0.0051	$16 437	0.0005	0.0001	0.0003
Total	Min	0.0122	$7 536	0.0011	0.0001	0.0007
Total	**Max**	**0.0366**	**$117 409**	**0.0034**	**0.0004**	**0.0022**

Table 2 Level 2 tanker grounding report for the "s" turn conventional aids with ECDIS

Cause Factor	Statistic	Grounding Frequency	Total Cost	Oil Spill Frequency	Death Frequency	Injury Frequency
Grounding	**Annual**	**Annual**	**Annual**	**Annual**	**Annual**	**Annual**
Position Fixing	Min	0.0027	$1 647	0.0003	0.0000	0.0002
Position Fixing	Max	0.0080	$25 654	0.0008	0.0001	0.0005
Shiphandling	Min	0.0044	$2 719	0.0004	0.0000	0.0003
Shiphandling	Max	0.0132	$42 385	0.0012	0.0001	0.0008
Engine, power or prop failure	Min	0.0029	$1 808	0.0003	0.0000	0.0002
Engine, power or prop failure	Max	0.0088	$28 179	0.0008	0.0001	0.0005
Steering gear breakdown	Min	0.0017	$1 054	0.0002	0.0000	0.0001
Steering gear breakdown	Max	0.0051	$16 437	0.0005	0.0001	0.0003
Total	Min	0.0118	$7 304	0.0011	0.0001	0.0007
Total	**Max**	**0.0355**	**$113 829**	**0.0033**	**0.0004**	**0.0021**

Validation

The outputs from the 99.9% pre-processor and the United States Coast Guard Waterways Analysis Management System (WAMS) [5] were compared by the Institute for Risk Research [6]. The results of the WAMS study provide an excellent source of data to assist in validating the 99.9% pre-processor. Unfortunately, the comparison is subject to certain limitations of the WAMS data. For example, the sea trials were done with a group of ships of less than 45 000 DWT, and estimates for larger ships were obtained by using a scaling factor.

Mapping the parameters

Many of the six independent factors in the 99.9% pre-processor are represented in the WAMS system, but not always to the same level of detail. Also, some of the level of detail contained in the WAMS system (e.g., number and configuration of conventional aids) is not available in the MNSS system's 99.9% pre-processor. Table 3 provides a descriptive comparison of the input parameters used to compare the results of the two systems.

Results of the comparison

The 99.9% pre-processor has more variables and a wider range of possible input values for many of the variables.

For 600' vessels, the 99.9% pre-processor results tend to be higher (i.e., more cautious) than the WAMS results. WAMS results (especially when comparing turns or the use of ECDIS) change dramatically when scaling up from the 600' vessel to the 1000' vessel. For example, the turn comparison results are illustrated in Figure 5 for 600' and 1000' vessels, where the range of deviation from the line of equality is very large, i.e., +100% to -50%.

For the 1000' vessel on the 35° turn, the 99.9% pre-processor results tend to be lower than the WAMS results. The reverse is true for the 1000' vessel on the 15° turn, i.e., the 99.9% pre-processor results tend to be higher than the WAMS results. For the 600' vessel, on both 35° and 15° turns, the 99.9% pre-processor results tend to be higher than the WAMS results.

The results of the comparison show that the 99.9% pre-processor and WAMS approaches have many points of difference that should be examined more closely to determine the reasons. This could be done by research on the observed variation in position of vessels in the channel or by expert judgment.

Next Steps

Improvements to the 99.9% pre-processor and other MNSS components will be pursued under the next development initiative, where the focus of the waterway analysis will shift to the St. Lawrence River.

Table 3 MNSS and WAMS Parameters

Parameter	MNSS (99.9% pre-processor)		WAMS	
	Present	**Input Range**	**Present**	**Input Range**
Beam (feet)	Yes		Yes	
Length (feet)	Yes		Yes	
Displacement (GRT)	Yes	Not used	Yes	Used to scale-up from standard ship size
Speed (Knots)	Yes	Used in calculating of “Shiphandling” component	No	
Bridge Experience Multiplier	Yes	Used in calculation of “Position” component	No	
Crab Angle (degrees)	Yes	Continuous, range is 2.7° to 6°	Yes	2 categories: I = 0-2 degrees II = 2-5 degrees
Navigation Conditions	Yes	Values include: day; night; poor visibility	Yes	Values include: day; night; day or night; poor visibility
Sig. Visibility Hazard (NM)	Yes	Four choices: <0.5; <1.1; <2.2; <5.4	No	
Poor Visibility Frequency	Yes	User can choose from 10-90% in increments of 10%	No	
Conventional Aids	Yes	6 broad categories	Yes	Preset configurations
Degree of Turn	Yes	Continuous, range is 0° to 180°	Yes	Values include: 0-20° degree <20°
Turn Type	No	Used to calculate the turn path cross track distance	Yes	Values include: cutoff; noncutoff
Weather	Yes	• Used as input to: “Beam and Crab”, “Position”, “Shiphandling” • Combination of: Wind Speed; Wave Height; Current Speed. Can specify percentage of each of 3 categories: I = light winds, etc. II = moderate winds, etc. III = strong winds, etc.	Yes	Called “Environment”, 2 categories: I = 0-2 degrees of crab II = 2-5 degrees of crab
F) Passing	Yes	If yes, user can specify number of feet to be added	Yes	

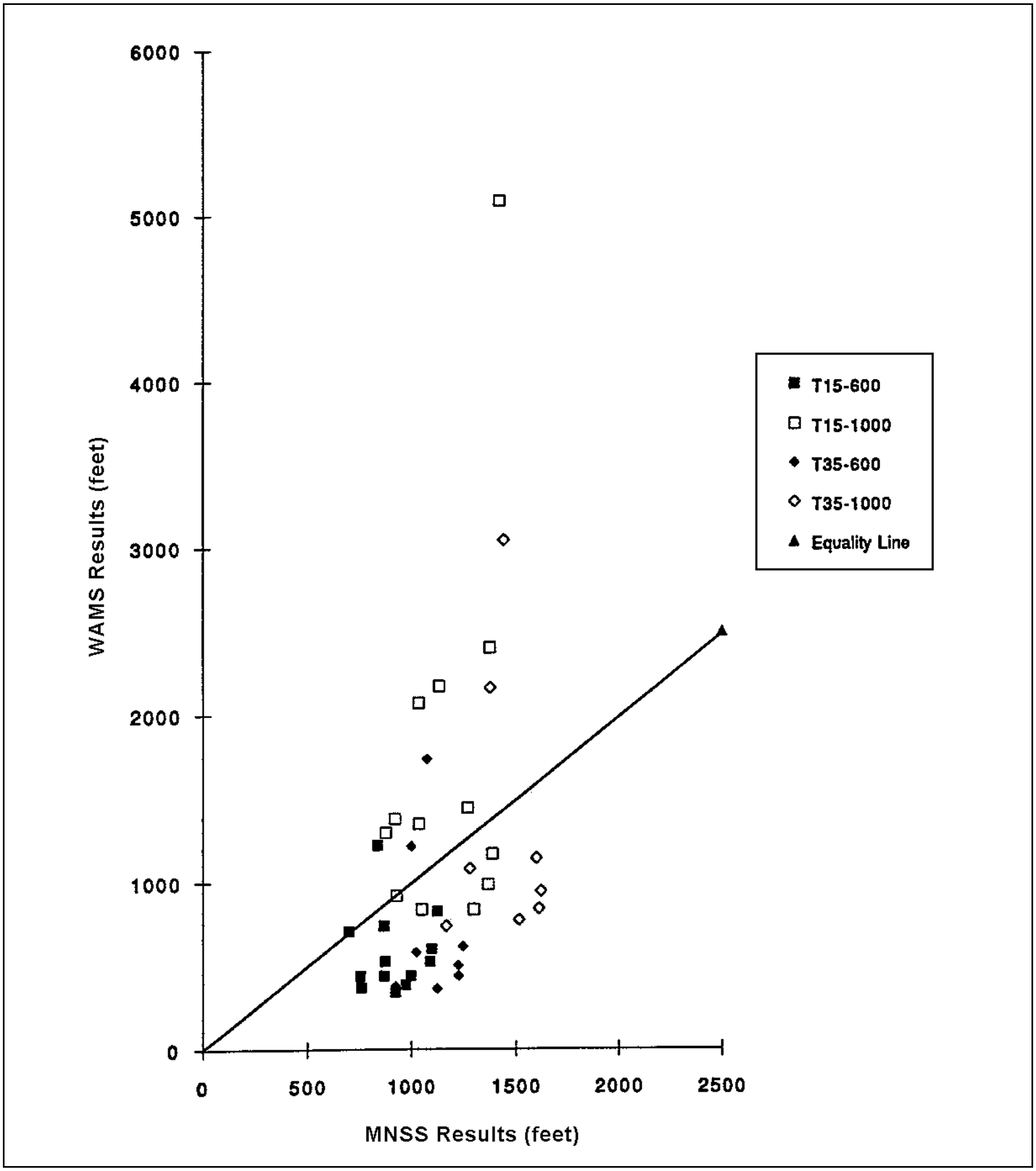

Figure 5 **Results for turns of 15 and 35 degrees for 600 and 1000 foot vessels**

References

[1] Loughnane, D., B. Judson, and J.D. Reid, *Arctic Tanker Risk Analysis Project,* Marit. Pol. Mgmt, 1995, Vol. 22, No. 1, 3-12.

[2] Loughnane, D. (1993) *Final Report: Arctic Tanker Risk Analysis, Phase I*, TP11540E, Transportation Development Centre, Transport Canada.

[4] Judson, B. (1996) ATRA III *Tanker Navigation Safety System*, TP12814E, Transportation Development Centre, Transport Canada.

[3] Loughnane, D. and B. Judson. (1994) *Final Report: Arctic Tanker Risk Analysis, Phase II*, TP12325, Transportation Development Centre, Transport Canada.

[5] Smith, M.W., K.L. Marino, and J. Multer. (1985) *Short Range Aids to Navigation Systems Design Manual for Restricted Waterways,* United States Coast Guard, Washington, D.C.

[6] Shortreed, J. and D. Del Bel Belluz. (1997) *Risk Analysis of Marine Navigation Aids, A Comparison of WAMS and MNSS Results*, IRR Report 33, Institute for Risk Research, University of Waterloo.