COLLISION RISK IN THE APPROACHES TO THE STRAIT OF JUAN DE FUCA:
An Analysis of Circumstances and Traffic Routing

by

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Abstract

Marine traffic casualties in the approaches of the Strait of Juan de Fuca risk the accidental release of oil or other hazardous liquids which threatens the loss of property, human life and the spoiling of the coastal zone. Traffic in the approaches to the Strait has increased at three percent annually from 15 828 vessel transits in 1980 to 19 887 transits in 1989. This traffic carries as fuel about 40 percent of the total volume of crude oil transported from Valdez, Alaska to Puget Sound by about 333 tankers annually. Collisions are of particular concern as they accounted for 83 percent of those casualties caused by human error. The problem of marine collisions in the approaches to the Strait of Juan de Fuca was investigated with the purpose of identifying causal and contributory factors, modelling collision risk as a Poisson distribution, and designing an alternate traffic routing scheme intended to reduce casualties.

Initially, the causal and contributory factors to marine collisions in the study area were identified to direct the investigation towards practical and applicable solutions to the specific problems encountered. Traffic patterns were reconstructed by using a Geographic Information System to plot traffic positions sampled from radar position information obtained from Tofino Vessel Traffic Services and fishing vessel positions surveyed by Fisheries and Oceans. This enabled the calculation of traffic density, courses and speeds. It was found that through vessel traffic nearly doubles in frequency during summer months coincident with the fishing season, and, while vessel traffic tends to separate into inbound and outbound sectors, average traffic routes pass through the most active fishing areas.

Collision reports indicate problems of excessive speed, low visibility and high traffic density. A detailed analysis of the climatological and navigational conditions associated with vessel traffic and the circumstances of collisions confirmed the significance of these contributing factors. Speed was found to be excessive in eight out of ten collisions, seven collisions occurred in an area of high traffic density and six occurred in restricted visibility. Furthermore, the finding that mariners proceed through the approaches to the Strait uncontrolled at an average speed of 12.5 knots, without a significant reduction in vessel speed where prudent, indicates that an inappropriate level of risk is accepted.

It was demonstrated that the collision rate in the approaches to the Strait of Juan de Fuca is Poisson distributed with a probability of 0.25 per 5 000 transits. Since the collision rate is correlated with average traffic densities encountered and ship-miles, it can be predicted and reduced through the modification of traffic patterns. The benefit of traffic routing in the approaches to the Strait was demonstrated by a 68 percent reduction in absolute risk of collision during the peak traffic month of July and an annual reduction of 40 percent.

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1 Introduction

This thesis is concerned with marine traffic safety and the prevention of accidental release of oil or other toxic cargoes into the sea. Human capacity for error is recognized as a factor which can neither be eliminated through investment in technology nor unilateral certification requirements. Human error can be accommodated in risk reduction measures which permit a deviation from the norm to be recognized in sufficient time to prevent a casualty–through traffic routing.

1. Problem area

Oil transported through the entrance to the Strait of Juan de Fuca includes bunker and distillate carried as fuel in merchant ships, crude oil carried by tank vessels to refineries in Puget Sound and crude oil from Vancouver to the Far East. In 1988, 14 tankers each carrying an average of 65 000 cubic metres[1] of Alberta heavy crude oil proceeded from Trans Mountain Pipeline's terminal at Westridge in Vancouver to Japan, Taiwan, Malaysia, South Korea and Thailand (Shaffer, 1990, p. 21). During the same year, 333 tankers transported over 25 million cubic metres of crude oil to Puget Sound refineries at Cherry Point and Anacortes–a 25 percent increase in ten years. Alaska North Slope crude was

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[1] Both weight and volume can be used to measure cargo and tonnage of a ship. The usual measurement of volume is cubic metres, which is applied here, where one cubic metre is equivalent to 1000 litres or 6.29 barrels (United Kingdom Ministry of Defence, 1983).

carried in 90 percent of inbound oil tankers entering the Strait of Juan de Fuca in 1988, but accounted for only 55 percent ten years earlier (Shaffer, 1990, p. 21; Wolferstan, 1981, pp. 8-11).

Declining reserves in Alaska do not necessarily imply a decline in imports of crude oil to Washington refineries. The requirements of these refineries will undoubtedly be met by other sources in the future. Furthermore, Trans Mountain Pipeline (TMPL) is in the process of expanding its crude oil exports by 1.4 million cubic metres per year which means an additional 21 outbound tankers (Canadian Resourcecon, 1990). This is likely to be a conservative estimate as TMPL plans further expansion of its facilities at Westridge to increase its export activity. Pressure to export crude oil from Westridge may increase if high oil prices result in further development and shipment of Alberta crude offshore. It is fair to say that, given the declining world supply situation, a decline in tanker traffic is unlikely in the short term.

It is the increased commercial traffic in the eighties and the anticipated growth during the nineties, associated with an increased risk of a collision, grounding or mechanical failure and the possibility of a catastrophic release of oil or other chemical into the waters of the coastal zone which poses a problem of proportions that must be dealt with. This study will focus on collisions and their causes, for it is the "safe, efficient movement of marine traffic" which is the primary task of vessel traffic management systems (Canadian Coast Guard, *For a Safer Passage*, 1989, p.3).

2. Research significance and rationale

Environmental awareness of the risk of oil pollution is once again high on the political agenda. One should be concerned with the increasing frequency that this hazard is dominating this agenda as necessitated by catastrophic spills. Recent oil spills by the *Tenyo Maru* (1991), the *American Trader* (1990), the *Mega Borg* (1990), the *Frank Brown* (1990), the *Rose Bay* (1990), the *Exxon Valdez* (1989) and the *Nestucca* (1988) have demonstrated the trans-boundary nature and global problem of the oil pollution hazard. What is not as well perceived by the public, and only recently appreciated by government, is that hazardous oil spills are not limited to tankers. In July of 1991, Senator Slade Gorton introduced an amendment to the United States Coast Guard budget legislation in Congress to work with Canadian agencies to improve safety in the approaches to the Strait of Juan de Fuca (*Seattle Post-Intelligencer*, July 31, 1991, p. B2). However, the United States and Canadian governments appear to be responding to, rather than attempting to prevent environmental crises. Spill prevention research is in its infancy in North America.

The collision of the factory fishing vessel *Tenyo Maru* and the freighter *Tuo Hai* in the approaches to the Strait of Juan de Fuca on July 22, 1991 grasped public attention by clearly illustrating several of many possible catastrophic consequences of collisions at sea—the loss of life, property and the fouling of the coastal environment. Moreover, it illustrated the commonality in collisions occurring in the approaches to the Strait.

> Vessels bound to or from the open Pacific converge on Juan de Fuca Strait on hundreds of different tracks. They are without port pilots until they are inside the Strait and, because of language problems, many of the foreign ships have trouble talking to the Canadian Coast Guard station Tofino, which is sweeping the zone with radar. Every year there is at least one serious collision on the Big Bank–beyond vessel traffic lanes–and it usually takes place in July or August, at the height of fishing season. The crash of the *Tenyo Maru* and *Tuo Hai*, then, was statistically predictable (*Vancouver Sun*, August 3, 1991, p. B8).

Recent Canadian and United States government decisions reflect the current high profile of the oil pollution hazard. Canada's Environmental Impact Review Board recently recommended the rejection of Gulf Canada's drilling program in the Beaufort Sea because it found the federal government and industry have failed to adequately address issues of environmental safety and preservation (Environmental Impact Review Board, 1990, pp. 54-60). The United States has just signed into law the Oil Pollution Liability and Compensation Act (1990) which provides for prevention and response measures, as well as increased financial responsibility for spills. In addition, the United States placed a moratorium on offshore oil and gas leasing and development in Georges Bank, much of the West Coast and Florida.

Public concern for oil pollution has resulted in a flurry of extensive government investigations into tanker safety and oil spill response. Among the many recommendations is the need to increase research into the reasons for and prevention of accidents due to human error. In particular, Brander-Smith recommended in *Protecting Our Waters* (1990, p. 195) that: "As a priority, the Canadian Coast Guard examine existing traffic routing schemes with a view to reducing the risk of collision due to traffic concentration at the entrance to Juan de Fuca Strait." Furthermore, Anderson's *Report to the Premier on Oil Transportation and Oil Spills* (1989, p. 50) contains a similar recommendation that "consideration be given to extending the routing system some more miles to seaward of the entrance to the Strait of Juan de Fuca, so as to increase separation and to move the Far Eastern traffic route more to the west." These, and other reports are generally in harmony in recommending the need to investigate the requirements for mandatory traffic routing systems, tanker exclusion zones, and vessel movement restrictions according to weather and visibility limitations (States/British Columbia Task Force, 1990; United States Coast Guard, 1989).

Given the problem of increasing tanker traffic in a confined sea area, the question arises, what are the risks of a vessel collision which may lead to oil pollution of the environment? A risk analysis that could identify and quantify the relevance of causal and contributory factors and assess risk reduction alternatives based upon this analysis would provide practical direction for marine risk management authorities.

One must be wary of marine casualty analyses that do little more than suggest the obvious fact that most accidents are due to human failure rather than engineering or structural failure. Wenk (1982, p. 181) suggested that 64 percent of accidents are caused by human error. Given this percentage, one is left to question the circumstances leading to human error. Furthermore, if the primary cause of collisions is human error and the primary cause of a foundering is engineering equipment failure, it is highly questionable to generalize about the nature of "casualties."

The States/British Columbia Task Force (1990) advocated solutions such as improved training of the mariner, mandatory double-hulling and electronic charting. However, it is insufficient to conclude that human error is the culprit, therefore, training, certification or a technical solution are in order. One must recognize that a well trained master driving a double-hulled tanker equipped with electronic charting must continue to navigate with other vessels not so well equipped, therefore, the common denominator of risk remains essentially unchanged. The nature of collisions through investigation of the conditions present at sea must be understood before one should conclude that mariners require further training, or an "armoured" vessel is required as a substitute for poor watchkeeping.

Over two thousand hours of watchkeeping at sea have given this author an intimate knowledge of the circumstances when errors in judgement are most likely to be made. For example, collision avoidance in reduced visibility in a narrow channel or on a fishing bank requires a continuous estimation of safe speed. It is increasingly difficult to proceed at the same speed as one enters a fog bank with numerous unidentified radar contacts at close proximity with varying courses and speeds. Hence, the possibility of making an error increases with the addition of each factor which is considered when assessing a safe speed. It is not sufficient to conclude that most accidents at sea are caused by human error when the circumstances leading to an accident can be modified to reduce the risk.

International research has recognized the human element in decision-making at sea and the importance of circumstances leading to an error in judgement.

> It has frequently been said that human error is responsible for 80 percent or more of all casualties. This figure is of doubtful significance; as much depends on the type of casualty and extent of damage being considered, and the proportionate contribution of other factors. Almost all serious collisions can be at least partly attributed to human error. Some groundings result from vessels breaking adrift from moorings, or from the parting of tow lines in exceptional weather conditions, but human error contributed to a very high percentage of this type of casualty (Cockcroft, "A Comparison of Safety Records" *Journal of Navigation*, 1981, p. 219).

Certainly some accidents can be solely attributed to human error where training and certification are in doubt, however, the investigation of the circumstances surrounding human errors in judgement has identified likely contributing or causal factors. This provides an impetus and framework for a local investigation.

International research has concentrated on improving marine safety through the systematic study of casualty data and the evaluation of traffic rules, traffic management and routing systems. The development and subsequent assessment of traffic separation schemes is an important method of organizing marine traffic to reduce the incidence of collisions, and it is the management of traffic which appears to be the most promising path for this investigation.

3. Purpose and objectives

It is hypothesized that the risk of collision is related to vessel speed, traffic density and other factors which could be controlled through vessel traffic regulation and traffic separation schemes. This study seeks to model the probability of vessel collision and identify the relative importance of various contributory factors to marine collisions in a congested marine environment–the entrance to the Strait of Juan de Fuca. This will be accomplished by measuring the significance of collision risk factors such as visibility, time of day, traffic density, vessel type and speed, and by modelling collision risk as a Poisson distribution. In particular, the coincidence of collision location with high density fishing and through traffic areas will be examined.

This thesis should help to identify routing and traffic control options which could effectively reduce collision and pollution risks. The effectiveness of the current traffic routing system will be analyzed by comparing the results of the collision probability estimates with those of a modified scheme which is designed to reduce the traffic density and potential conflicts with fishing vessels, through traffic and military exercises.

4. Research objectives

(1) Identify those contributory factors which have been found to increase the probability of collision by previous studies on the West Coast and elsewhere.

(2) Quantify the various contributory risk factors identified in contributing to collisions and model collision risk as a Poisson distribution.

(3) Design an alternate traffic routing scheme according to United Nations standards and evaluate its effectiveness in risk reduction.

5. Study area

The approach to the Strait of Juan de Fuca is the focal point for marine traffic transiting to ports of the Strait of Georgia and Puget Sound (Figure 1). It is a threshold between two forms of navigation, ocean passage and pilotage, and has a localized navigation risk resulting from the shift to a more intense level of watchkeeping. The study area encompasses 1 851 square nautical miles,[2] including the waters from 124° 40′ west longitude extending 54 miles to seaward to 126 degrees west longitude. It is bounded to the north by Cape Beale and the shoreline of Pacific Rim National Park and extends southward to 48° 12′ north latitude (Figure 2). Olympic National Park and Flattery Rocks National Wildlife Refuge are located along the Washington coast to the southeast. The international, Canadian and United States waters within this area are under continuous, recorded radar coverage from Tofino Vessel Traffic Services (VTS) at Ucluelet, British Columbia.

Freedom of movement in the approaches is further complicated by the presence of military exercise area W601 and the concentration of fishing vessels which frequent La Pérouse, Finger, Soquel and Swiftsure banks. Military exercise area W601 is under United States jurisdiction, however, it is most frequently used by the Canadian Navy. Although the Canadian military probably would be interested in continuing to use this area, the United States military is

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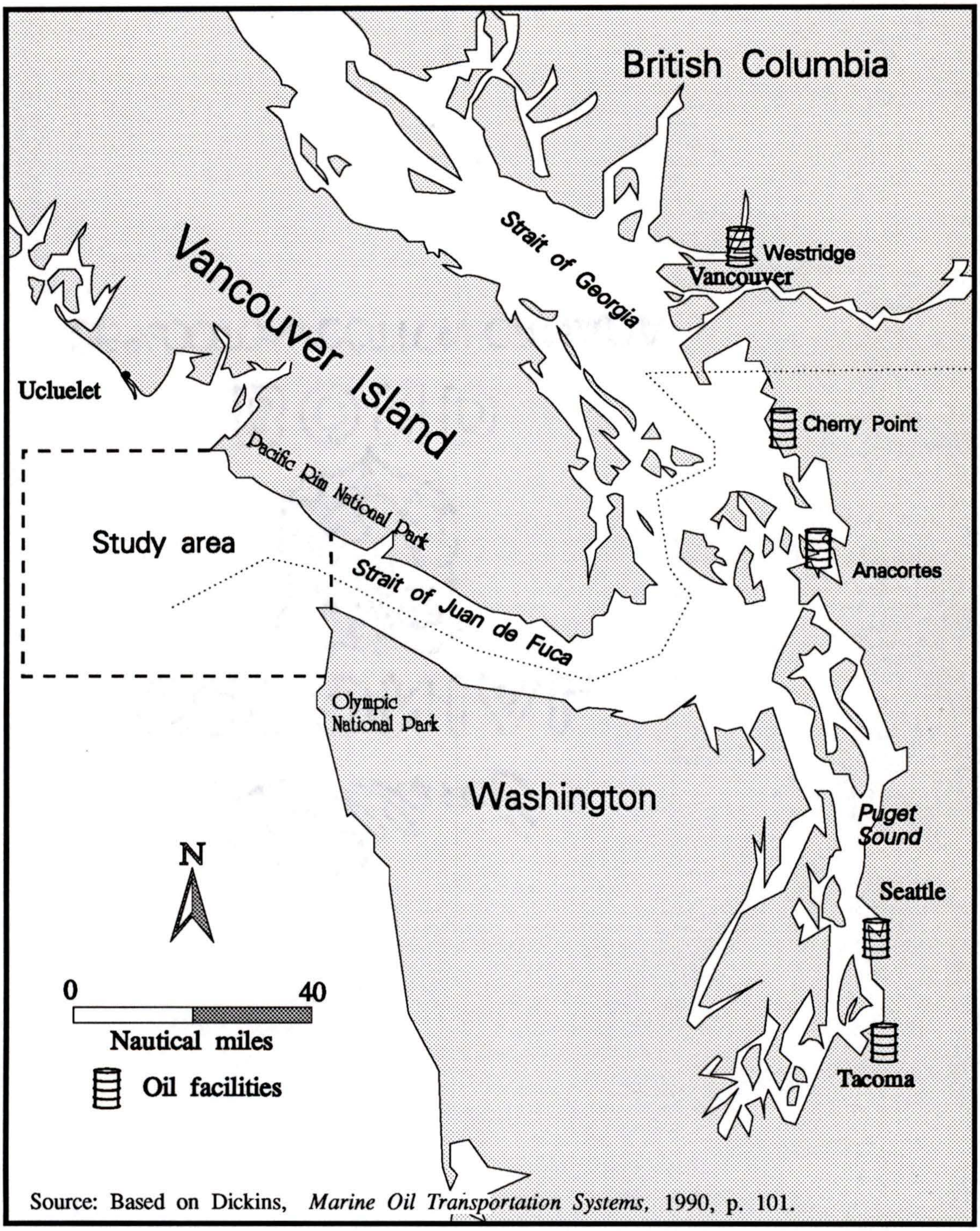
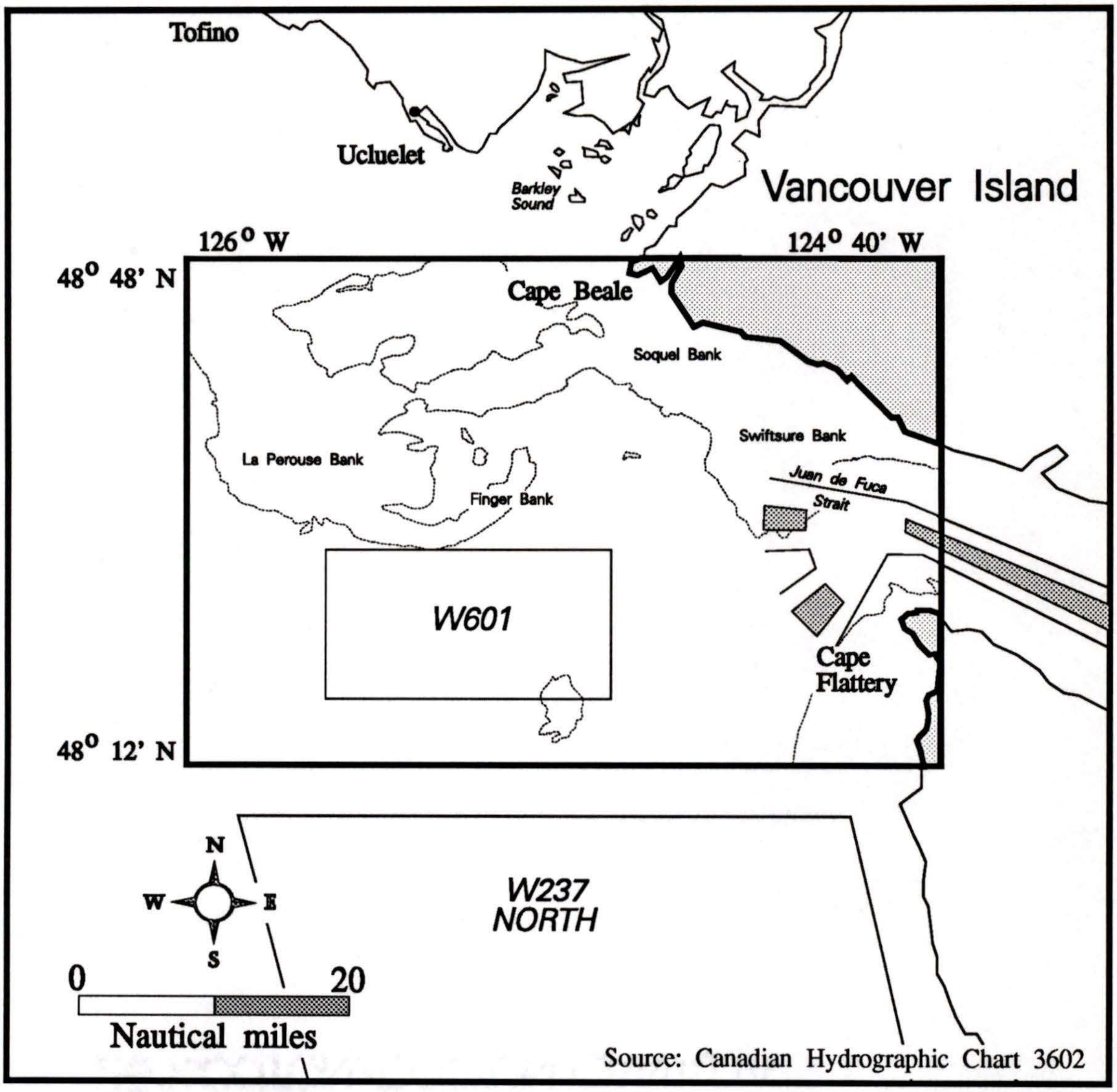
[2] Henceforth, the unit "mile" will be used as it is customary to refer to the nautical mile (n.m.) as a mile by mariners. The nautical mile is equivalent to one minute of latitudinal arc–1 852 metres or approximately 2 000 yards.



Source: Based on Dickins, *Marine Oil Transportation Systems,* 1990, p. 101.

Figure 1. Ports and oil facilities of the Pacific Northwest



Source: Canadian Hydrographic Chart 3602

Figure 2. Approaches to the Strait of Juan de Fuca

proceeding with its elimination. The areas of potential traffic conflict between the fishing banks and the military exercise area W601 are indicated in Figure 2.

The *United States Coast Pilot* publication describes the coastline from Carmanah Point to Cape Beale as "very dangerous and, except during fine weather and offshore winds, should be given a wide berth" (National Oceanic and Atmospheric Administration, 1985, p. 281). This is particularly important for the numerous fishing vessels which frequent the fishing grounds during summer months, as these vessels are apt to manoeuvre closer to shore than deep sea shipping.

Fog is prevalent year round on the fishing banks, with a moderate abatement in spring (Canadian Hydrographic Service, 1987, p. 85). Cold-water advection fog, a common contributor to restricted visibility in summer, results from the condensing of warm moist air from the west or northwest over cold upwelling coastal waters (Oke, 1978). Winds near the entrance cause the fog to stand "like a wall, and vessels entering the strait run out of it into clear bright weather, even before passing Tatoosh Island" (National Oceanic and Atmospheric Administration, 1985, p. 282).

2 Literature review

1. Risk assessment

Some of the earliest risk assessment research in geography was White's investigation of the flood hazard in the United States (White, 1942). However, risk assessment was considered still in its infancy in the seventies (Whyte and Burton, 1980). Catastrophic oil spills by the *Torrey Canyon* (1967) and the *Arrow* (1970) shifted the focus towards catastrophic environmental changes resulting from human rather than natural causes. In the seventies, risk estimation developed an engineering approach by applying fault-tree and event-tree analysis to nuclear power facilities and the space program (Burton and Pushchak, 1984; Rasmussen, 1975).

Catastrophic events continue to bring the safety of marine oil transport into question and necessitate on-going research on the oil pollution hazard. Whyte and Burton (1980) recognized a problem in the method of analysis and the need for international collaboration to develop risk assessment methodologies. It was suggested by Burton and Pushchak (1984, pp. 463-475) that "there is no consensus as to the scope and content of risk assessment", and "there is no assurance that two risk assessments done for the same project will have the same contents or reach the same findings." However, despite the subjective nature of risk assessment, many of the researchers in the field have attempted to be empirical and have employed a basic methodology which includes hazard identification, measurement and evaluation (Kates, 1978; Whyte and Burton, 1980).

The existence of marine traffic collision risk and the consequences of oil pollution to the coastal zone needs no identification. The threat of oil pollution by marine tankers in Puget Sound and Georgia Strait was clearly established in the early seventies (Ross, 1973) and has remained on the public agenda at various levels of intensity (Sewell and Swainson, 1980). However, risk measurement techniques must be designed according to identified causes and contributing factors of accidents (Williams and Heins, 1981, pp. 43-60). These factors must be measured using replicable techniques.

Risk measurement is the process of determining the probability of a future event calculated from statistical data provided by past events. Measurement has been called an actuarial science, however, Kates (1978, pp. 26-30) described three methods of measurement including: revelation, intuition and extrapolation. Experience has been used by Dickins (1990) as an intuitive means to estimate the risk reduction associated with various technological measures such as double-bottom hulls and electronic charting. His study *Tanker/Barge Safety* (1990) demonstrated the use of the Delphi[3] technique to evaluate risk mitigation. The Delphi technique was used also by Sandwell to modify casualty risk probabilities derived from a Poisson model (Sandwell, 1991, Section 6, pp. 37-40).

Risk evaluation has a broad scope as a field of study. It includes most evaluation tools: the assessment of risk-benefit, risk perception, cost

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[3] The Delphi technique is an estimation or evaluative process based upon the achievement of consensus of opinion amongst experts.

effectiveness, risk reduction and the determination of acceptable risk (Kasperson and Kasperson, 1983; Wilson and Crouch, 1982). This field of inquiry is growing and has found a means for collective expression in the journal, *Risk Analysis.*

Risk analysis has been used by Det Norske Veritas, an international marine consulting organization, as a method of evaluating shipping and offshore operational risk for over seventeen years (Cuming and Jenssen, 1984, p. 37). Studies have focused on the relative risk of collisions and strandings without analyzing the absolute risk associated with contributory factors. Many marine casualty studies have used a risk assessment framework without referring to the field of risk analysis, or assessment; however, more recent studies such as the *COST 301* (Commission of the European Communities, 1988) project, which was a multi-national study of traffic and casualties in the entire northern European waters, have used risk analysis techniques in the development of risk indexes (Kemp and Glansdorp, 1988). Risk analysis techniques used in the COST 301 project involved the calculation of mean risk modified by the subjective weighting of risk factors which were then weighted by local conditions.

Most international marine traffic research can be characterized by two methodologies: mathematical modelling of collision probability, which relies upon simplifying assumptions about causal factors; and analyses using descriptive statistics to outline the relative importance of causal factors (e.g. Lamb, 1987; Cockcroft, 1982). Local studies have either focused on the relative risk of collisions and strandings in different areas without analyzing the risk associated with contributory factors or they have used expert opinion to weight risk factors (Fisheries and Environment Canada, 1978; Cohen and Aylesworth, 1990, Dickins, 1990, Sandwell, 1991).

2. Analysis of marine casualties in maritime geography

Relatively few academic research papers have applied parametric or non-parametric statistical techniques to the study of marine casualties in the field of maritime geography. Techniques used to estimate the insurance risk of automobile claims typically attribute greater risk from various factors such as driver age, driving record, type of automobile and geographic location (Hossack et al, 1983).

Protection and Indemnity Clubs, or shipowners' insurance underwriting companies, underwrite over 90 percent of the world's ocean-going tonnage (Hazelwood, 1989, p. v). These associations require detailed information regarding vessel type, age, flag, size, design, class, cargo, routes, season, management, training, maintenance and claims record (Hazelwood, 1989, pp. 121-122). However, the following comment by a Lloyd's underwriter when asked by a British Ministry of Defence researcher about the probability of casualties, is intriguing:

> Well, you may think this odd for people who make their money out of the accidents, but we do not really know; if you will tell me who your captain is, and his experience, and the ship, I will quote you a rate; but we are not really interested in the overall probabilities of accidents (Stratton in Cockcroft, 1976, p. 227).

Most research on the causal factors of collisions and groundings has been conducted in the United States, Europe and Japan and has been published in *The Journal of Navigation*, however, several studies have been done in Canada. A report prepared for the States/British Columbia Oil Spill Task Force (1990) identified casualty risk factors such as winds, visibility, currents, channel widths, course changes and shipping density (Cohen and Aylesworth, 1990). This cumbersome risk analysis creates the impression that all relevant factors were considered in the creation of a casualty risk model, when in reality the navigational factors were arbitrarily weighted and lost, with the undemonstrated assumption that spill probability was proportional to distance travelled. Perhaps it was politically correct to provide a seemingly exhaustive study that suggested a lower risk could be achieved with fewer ship-miles, and recommended the shifting of the oil terminals out of Vancouver and Puget Sound to a common terminal at Low Point, Washington, 15 miles west of Port Angeles.

Unfortunately, the report was just an updated version of a previous study by Fisheries and Environment Canada (1978) which tried to identify marine risk with too many assumptions about too large an area.[4] An attempt was made

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[4] The accuracy of the earlier report in describing relative risk is questionable because of an inappropriate weighting of risk factors. For example, since water depth was weighted as 20 and shipping density 18, an area with no traffic and a depth of 16 to 18 fathoms would have a higher relative navigation risk rating (20x4 + 18x0 = 80) than an area with greater than 15 000 annual vessel movements and depths in excess of 33 fathoms (20x0 + 18x4 = 72), other factors being equal. Is grounding risk that much higher with depths of 16 fathoms than collision risk in an area such as the approaches to the Strait of Juan de Fuca with traffic in excess of 15 000 transits? Tankers entering Washington inland waters are limited to 125 000 deadweight tons. The *Arco Anchorage*, a typical tanker of 120 000 dwt, with a draught of 10.3 metres or 5.7 fathoms would not be concerned about grounding with 10 fathoms under the keel. Therefore, not only is grounding risk lower in 16 fathoms, it is non-existent, except for submarines and submerged fishing apparatus.

to weight navigational risk factors, in order to indicate their relative importance, as decided by a group of Fisheries and Environment staff. However, it was soon realized that relative risk was insensitive to the weighting scheme chosen, but this was not resolved. Since navigation risk is geographically specific, one cannot simply ignore the importance of variable weighting. This scheme was applied from Dixon Entrance to Rosario Strait, completely obscuring the geographic variability in the nature of marine casualties.

In the process of updating of the earlier study, the factor of water depth was eliminated. Cohen suggested that "water depth is eliminated as a geographic transit risk indicator because the 1978 tanker size assumption of 325,000 deadweight tons[5] (dwt) has been reduced to 120,000 today, thereby significantly reducing the chances of a grounding" (Cohen and Aylesworth, 1990, p. 7). This significance was neither demonstrated nor realistic. In 1988, over 1400 barge shipments of petroleum products from Vancouver alone proceeded to remote harbours along the British Columbia coastline (Shaffer, 1990, p. 21). It is inconceivable that depth should be excluded in assessing the navigation risk of barge traffic, or any marine traffic. Even if only crude tankers were considered (barges were included in the Task Force study) the terminals, of course, have limited depths which would necessitate the inclusion of this factor. Less than one year after the study, the *Arco Texas* ran aground in Port Angeles harbour carrying

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[5] The United Kingdom Ministry of Defence (1983) describes deadweight tonnage as the usual method of expressing the tonnage of cargo ships. It is the total weight of cargo, people, stores, fuel and water that a ship can carry and is measured by the tonne equivalent to 1000 kilograms.

at least 90 000 cubic metres of crude oil.[6]

It is of greater concern that twenty years after Ross (1973) analyzed the international problem of oil pollution risk in Puget Sound and the Strait of Georgia reports continue to be written with recommendations that go unheeded. It is crisis that drives governments to propose commissions, task forces and studies, however, the update of a report over ten years old is not indicative of government action in the area of oil spill prevention. National governments may perceive the threat of oil spills by tankers, but are only beginning to appreciate the geographic variability in the nature of marine casualties.[7]

A less recent federal study of Canadian casualties by Transport Canada (1984) combined all casualty types together and provided a percentage distribution of casualties by primary cause (Figure 3). It was found that 33 percent of accidents are caused by human error or "operational mistakes" and implied that this finding was realistic and useful by arguing that those who suggest that most casualties result from human error are not advocates of useful casualty research. It was stated that "it could also be argued that a casualty always results from some human error or failure if we go far enough back into the causation chain since, of course, there would never be a casualty if no ships

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[6] *Vancouver Sun*, June 25, 1991, p. A7 and personal communication with the Marine Safety Office, Seattle. A Marine Safety Officer suggested that "the master acted as his own pilot and misjudged the wind while restricted in shallow water."

[7] Mr. C. Hendry of Regional Marine Emergency Operations of the Canadian Coast Guard wrote less than one week prior to the oil spill caused by the *Tenyo Maru*: "It is interesting to note your theory that vessel speed is a major factor in assessing the causes of collisions within your study area, even though the Juan de Fuca Strait contains no less than 7 nautical miles width of navigable water."

were ever built" (Canada, Transport Canada, 1984, p. 55).

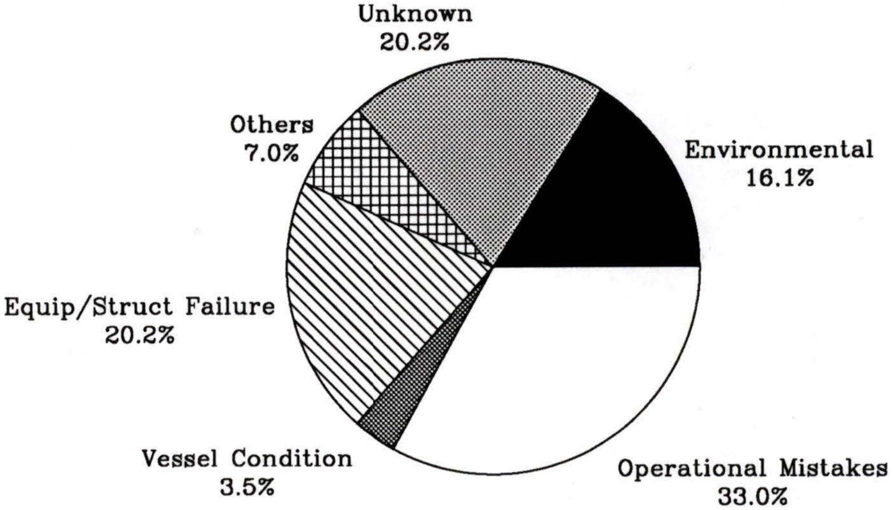

Figure 3. Casualties by primary cause, Canada, 1982

Source: Canada, Ministry of Transport, *Study on Marine Casualty Investigations in Canada* Ottawa, 1984, p. 56.

While the intent of the previous statement may have been to justify the inclusion of human error as a factor and imply that investigations of cause are important, two problems arise. Firstly, by grouping all accidents together the certainty that casualties are different and have specific causes was overlooked. For example, collisions usually are caused by a driving error; founderings by an engine, steering gear or total power breakdown; and groundings by a navigational error. Secondly, the use of casualty databases to analyze cause requires some scrutiny of the choice of primary factor. The attribution of primary factors, secondary factors and most probable cause by accident investigators is inconsistent within and between the Canadian Marine Casualty Information System and the United States Casmain database. For example, human error may be suggested as the primary cause, with visibility as a primary factor and human error as a secondary factor. Clearly, one must distinguish between a cause, such as human error and a contributing factor, such as visibility.

A United States study of casualties in the waters of Puget Sound and Georgia Strait attempted to derive a similar distribution of causes based on the two North American databases, however, at least groundings and collisions were treated as distinct casualty types (Wenk, 1982). As in the Canadian studies, several environmental factors were indicated to be casualty causes. For example, visibility was cited as a cause in five of 58 collision cases in Puget Sound, and human error in 47. One is left wondering how often human error was involved in conditions of restricted visibility or in any of the other causal conditions in Wenk's cause frequency analysis. Again, to suggest that the environment is the primary cause of a casualty, rather than a contributory factor, is to suggest that zero visibility causes collisions rather than excessive speed or lack of judgement.

While it is recognized in his study that "traffic density has been found a major factor in maritime casualties," (Wenk, 1982, p. 27) his estimate of cause frequency is of doubtful significance because of the exclusion of traffic density data. He reasons the exclusion of this factor because it is not included as a distinct category in the Canadian database (Wenk, 1982, p. 179). However, since collisions require the close proximity of at least two vessels, traffic density would seem to be a factor that one should not eliminate so quickly without further investigation. Traffic density information is included in Canadian investigation reports and in the United States database where it is considered significant.

Similarly, the importance of excessive speed is lost by its inclusion in the human error category. Again, it appears that speed information was available from Canadian investigation reports, but not the Canadian database. However, intuitively, vessel speed is a factor which warrants examination. In a report of the Tanker Safety Study Group, the United States Coast Guard recognized that "the demanding operating pressures on masters to maintain schedules encourages excessive risk taking such as excessive speed in fog and setting hazardous courses to reduce distances travelled. Some company policies have a tendency to discourage prudent safe operations" (United States Coast Guard, 1989, p. 38). Vessel collision speeds can be extracted or estimated from Canadian accident investigation reports.

The United States Casmain database was used by Dickins in an examination of the means to reduce tanker and barge risk on the west coast of North America (Dickins, *Review of Tanker/Barge Safety,* 1990). Conditional probabilities were derived from the frequency of occurrence of contributory factors in the database. Visibility, wind and sea conditions were identified as contributory factors to human error resulting in a casualty, however, vessel speed and traffic density were not examined as separate factors. It was found that 49 percent of collisions resulted from unspecified human error (Dickins, *Review of Tanker/Barge Safety*, 1990, pp. 43-58). This project reflected current government concern for the Valdez spill which focused attention almost entirely on solutions which address human frailty or technological improvements to equipment, rather than operational problems with Vessel Traffic Services (VTS). However, Dickins' study, *Marine Oil Transportation Systems: Evaluation of Environmental Risk and Alternatives for Risk Reduction*, identified possible limitations of Cohen's risk analysis by providing evidence that ships other than oil tankers carry as bunker fuel the equivalent of 40 percent of the total volume of Alaskan crude transported into the Strait. The significant threat of non-tanker traffic and the implication that technical improvements to ships will do little to reduce the hazard were recognized (Dickins, 1990, pp. 96-109).

An investigation for the Vancouver Port Corporation entitled, *A Risk Analysis of Tanker Traffic Movements within the Port of Vancouver*, used United States casualty and spill data because of the small local casualty experience (Sandwell, 1991). Since Vancouver harbour casualty risk probabilities were modified by a qualitative appraisal of the accuracy of estimated casualty probabilities, the study's usefulness in risk reduction is limited because the specific causes of casualties in Vancouver harbour were not identified. Had the panel of marine traffic experts been used to weight the importance of causal factors, casualty probabilities would reflect the differences and similarities to conditions found in United States ports and recommendations could have been made to improve traffic safety. Consequently, the report did not show where casualties are likely to occur nor what the most likely causes would be, therefore, problems within the harbour may have been missed and risk would remain high even if all recommendations were to be implemented.

The scope of most international studies has varied from worldwide analyses of cause to a very specific study of the relationship between darkness and casualty risk in Japanese waters (Commission of the European Communities, 1988; Cockcroft, 1982; Fujii, 1974). In a worldwide study of the causes of over 500 collisions, Cockcroft (1976, p. 216) found that the incidence of collision in darkness with clear visibility was twice that during daylight. The same author and others have shown that a greater percentage of casualties occurs in conjunction with poor visibility, high vessel traffic density, high speed, uncontrolled waterways, older vessels and flags of convenience (Fujii, 1974; Lewison, 1980; Peterson, 1981; Cockcroft, 1982; Wenk, 1982). Dickson supports this with his summary that "the most common failure is undoubtedly, ships attempting to navigate areas of high traffic density in conditions of low visibility at too high speed" (Rother, 1980, p. 41).

3. Summary of navigation risk factors

Many causal factors have been assessed in the literature which reflect the considerations for safe speed outlined in the *International Regulations for the Prevention of Collisions at Sea* (1990) adopted by the International Maritime

Organization of the United Nations (IMO). These regulations often are referred to as the "rules of the road" or "collision regulations".

International regulations have been in force since 1965; presently, Rule 6 establishes the requirement to maintain a safe speed. A safe speed is one where a ship "can take proper and effective action to avoid collision and be stopped within a distance appropriate to the prevailing circumstances and conditions" (Canadian Coast Guard, *Collision Regulations,* 1989, p.7). Further examination of stopping distances and the circumstances and conditions referred to in the international definition of safe speed highlights many factors to be considered when analyzing navigation risk.

Ship manoeuvring characteristics are compiled in a ship's data book during sea trials, however, Cockcroft (1987) has conveniently summarized stopping and turning characteristics for a cross-section of ship types. For example, a 150 metre ship of 15 240 tonnes proceeding at 18 knots could alter her course 90° in about 3.8 ship lengths (Cockcroft, 1987, p. 230). In other words, if there were sufficient sea room, collision avoidance with a stationary object such as a drilling platform would require a minimum distance of 610 metres or 0.33 miles if full helm were applied. Twice this distance would be required of two vessels proceeding head on at the same speed. Quite clearly, the proximity of other vessels and hazards, visibility and radar performance must be considered when assessing safe speed.

Other geographic, technical and human limitations must also be considered in the assessment of safe speed. Many of these are listed in Rule 6 (Canadian Coast Guard, *Collision Regulations*, 1989, p.7) as factors to be considered by all vessels and by those with operational radar. Those factors to be considered by all vessels include:

(1) the state of visibility

(2) the traffic density including concentrations of fishing vessels or any other vessels

(3) the manoeuvrability of the vessel with special reference to stopping distance and turning ability in the prevailing conditions

(4) at night, the presence of background light such as from shorelights or from back-scatter of her own lights

(5) the state of wind, sea and current and the proximity of navigational hazards

(6) the draught in relation to the available depth of water

Additionally, by vessels with operational radar:

(1) the characteristics, efficiency and limitations of the radar equipment

(2) any constraints imposed by the radar scale in use

(3) the effect on radar detection of the sea state, weather and other sources of interference

(4) the possibility that small vessels, ice and other floating objects may not be detected by radar at adequate range

(5) the number, location and movement of vessels detected by radar

(6) the more exact assessment of the visibility that may be possible when radar is used to determine the range of vessels or other objects in the vicinity

Thus, the following factors are included above: speed, visibility, density, windspeed, currents, sea state, navigation hazards, depth, and radar limitations.

Those factors considered in this study are similar to those recognized and assessed by numerous authors, including Fukushima (1976), Rother (1980), Cockcroft (1982), Kwik (1986). A compilation of factors frequently considered in the literature is provided in Table 1.

Table 1. Marine casualty risk factors

Vessel characteristics	Type of vessel
Geographical factors	Visibility Windspeed/Seastate Time of day Season Traffic Density
Engineering factors	Propulsion/Steering failure Equipment failure
Operational factors	Excessive speed for the conditions Lookout error Navigation error

4. Traffic separation schemes

The original purpose of traffic separation was to reduce the collision rate between meeting vessels or those proceeding in opposite directions. The IMO is responsible for the regulation and implementation of separation schemes and publishes all approved routing schemes in *Ship's Routeing* (1989). Much of the work in the establishment and evaluation of traffic separation schemes in the previous twenty years can be attributed to Norman Cockcroft, Chairman of the IMO Traffic Safety Study Group (Cockcroft, 1987, 1986, 1983, 1982, 1981, 1978, 1976). His analysis of the traffic scheme off North West Europe from 1957-1976 demonstrated that an 85 percent decrease in meeting collisions occurred during the period (Cockcroft, 1978, p. 217). He attributed this improvement to the effectiveness of traffic separation in reducing head-on collisions.

No local studies have been conducted to assess the effectiveness of the limited routing scheme or the probability of a casualty in the approaches to the Strait of Juan de Fuca. Since the routing of traffic clear of the fishing grounds and away from the United States and Canadian shorelines would serve to reduce traffic density, separate opposing streams of traffic and increase the overall distance from the shoreline in the event of a spill, a local analysis is overdue.

3 Methodology

1. Background

The purpose of this chapter is to introduce the methodological framework used for the analysis of collisions and their causes within the study area, identify data sources and provide details of the techniques used in the analysis. Since the assessment of collision risk requires the analysis of vessel traffic patterns, a survey of vessel movements is an integral component of the analysis.

2. Risk analysis

Risk is the range of possible outcomes, with known probabilities, which result from a decision or action. It is distinguished from uncertainty where probabilities cannot be established (Smith in Johnston, 1988, p. 412). Risks fall into two categories distinguished by their cause: natural and human, and may be further described by their consequences. These include risks to people, goods or to the environment. Kates (1978, pp. 12-54) described the methodology of risk assessment, as identifying hazards, estimating the threat they pose to humanity and the environment, and evaluating risk in comparison with societal values. Risk is simply defined as the product of a hazardous outcome and its probability of occurrence (Canadian Standards Association, 1991, p. 24).

Risk = probability x severity of outcome

This thesis employs a modified risk estimation framework by identifying contributory factors, estimating present and future collision probability and evaluating risk reduction measures. A consequence analysis was not conducted.

3. Approach

A ten year period (1980-1989) was chosen for analysis to maximize the validity of conclusions reached about the nature of collision risk in the study area. Prior to 1980, records from various sources were not retained on a consistent basis. The spatial extent of the study area was chosen to capture all through traffic and include the Swiftsure and La Pérouse fishing banks and military exercise area W601.

An empirical approach was used to measure the significance of several contributory factors and collision events and to test the hypothesis that marine collisions are Poisson distributed. Collisions are a rare event, therefore, it is likely they can be modelled as a Poisson distribution.[8]

Of the navigation risk factors described earlier, the most notable contributing factors identified in the literature include: traffic density, visibility, windspeed or sea-state, time of day, season, vessel type and speed. Each of these factors are analyzed–the methods used are consistent with the type of factor. While data for some of these factors need not be transformed to be useful in the

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[8] A total of ten collisions or near collisions involving 20 out of 171 130 vessel transits have been recorded by the Canadian and United States Coast Guard services in the study area for the period 1980-1989.

measurement of significance, the measurement of vessel speed and traffic density involved calculations based on historical vessel transit records and fishing vessel counts. The expected number of vessels per grid cell per month was determined.

If collision frequency in the area were a function of vessel traffic density or fishing vessel density, one would expect to find collisions in high traffic and fishing areas. The proximity of collisions to areas of fishing activity and concentrations of through traffic was examined. Specific considerations in designing an alternate routing scheme include existing air and sea lanes and routes, military exercise requirements, resource uses and technical limitations of navigation aids. The effectiveness of the current traffic routing system was analyzed by measuring the potential risk reduction of an alternate routing scheme which accounts for these considerations.

4. Data sources

Ship traffic patterns could be established by the use of remotely sensed microwave imagery where long-term records are available (Werle, 1988, pp. 84-85), however, the use of a locally situated radar provides the benefit of continuous position information. When radar position data are combined with VHF radio information, as it is with VTS, the resulting survey of marine traffic becomes much greater than a simple identification of traffic patterns.

As the study area is completely under the VTS control of the Canadian Coast Guard by joint United States/Canadian agreement (Canadian

Coast Guard, 1979, Appendix C), all traffic position and identification data, except casualty statistics, are available at Tofino Vessel Traffic Centre at Amphitrite Point in Ucluelet. These data include traffic flow, vessel type and frequency characteristics. Since digital imagery is not stored, complete data for each vessel transit were extracted from vessel control card records held for seven years only and then discarded. In addition, computer records have been kept since 1989 which include summary information of yearly vessel frequency characteristics since 1979. Fishing vessel counts also are recorded at Ucluelet, but are maintained and analyzed by Fisheries and Oceans.

Casualty statistics are maintained by the United States Department of Transportation, Marine Casualty Branch (post-1979) and the Canadian Transportation Accident Investigation and Safety Board (post-1975). Both the United States CASMAIN and the Canadian MCIS databases, covering the same geographic area, were used to establish all reported casualties because, unlike vessel transits, accidents can be reported to either Canadian or United States authorities. Furthermore, the use of these two databases enabled a cross check for validity. Casualty records attempt to summarize significant conditions during an accident, however, data such as visibility and windspeed were obtained from Environment Canada. Further casualty information was drawn from accident reports, although these reports are not necessarily completed in every case.

The availability and quality of statistics to conduct analyses of marine spills has recently been criticized by Brander-Smith (1990). Brander-Smith was "appalled by the lack of complete and accurate data" (Brander-Smith, 1990, p. 40). He continued by stating that "even when spill reports are made, statistics seem to disappear into a bureaucratic vacuum." This criticism is surprising considering that the United States and Canadian government agencies provided this author with marine casualty data promptly, at no charge and without reservation prior to the release of Brander-Smith's report. Furthermore, a comparison of the two casualty databases and accident reports revealed relatively few errors. While pollution statistics were not used in this thesis, these data could have been accessed with the allocation of considerable government time and at the expense of the author. The measurement of the consequences of a marine casualty would involve a process of pairing spills recorded on one database with casualties on another. Casualty records include notations of pollution and an indication of severity, however, marine pollution incidents are recorded on the National Analysis of Trends in Emergencies System (NATES) database of Environment Canada and in the United States Coast Guard Marine Safety Information System (MSIS) database. Both agencies indicated that the source of pollution is not uniformly listed for all pollution incidents on record because it is unknown or because of a time delay (Personal communications, Environment Canada and United States Coast Guard, MIM2, 1990). Consequently, pollution incidents are not linked to case numbers of marine casualties–this complication would increase the difficulty of analyzing the impact of marine casualties on the coastal zone.

5. Measurement

The type of marine casualties and the composition, growth and variation of marine traffic under Tofino VTS radar coverage from 1980 to 1989 were analyzed. At the time of data compilation, this was the only period for which nearly complete Canadian and United States data records existed. The survey included the measurement of average monthly traffic volumes by vessel type and the comparison of annual vessel counts with that of traffic for 1989. The comparison of annual data measured any difference in the traffic characteristics, other than growth, over the study period. Vessel types included freight, tanker, tug/barge, fishing, government and miscellaneous vessels. These data were used also in conjunction with fishing vessel counts in the calculation of traffic density.

Ship positions and times extracted from VTS card records were plotted to determine average traffic routes, speeds and areas of conflict. The plotted courses along with fishing vessel counts provided the basis to model traffic density. This calculation used the raw data for daily fishing vessel counts and positions, average vessel transit routes calculated from average courses from sampled transit data, as well as monthly and yearly vessel traffic volumes. Average traffic density was established for each vessel transit and collision record by using a grid system in the approaches to Juan de Fuca Strait.

The most recent year for which complete statistics existed was 1989. Sampling from a single year was necessary to reflect the month to month change in vessel frequency, traffic density and meteorological conditions encountered.

One could describe the meteorological conditions in the region as they occur however, this would not be representative of the conditions experienced by mariners if traffic volumes varied throughout the year.

Data used for analysis included all ten collision occurrences involving 20 vessels from 1980 to 1989 and a one percent random sample of 19,887 vessel transits in 1989 extracted from VTS card records. An initial inspection of vessel movement records suggested that traffic characteristics were predictable from year to year. The sample was stratified by month to enable a monthly comparison in the data. Furthermore, number of transits chosen for each month was weighted by monthly traffic volume in order to derive a spatial traffic pattern indicative of busier months. Since there is no single ideal sample size for any particular study,[9] and previous studies have employed traffic frequency data, rather than the radar position data used here, guidance for the estimation of a sufficient initial sample size was limited. It was accepted that a larger sample could be obtained if warranted by preliminary findings. Of the 190 vessels chosen, four proved to be outside the study area or had positions which were not identifiable. This left 186 vessel transits available for analysis. All extracted and calculated data used in the study are tabulated in Appendix A.

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[9] Silk (1979), p. 163 provides an illustration of the problems associated with determining an ideal sample size.

6. Vessel transits

Ship positions and times were plotted by range and bearing from the VTS radar on Mt. Ozzard at Ucluelet by using an artificial radar display programmed into the PAMAP Geographic Information System (GIS) (Figure 4).

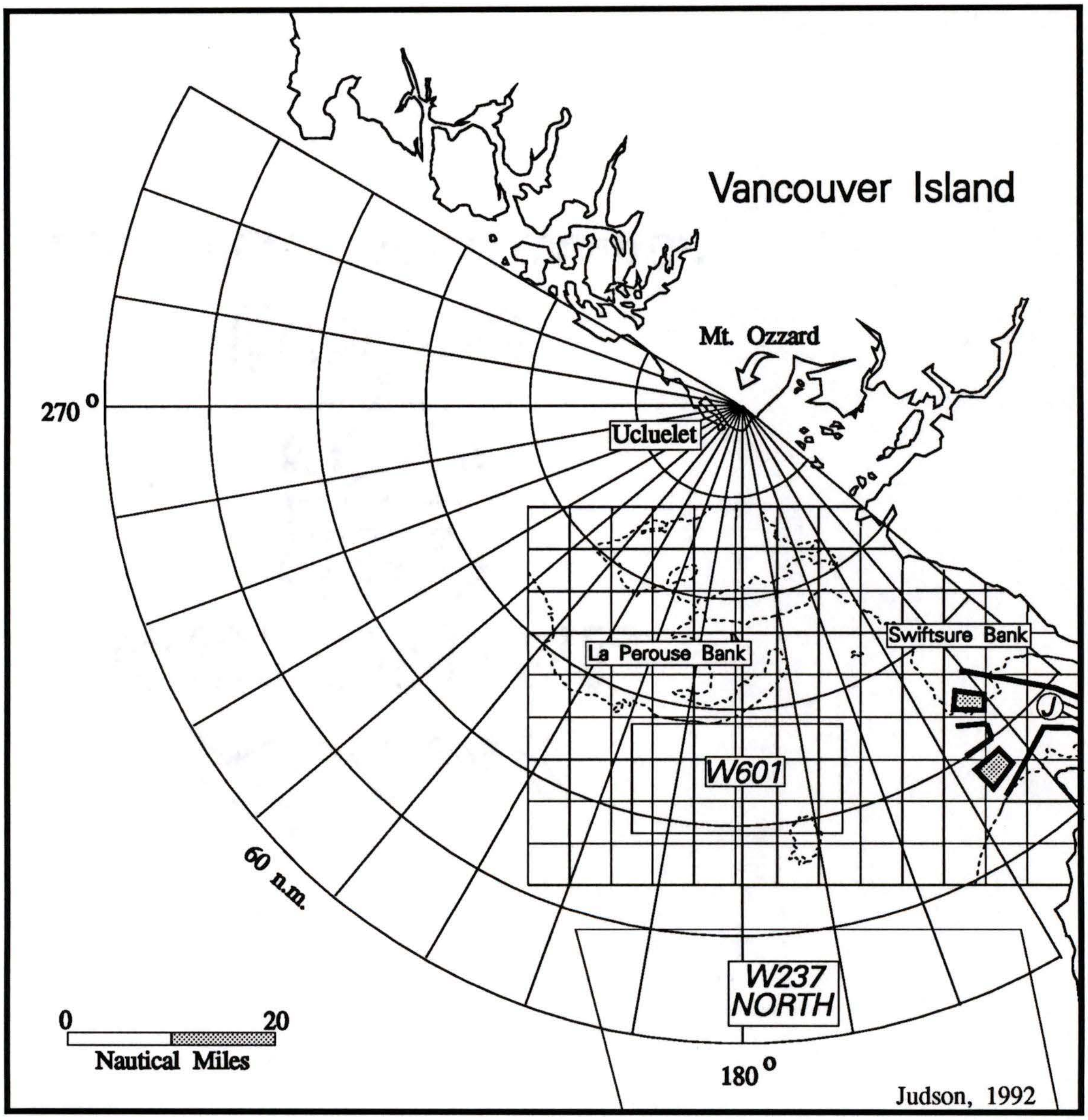

Figure 4. Radar coverage area and study area grid

A traffic separation buoy (Buoy J) at the mouth of the Strait was used to simplify the departure/convergence point in the narrow traffic lanes.

The use of GIS provided an efficient means of organizing traffic data and simplified the measurement of average course and speed for each transit. Measurement of the distance run by each vessel in yards was converted to miles to calculate average speed[10] in knots. A ship's actual average course[11] was plotted to the nearest degree and subsequently rounded to the nearest 10°, except near the extreme limits of possible courses which included an accuracy to 5°. Vessel courses and speeds for collision incidents were calculated from VTS data where possible and verified and supplemented by Coast Guard records and investigation reports. In addition to enabling the calculation of a contributing variable–speed, the plotting of vessel transits provided the means to model traffic density, illustrate areas of conflict and areas avoided by mariners and evaluate adherence to traffic separation schemes.

7. Derivation of traffic and fishing vessel counts

The study area was divided into grid cells approximately four miles square in size (Figure 4). This size permitted a close approximation of the traffic density for a particular area without introducing a level of detail which exceeds the accuracy of fishing vessel locations reported by fishery patrol aircraft and

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[10] Average speed is also referred to as "speed made good" over the ground.

[11] Average course is referred to as "course made good."

radar counts. It is appropriate also in that VTS alarms for tankers are set at four miles and this distance is the minimum closest point of approach in restricted visibility requiring a Canadian naval bridge-watchkeeper to inform the captain.

Vessel transit counts were determined by summing the number of transits through a particular grid cell in the study area during 1989. This provided an indication of through traffic concentrations and was used in conjunction with fishing vessel counts to establish total traffic density statistics.

Fisheries patrols by aircraft are conducted on the West Coast several times per month. Patrols are conducted within the study area at least once per month. In addition, VTS radar counts of fishing vessel concentrations are conducted throughout the fishing season, May through September, and some details are provided in collision reports. Data collected from these observations were used to estimate the fishing vessel density for each month in 1989 and for each collision incident.

Where fishing vessel counts by aircraft were reported to be within a defined radius the total count was divided among the grid cells covered by that radius. Whole numbers were used to be consistent with the level of accuracy provided by the original counting methods. For example, where 105 vessels were sighted within a five to six mile radius of a position, rather than indicate a density of 11.6, nine cells would each be allotted 12 vessels. Where a radius of three to four miles was reported the fishing vessel count was divided among five cells centred on the given latitude and longitude. VTS radar fishing vessel counts recorded in standard reporting areas used by Fisheries and Oceans were converted to the grid cells they covered.

Because observed locations and concentrations of fishing vessels in the study area have been shown to be closely related to certain local water properties and circulation which tend to persist throughout the fishing season (Healey et al., 1990, p. 1846), average fishing vessel densities would remain fairly stable and are assumed to be constant during a particular month.

8. Traffic density

Traffic density measured in vessels per grid cell per month was calculated for each grid cell in the study area for each month *k* in 1989, and for each collision incident. Each grid cell was the sum of its average fishing vessel count during month *k* (for each year) with the weighted impact of its annual vessel count in 1989. The weight was the product of the ratio of the average transit time through a grid cell to the average number of hours in a month, the ratio of monthly transits to total transits in the sample[12] and the ratio of yearly traffic to the total sample size. It is calculated using the following formula where G is the estimated number of vessels per 19 minutes in cell *i j* during month *k*:

$$G_{ij_k}=F_{ij_k}+V_{ij}\left[\frac{(\frac{d}{S})}{H}(\frac{n_k}{N})(\frac{T}{N})\right]$$

---

[12] This represents the ratio of monthly to yearly traffic volumes because the monthly sample size reflects this weighting.

and

F is the fishing vessel count for grid cell *i j* in month *k*,
V is the total sample transiting vessel count for grid cell *i j* in a sample year,
d is the mean distance through a grid cell in miles,
S is the sample mean transiting vessel speed in knots,
H is the mean number of hours per month (365.25/12x24=730.5),
n_k is the number of transiting vessels sampled in month *k* in 1989,
N is the number of transiting vessels in a one percent sample of those vessels transiting the study area in 1989, and
T is the actual number of transits in 1989 or the year of a collision.

Traffic density values for each ship were estimated by calculating the average density encountered by each vessel as it transited through its grid cells in the study area. The grid cell containing Buoy J was not included in calculating vessel traffic densities because most vessels passed through that area (Figure 4). Its inclusion would unnecessarily dilute the spatial variation in the data. In addition, since two vessels are involved in a collision, an average of the traffic densities encountered by each vessel prior to collision was used to represent the traffic density of the collision incident. This estimate was chosen to provide consistency in the comparison of traffic densities encountered by vessels in transit and by vessels in collision.

9. Collision probability

Cockcroft (1978) modelled collision probability using the frequency of months during which *i* collisions occurred over a 20 year period (where *i* is the number of collisions). He suggested that marine collision probability does not fit the Poisson model well because of variable factors such as visibility. However, because he modelled his data on a monthly frequency interval he obtained a seasonal variability in collision frequency, as one would expect if weather were an important factor, which was inconsistent with his hypothesis. Had he modelled his data on a yearly or month to month basis, as was done by Maes and Muir (1988) in their investigation of the arrival rate of storms on Canada's East Coast, he may have found collision frequency to be Poisson distributed. More recently, the Poisson model was chosen by Sandwell (1991) to estimate vessel casualty probability in the Port of Vancouver.

In order to test the assumption that collision probability in the study area can be modelled as a Poisson process, all reported collisions and near collisions from 1980 to 1989 were utilized. Unfortunately, close-quarters situations usually go unrecorded unless a report is made to VTS. This is because a close-quarters situation varies with the circumstances. However, it is reasonable to test the assumption by utilizing the data available within the study area.

There are several ways to express a marine collision rate. Depending on the scope of the study area or nature of the collision problem, the Commission of the European Communities (1988, p. 61) suggests that any of the following could be used–collisions per:

(1) number of vessels passing a line at a given time interval (transits or port calls)

(2) number of vessels present at any one time in a given area (such as traffic density)

(3) ship-miles

(4) encounters (close approaches to a ship)

It is known that most collisions in the study area involve fishing vessels. Since the movement of vessels engaged in fishing often is unpredictable, it would seem likely that the collision rate would be a function of the time of year and the number of transits. If the probability of collisions is a function of vessel traffic frequency, one cannot simply use the sample mean number of collisions per year during the ten year period to estimate the Poisson probability distribution. This is because traffic volumes vary throughout the year. Therefore, the collision rate per 5 000 transits was determined using the mean,

$$\lambda = \frac{i}{n}$$

where n is the number of time periods during which there were 5 000 vessel transits and i is the total number of collisions in ten years. According to the Poisson distribution, the probability that there will be r collisions per 5 000 transits is

$$P_{(r)} = \frac{\lambda^{r} e^{-\lambda}}{r!}$$

where λ is the mean or expected value, e is always 2.71828..., and $r!$, called factorial $r!$, is equal to $r(r-1)(r-2)...1$. A Kolmogorov-Smirnov goodness of fit test procedure was used to compare observed collision frequencies with estimated

Poisson probabilities. The derivation of a collision probability estimate provided the basis to quantify risk reduction measures.

10. Quantitative methods

It is likely that collisions are more prevalent among one type of vessel than another, such as collision with a fishing vessel by other classes of vessels. In addition, the risk may be further compounded by darkness where the numerous lights of a fleet of fishing vessels may confuse a mariner. Given that higher speeds reduce the decision making time in the previous situation, the risk of collision presumably increases in any situation with the introduction of low visibility, high vessel speeds and high traffic density. However, few research papers have illuminated how significant these factors are when all traffic, or the "non-collisions" are included in an analysis: in other words, comparing the collision circumstance with that normally experienced in an area. If one analyses the circumstances of collisions in isolation from the conditions regularly experienced by other traffic the significance of any findings is lost. Is it significant if 70 percent of collisions occur in darkness if 70 percent of all vessels transit in darkness? It is intended that this analysis consider total traffic characteristics and patterns, rather than just collisions.

Various software programs were used in the data analysis. Initially, the PAMAP GIS was used to reproduce vessel courses and speeds. These data were combined with those for fishing density to produce traffic density data in the Lotus spreadsheet. All data then were analyzed using the SPSS/PC+ statistical analysis program. The measurement of the relationship of causal factors to collisions included parametric and non-parametric methods. Kolmogorov-Smirnov tests, means tests (t-tests and multiple one way ANOVA tests), and tests of correlation were used to establish the significance of contributing factors. Parametric tests of correlation and regression were used to test relationships between variables where a strong association was suggested and to predict collision frequency.

11. Uncertainty and bias

Problems associated with risk assessment include inaccuracies in describing or modelling the problem and limitations in available data used for quantification (Cuming and Jenssen, 1984, p. 46). Under-reporting in the early years of vessel traffic management suggests a degree of uncertainty, however, it is expected that significant accidents would not go unnoticed, and the use of two databases reduced this uncertainty. Nevertheless, this problem would result in a conservative estimate of the accident rate. The risk factors available for study were restricted by the information collected during and after an accident at sea. Errors in information were investigated through further examination of accident reports, meteorological data and hydrographic charts and records.

It is reasonable to question the validity of conclusions reached about the nature of collisions within the study area based upon a sample of ten collisions. However, ten collisions represent the experience of at least twenty vessels, and probably represent the experience of many more vessels involved in unrecorded near-collisions. Furthermore, collisions represent an identifiable group within a much larger representative sample of a population of about 20 000 transits per year. Sandwell (1991) used a larger database of selected United States ports to determine casualty type and casualty rate for the Port of Vancouver, but did not link causes in a quantifiable way. Consequently, risk reduction could not be determined in the risk analysis. Transport Canada draws conclusions about individual collision incidents and may modify policy on the basis of this information, therefore, it is suggested that if a commonality exists among the ten incidents which is significantly different from that of "non-collisions" it is relevant.

Other studies have used a larger collision database from which to draw conclusions about collision circumstances. However, generalization about the causes of collisions in a broad geographic area will be dependent upon the extent of variation in traffic problems encountered in the area. Problems, such as traffic density, visibility and excessive speed, are frequent concerns, but the weighting of any of these or other factors is geographically specific. The uncertainty in this methodology was illustrated by the European COST 301 project which attempted to modify risk established elsewhere by the qualitative weighting of local factors.

A global analysis of risk factors could not be sufficiently modified to the conditions in a specific region unless the analysis established risk under a continuous range of conditions for each factor. For example, if a correlation was found between the collision rate and visibility, the collision rate could be estimated for an area with known visibility characteristics. Previous studies have not demonstrated the correlation of collisions to contributing factors, therefore, the scale of this examination into the nature of collisions provides both a useful description of local problems and a database which could be used in future studies. A sufficiently large database could then be used to predict traffic problems in an area with no recorded traffic experience.

Bias is introduced by the use of empirical methods—a qualitative survey of the experiences of mariners may not be able to establish collision probability and quantify risk reduction, but it would be comparable to a quantitative survey in its ability to identify risk factors. The use of qualitative methods to evaluate risk reduction may lead to erroneous results which may influence public perception. The public perception of risk reduction may be greater when a well organized spill response team is in place than when ships are required to participate in a routing scheme, even though spill response does nothing to prevent spills. Since decision-makers can facilitate change in public perception through education programs, the empirical measurement of risk reduction is a superior means of justifying change.

4 Results

1. Spatial pattern of traffic

A most striking traffic pattern resulted from the plotting of courses made good by vessels of all types through the study area. This was the pronounced separation of inbound and outbound traffic in the west and northwest approaches to the Strait (Figure 5). Traffic routing is limited to territorial waters, and voluntary traffic separation in the international waters of the study area occurs in the absence of any traffic routing scheme.

The Canadian Coast Guard (*Tanker Exclusion Zone,* 1989, p. 5) requests that loaded inbound tankers refrain from operating within the Tanker Exclusion Zone (TEZ) and *Notice to Mariners No. 8* states "...vessels approaching these areas from any direction are advised to pass to seaward and clear of the banks...vessels which are obliged to cross the banks should navigate with extreme caution in order to avoid risk of collision with fishing vessels" (Canadian Coast Guard, 1990, p. 40). The TEZ is voluntarily observed by inbound oil tankers from Valdez, Alaska and is designed to keep tankers a sufficient distance offshore so that the risk of grounding is reduced should a propulsion or steering breakdown result in a foundering. It is hoped that assistance by an ocean-going tug could reach a stricken tanker to prevent further complications, however, in the event of a spill, the greater distance offshore would increase the time available for decision-making. While these two recommendations should result in additional

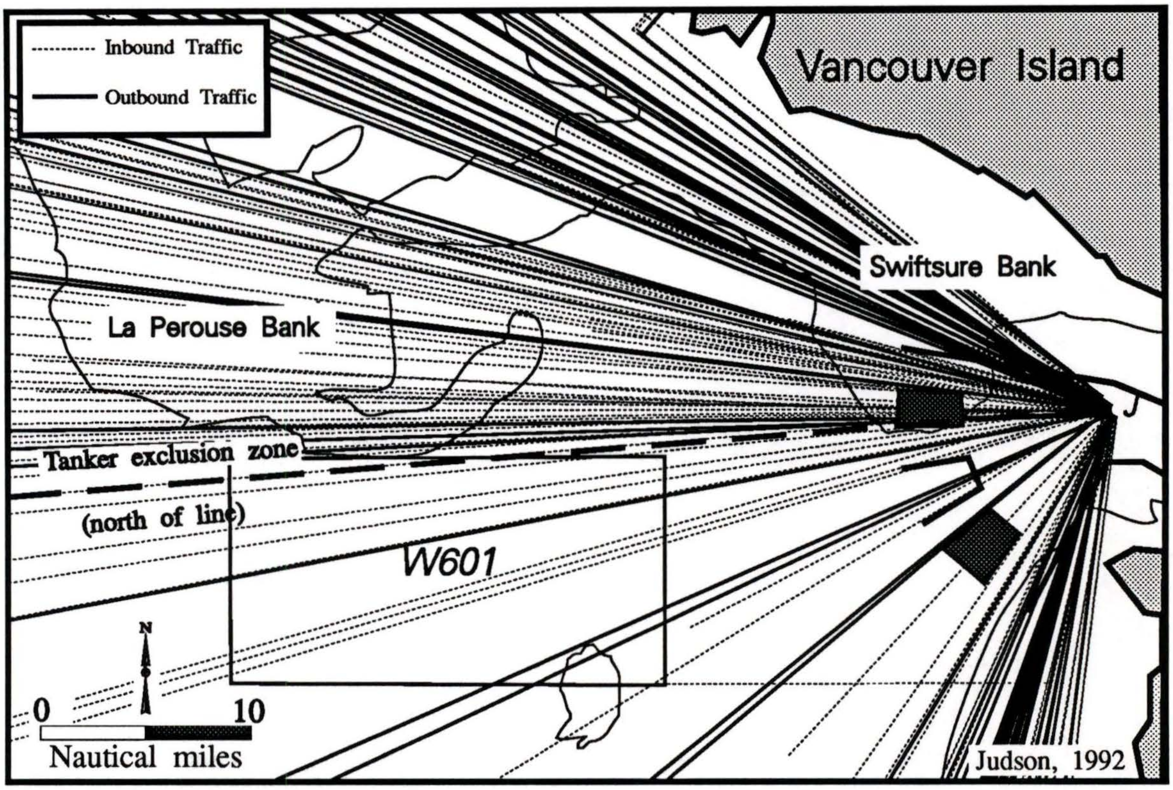

Figure 5. Traffic flow in the approaches

caution, several other explanations are offered which may better explain the traffic pattern.

It can be seen in Figure 5 that ship routes are concentrated in three arcs converging on buoy J. Mean inbound and outbound courses for these arcs are compiled in Table 2. In addition, a mean course of 143° was determined for nearshore traffic proceeding inbound from Vancouver Island harbours.

It is common practice for the captain of a ship making a land fall, or approaching pilotage waters, to require a call from the watchkeeping officer at a pre-arranged position. The choice of this position necessitates the consideration of outbound traffic, as the captain would have to be called

Table 2. Mean inbound and outbound traffic routes

	Mean Course	Standard Deviation	Minimum Course	Maximum Course	Sample Frequency
Inbound Routes	101°	14.24°	070°	125°	66
	022°	14.92°	010°	060°	38
	143°	25.00°	130°	180°	4
Outbound Routes	292°	16.66°	250°	305°	40
	201°	8.48°	189°	230°	38

Source: Appendix A, Column J

continuously if the ship were to proceed head-on into outbound traffic. For this reason, it would appear that mariners select a nearly easterly approach route to the Strait, with an average course of 101°, to avoid head-on traffic which is outbound to the northwest (Table 2 and Figure 5). This route approximates the recommended main shipping route from Japan indicated on United States pilot charts (Canadian Hydrographic Service, 1987, pp. 1-3).

Unfortunately, through traffic does not, on average, pass to seaward of the banks. Furthermore, it is obvious that inbound traffic tends to remain clear to the north of military exercise area W601, even though it is active on a discontinuous basis only. Because the time of its activation by the military is communicated to mariners by VTS regulators it is suggested that this area may be perceived as a hazard and is consciously avoided by 93 percent of traffic in the approaches. The combined result is that traffic which might otherwise keep clear to the south of the banks is constrained to proceed through the most active areas of La Pérouse and Swiftsure banks. Since the Canadian Hydrographic Service (1987, p. 11) recommends that seiners and trawlers be given a berth of at least 914 metres, this would require continuous manoeuvring if one were to proceed through the fishing fleet.

Nearshore coastal traffic, inbound from Port Alberni and elsewhere, tends to proceed on an average course of 143° (Table 2 and Figure 5). This traffic tends to be clear to the north of traffic outbound to the far east, however, it is particulary exposed to head-on encounters, as well as fishing activity in summer.

Outbound traffic proceeding to the far east tends to diverge in an arc to the northwest. An average course of 292° approximates the great circle route to Japan. Again, this route avoids encountering much of the inbound traffic, but does not pass clear of the fishing banks.

Traffic close to the Washington coast proceeds on a mean course of 201° when southbound and its near reciprocal 022° when approaching the Strait. On average, there appears to be little separation of traffic. The absence of a head-on collision in this area during the study period may be testimony to the mariners' abilities to correctly apply steering and sailing rules, however, the potential consequences of error in this area surely surpass the right to unrestricted passage.

In summary, the traffic routing scheme recognized by the IMO which extends 12 miles from shore appears limited to an approach or departure point for overseas traffic, and it is not able to separate traffic proceeding to or from the south. Contrary to recommendations by Coast Guard, vessels tend to manoeuvre through fishing areas rather than avoiding them entirely.

2. Traffic characteristics, volume and growth

In order to determine if collision frequency is a function of traffic frequency rather than time, to weight the occurrence of climatological factors by traffic frequency, and to support the assumption that there is no significant change in traffic composition so that traffic density can be modelled, it is necessary to analyze traffic composition and growth during the study period.

Figure 6 illustrates a moderate ten year growth in vessel traffic of 26 percent from 15 828 to 19 887 transits per year. By fitting a trend line, traffic volumes for 1990 and 1991 are estimated to be 20 510 and 21 140 based on an average growth rate of three percent or 627 vessels per year.

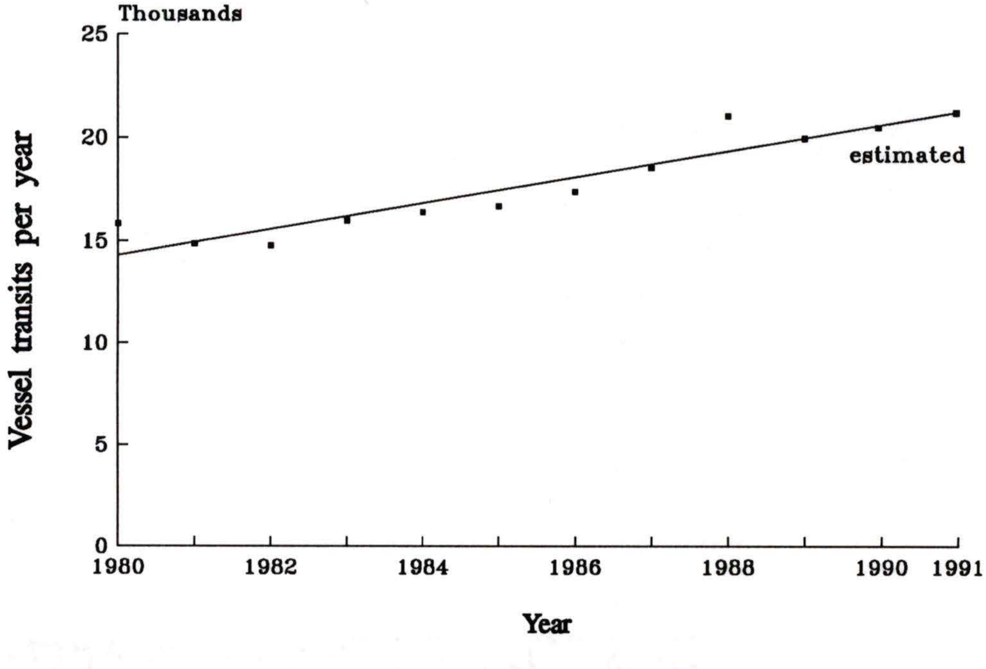

Figure 6. Traffic volumes, 1980-1989

Homogeneity is readily apparent in the limited variation in the composition of vessel traffic from year to year (Figure 7 and Table 3). On average, freighters, which includes cargo and container vessels, comprised 61.1 percent of vessel traffic. This is followed by tugs and tows at 15.6 percent, tankers at 9.7, miscellaneous vessels at 7.8 and government vessels at 5.8 percent. Fishing vessels proceeding through the approaches accounted for 3.8 percent of traffic in 1989, however, this category was not included for comparison because fishing vessels transiting the area were not distinguished from those engaged in fishing prior to 1987. Nevertheless, fishing vessel counts also grew by three percent from 32 448 vessels in 1988 to 32 510 vessels in 1989.

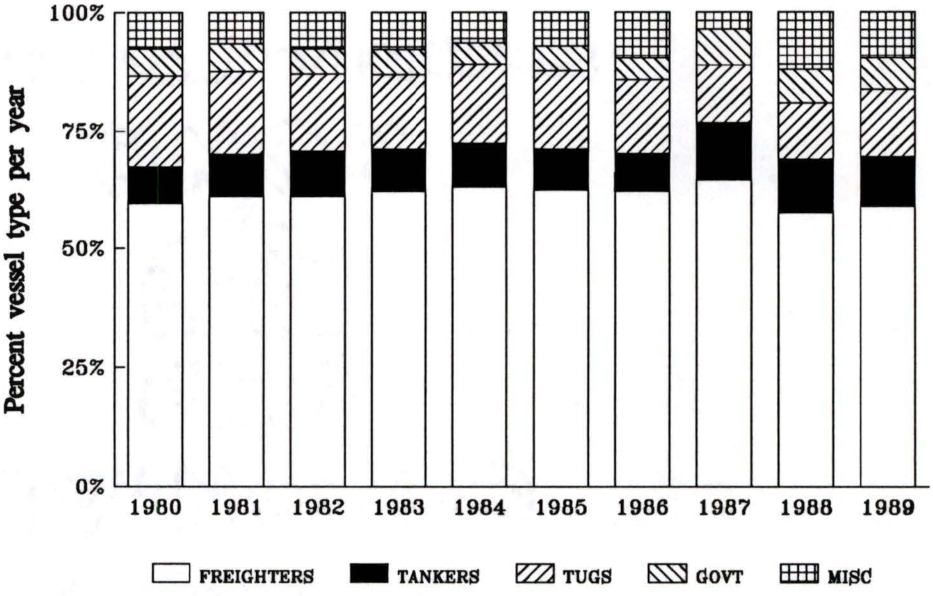

Figure 7. Traffic composition, 1980-1989

A comparison of the coefficient of variation for each category of vessels indicated very little dispersion other than that resulting from growth from

Table 3. Vessel traffic variation by year

Year	Freight	Tank	Tug	Government	Misc.
1980	9002	1256	2121	734	617
1981	9061	1363	2397	785	980
1982	9420	1422	2409	789	1046
1983	9923	1445	2514	836	1118
1984	10310	1454	2606	858	1171
1985	10379	1473	2658	860	1202
1986	10621	1542	2731	906	1243
1987	11265	2079	2754	1290	1630
1988	11393	2127	2763	1313	1841
1989	11583	2332	3041	1439	2417
Mean	10296	1649	2599	981	1327
S.D.	944	379	254	260	510
C.V.	9.2%	22.9%	9.8%	26.5%	38.4%

1980 to 1989 (Table 3). This was particularly gratifying because it supported the use of a single sample year to represent the characteristic patterns of marine traffic during the ten year period. The traffic frequency varied throughout 1989 from a low of 1 269 vessels in February to a peak of 2 444 in July (Figure 8). For this reason, any analysis of collision probabilities for a given area should not use a collision rate per year as the sole bench mark for comparison because that would eliminate the significance of this variation.

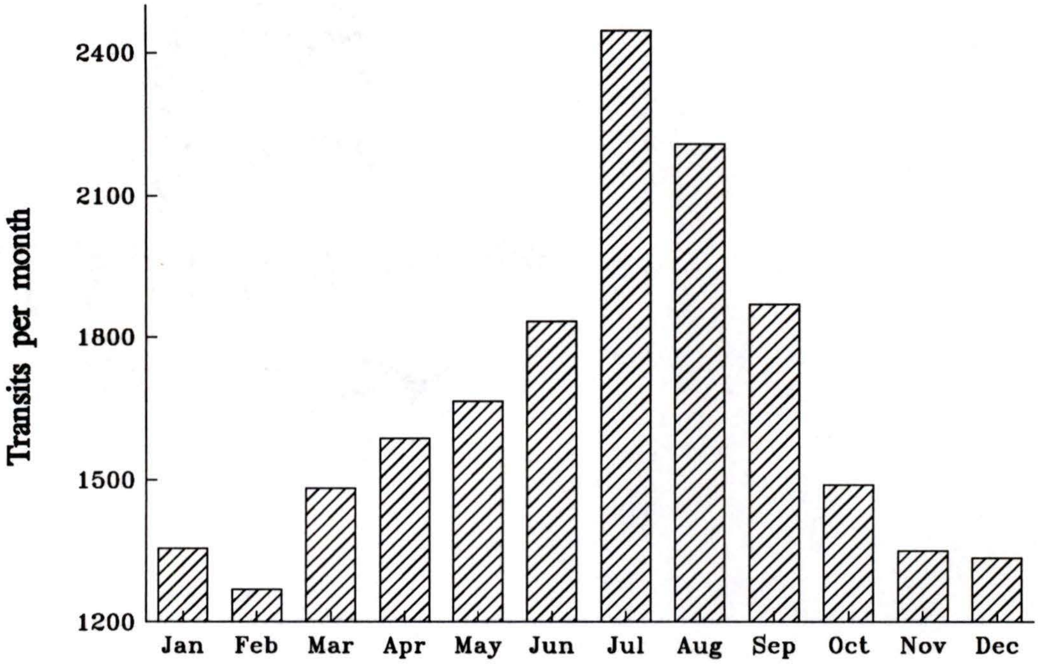

Figure 8. Monthly traffic volumes, 1989

3. Casualty characteristics

A summary of casualties by type, with causes and damages, is provided and defined in Table 4. Casualty types are grouped as collision, foundering, flooding, fire and other. The majority of casualties were either collisions (36 percent), or founderings (36 percent) (Figure 9). The absence of groundings presumably is due to the lack of offshore hazards and the directional assistance of VTS when a near grounding is recognized.

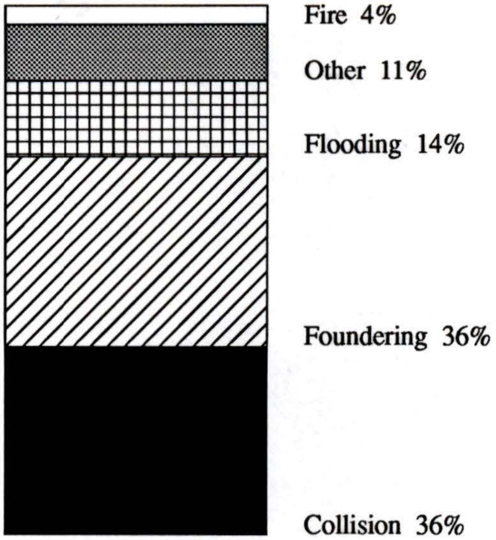

Figure 9. Vessel casualties by type

While engineering difficulties caused 54 percent of all casualties (Figure 10), this finding is of little importance because it sheds no light on the relationship between casualty type and cause. It is included to further illustrate the importance of examining casualties separately. Indeed, collisions accounted for 83 percent of those casualties caused by human or operational error, rather than engineering breakdown or other failure. This should not be surprising. How often is an automobile collision due to a component failure rather than inattention or risk-taking? Furthermore, no collisions were caused by environmental factors–environmental factors were generally noted as secondary causes or contributing factors.

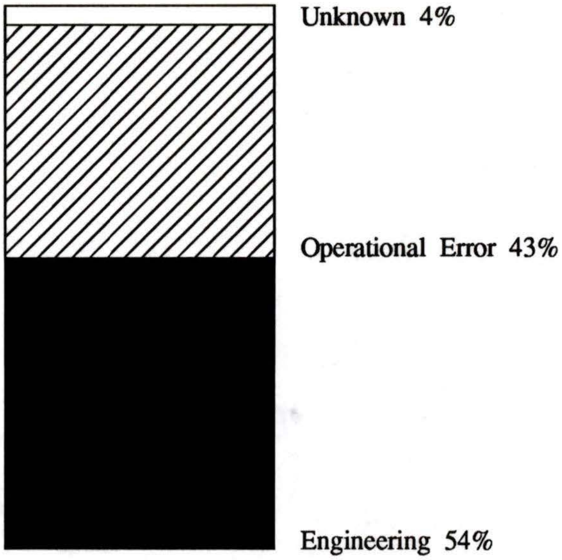

Figure 10. Vessel casualties by primary cause

A closer inspection of collision records reveals that most collisions involved cargo ships and fishing vessels: nine out of ten collision incidents involved at least one fishing vessel (Table 4). Vessel and cargo damage sustained ranged from none to $2.45 million. All collisions involved human error. These findings suggest that further investigation of contributing factors is essential to the understanding of marine collisions in the study area.

Table 4. Summary of vessel casualties

Date	Casualty Type	Name	Use	Primary/ Secondary Factors	Damage
800417	A	Vardiani Rogers Pass	cargo fishing	operator error darkness	none holed
800501	A	Alisher Navoi Beagle	cargo fishing	operator error visibility	none extensive
800929	B	President	cargo	engineering	none
810908	D	Norwes Gale	fishing	engineering	abandoned
820205	B	Western Ocean	fishing	engineering	none
821226	E	Dresden	cargo	operator error heavy weather	unknown
830183	C	Nyhorn	tanker	operator error heavy weather	some
830113	E	Sohio	tanker	engineering	$1 150
831207	C	Jackie Mar	fishing	engineering	$575 000
840515	B	Nore Dick	fishing	engineering heavy weather	$3 450
840704	A	Violet Island Ratmanova	cargo fishing	operator error visibility	minor minor
840730	A	Bum Han Ocean Prince	tanker fishing	operator error visibility speed	scratched scratched
850312	C	American S	fishing	engineering heavy weather	$1 150

Legend

Casualty types

A: collision or near collision
B: foundering
C: flooding
D: fire
E: other (cargo shift or equipment failure)

Table 4. (continued)

Date	Casualty Type	Name	Use	Primary/ Secondary Factors	Damage
850506	B	Ocean Mari	fishing	engineering	$1 380
850610	E	USNS Neptune	cable layer	engineering	$86 250
860924	B	President	cargo	engineering	$575
870313	C	Nanceda	fishing	engineering	lost
870701	B	Friendship	fishing	engineering	$5 750
870706	B	Friendship	fishing	engineering	$5 750
870913	A	Sea Crest Jo Brevik	fishing tanker	unknown	none none
880128	B	Kara Gail	fishing	operator error engineering	$115
880328	B	Arco Anchorage	tanker	engineering	$575
880819	A	Mors Chalore	fishing fishing	operator error darkness	some lost
880824	A	Irtyshsk Ocean Fame	fishing cargo	operator error visibility darkness/speed	$800 000 $1 650 000
890426	B	Exxon Philadelphia	tanker	engineering	$230 000
890601	A	Kootenay Nordpol	warship cargo	operator error visibility speed	$140 000 $300 000
890712	A	Papu Larain	cargo tug/tow	operator error visibility	$6 000 dent
890811	A	Capt J Fiddler Jeffrey Foss	fishing tug	operator error	none none

Source: Canada, Marine Casualty Information System and United States Casmain database.

4. Comparison of collisions and marine traffic by risk factors

Marine collision risk analyses have tended to describe the circumstances of collisions without comparison to the conditions encountered by marine traffic. In the absence of any test of significance, such an analysis is revealing, yet provides an incomplete basis for traffic management decisions.

This section begins with a discussion of the collision circumstances as described in casualty reports for the study area. This provides a background to the nature of marine collisions and supports the choice of factors analyzed. A discussion of the results of the analysis of the contributing factors of vessel speed, visibility, windspeed, daylight, season and traffic density follows. This analysis leads to an estimation of collision probability which is used in Chapter 5 to evaluate risk reduction.

5. Collision reports

Each collision or near collision occurring within the study area was listed with the Canadian Transportation Accident and Safety Board (CTAISB), whereas none were found on the United States Casmain database. The CTAISB was formed in 1990 to replace the Marine Casualty Investigations Branch of the Canadian Coast Guard. This was done to remove the potential conflict of Coast Guard investigating itself.

Of the ten collisions occurring from 1980 to 1989, five resulted in Summary or Investigation Reports and one was described in a Factual Audit.

With the exception of the Factual Audit, these reports are released to the public "for accident prevention purposes only and are confined to cause related circumstances."[13] For the purposes of familiarizing the reader with the contents and conclusions of these reports, and providing a background to collision circumstances in the approaches to the Strait, brief summaries of the six reports are provided in the following sections with collision occurrences illustrated in Figure 11.[14]

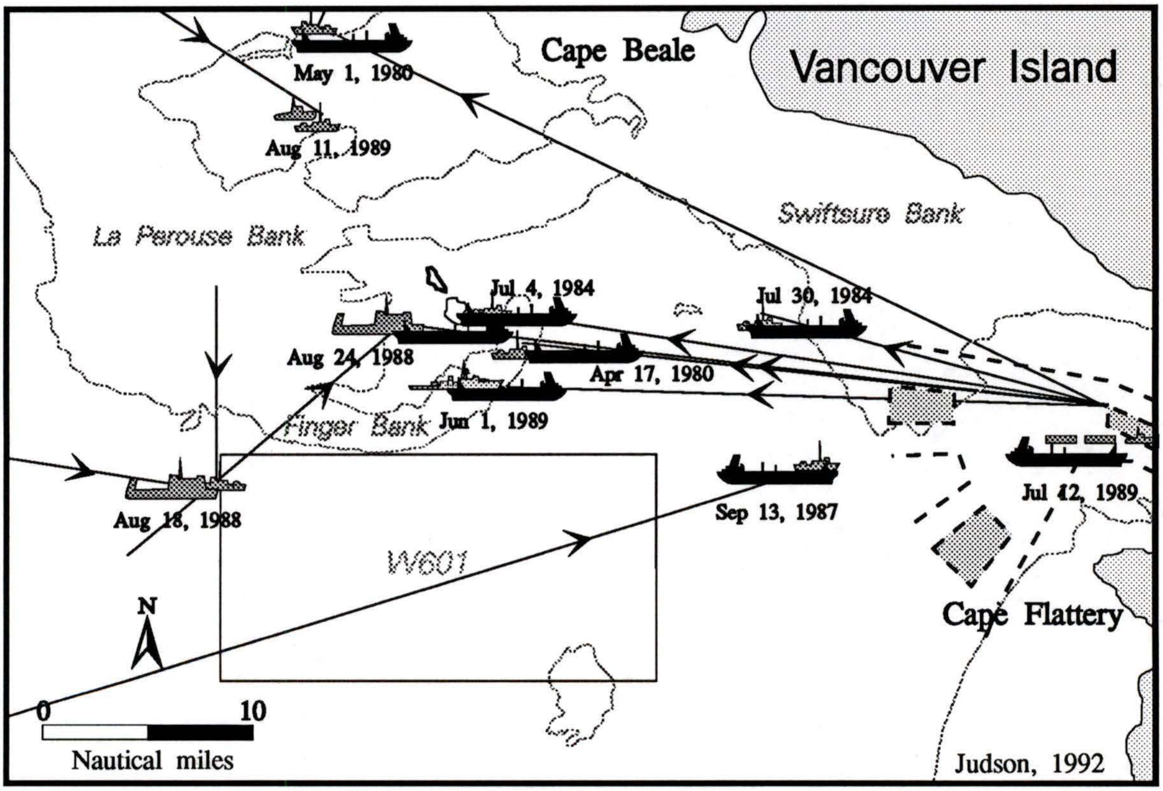

Figure 11. Collision occurrences 1980-1989

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[13] This disclaimer precedes the contents of each report.

[14] Undoubtedly some detail is lost in the synopses provided, however, the inclusion of all relevant factors was attempted. It is important that the reader refer to the original reports if all facts related to the incidents are required.

(i) Summary report 188

At 0138 hours on April 17, 1980, the cargo vessel *Vardiani* of 9247 gross tons[15] collided with the anchored fishing vessel *Rogers Pass* of 13 gross tons. The *Vardiani,* which was chartered by Chinese interests to carry potash to China, was westbound in the approaches to the Strait when it struck the *Rogers Pass* situated among five vessels anchored on Finger Bank, and near fifty other anchored fishing vessels on La Pérouse Bank.

Given clear visibility and a warning about extensive commercial trolling off the west coast of Vancouver Island, the officer of the watch on the *Vardiani,* although operating radar, must not have been keeping an effective lookout. Furthermore, the report concluded that the *Rogers Pass* may have been able to attract the attention of the *Vardiani* had an anchor watch been kept, however, is was unlikely that they could have got underway and manoeuvred clear.

(ii) Summary report 189

At 0521 hours on May 1, 1980, the cargo vessel *Alisher Navoi* of 10 152 gross tons was in collision with the fishing vessel *Beagle* of 11 gross tons. The *Alisher Navoi* was westbound for Japan loaded with rape seed and the *Beagle* was headed south, bound for La Pérouse bank when the collision occurred 17

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[15] A ship's gross tonnage refers to the internal volume of the ship expressed as the ton equivalent to 2.83 cubic metres, except for ships in construction after 1982 where a new formula applies which employs no equivalent units because both volume and weight are used in the measurement (United Kingdom Ministry of Defence, 1983).

miles west of Cape Beale.

Despite visibility of less than 600 metres, and warnings of extensive fishing activity (an estimated 200 vessels), the *Alisher Navoi* proceeded at an average speed in excess of 13 knots and the *Beagle*, six to seven knots, prior to their collision. Both vessels had operational radar—the *Beagle* was ranged to two miles with periodic ranging to eight miles, however, the *Beagle* was not equipped with a radar reflector. Sound signals were being sounded by the *Alisher Navoi*, but not by the fishing vessel *Beagle*. It was concluded that the *Alisher Navoi* was probably proceeding too fast for the visibility and traffic density and that the *Beagle* did not seem to have maintained an effective lookout, nor effective radar and listening watches.

(iii) Factual audit - sinking of fishing vessel *Chalore*

At 2205 hours on August 18, 1988, the fishing vessel *Chalore* of five gross tons contacted the trawl and transducer gear of the Polish factory fishing vessel *Mors* of 2501 gross tons. The collision occurred 40 miles west of Cape Flattery and resulted in the sinking of the *Chalore* and loss of gear from the *Mors*.

The *Chalore* was proceeding south from Barkley Sound at nine knots with clear weather and calm seas when the uncertified operator left the wheelhouse after a large trawler was observed 45° on the starboard bow at about two and one-half miles. The *Mors* was engaged in trawling when the *Chalore* was observed on a converging course with the trawling gear. A warning signal on the ship's whistle was given. No conclusions were provided, however, inexperience and operator error were identified.

(iv) Investigation report 531

At 0630 hours on August 24, 1988, the bulk carrier *Ocean Fame* of 14 187 gross tons was in collision with the Soviet factory fishing vessel *Irtyshsk* of 4407 gross tons. The *Ocean Fame* was loaded with barley and westbound for Japan when the collision occurred in a position 19 miles southwest of Cape Beale. The *Irtyshsk* was proceeding on a northeast course to meet Canadian catcher boats in the vicinity of Finger Bank and the *Ocean Fame* was aware of the concentration of fishing vessels and restricted visibility in the area.

The collision occurred in dense fog with the *Ocean Fame* making ten knots and the *Irtyshsk*, seven knots–speeds considered excessive where a close quarters situation is developing. The *Ocean Fame* held the fishing vessel on radar, on the port bow, at one mile and attempted to contact the vessel while altering 45° to starboard. Just prior to impact, the *Irtyshsk* sighted and became aware of the *Ocean Fame* close off the starboard bow and attempted to alter to port with engines astern. Both vessels were operating radar and sounding fog signals, yet neither vessel's avoidance actions were adequate nor made in sufficient time to avoid collision. Furthermore, the investigation found that the *Ocean Fame* did not maintain a proper lookout and that the *Irtyshsk*, in addition to her inability to detect the *Ocean Fame* on radar, did not maintain a proper radio listening watch.

(v) Investigation report 542

At 0726 hours on June 1, 1989, the 3 266 gross ton Canadian destroyer HMCS *Kootenay* collided with the bulk ore carrier *Nordpol* of 29 450 gross tons. The collision occurred in dense fog on Finger Bank, 18 miles southwest of Cape Beale. At the time of collision the *Nordpol* was proceeding westbound at 13.5 knots loaded with 49 968 tonnes of sulphur and 10 253 tonnes of potash. The *Kootenay* was manoeuvring unpredictably at about seven knots as part of an exercise.

The *Nordpol* was warned of fishing activity along her course line and held numerous unidentified contacts on radar. About 14 minutes prior to collision the *Nordpol* called VTS for help to identify what was probably *Kootenay*, however, while stating that it presumed the contact to be a fishing vessel, VTS did not offer information that naval vessels were exercising in the area. *Nordpol* attempted to raise the unidentified vessel on radio but did not alter her course nor speed. The master of *Nordpol* was informed that risk of collision existed only when the *Kootenay* was less than 1 000 metres on the starboard bow. Action to avoid collision by the *Nordpol* was limited to stopping the main engine when the *Kootenay* was sighted at less than 200 metres. Furthermore, the *Nordpol* did not sound fog signals and did not have a dedicated lookout on duty.

The *Kootenay* did not sound fog signals, did not exhibit navigation lights, was under radio silence and was not using radar. Furthermore, she failed to recognize the call by *Nordpol*, despite her capability of monitoring both the radio calls of *Nordpol* and international distress frequencies without compromising her passive state. The *Kootenay* first became aware of the *Nordpol* when reported by a lookout which gave a few seconds with which to order the engines full speed astern, however, no helm order was given.

In addition to the high risk accepted by the *Kootenay* in proceeding at seven knots without radar in dense fog in the vicinity of numerous fishing vessels on a through traffic route, she continued this operating risk during a bridge watch turnover. This undoubtedly raised the level of risk to a point where the avoidance of any vessel sighted was all but impossible.

It was found that actions by both vessels were insufficient to avoid collision, and that the inability of VTS to effectively monitor all close-quarters situations during fishing season was a factor. Despite the awareness of *Nordpol*'s excessive speed, VTS did not warn either vessel of the impending collision situation.

(vi) Investigation report 539

At 1112 hours on July 12, 1989 the 14 781 gross ton bulk carrier *Papu* was in collision with two barges in tow by the 237 gross ton tug *Larain*. The *Papu* was loaded with wheat enroute to Vancouver and the *Larain* was bound for New Westminster, having just dumped a load of gypsum waste. The vessels were approximately four miles northeast of Cape Flattery when *Papu* collided with the tug's barges while attempting to overtake *Larain*.

In visibility of less than 200 metres, the *Papu* proceeded on a northeast course at 13 knots and had just altered to starboard to enter Juan de Fuca Strait when she attempted to overtake the tug *Larain*. The *Larain* had begun to cross the traffic lanes, near the entrance precautionary area, with the intention of proceeding to the north side of the Strait. Her speed was eight knots.

Both vessels held each other on radar and were in radio contact prior to and during the collision, yet the were not able to communicate their actions in sufficient time. Had *Papu* reduced her speed in accordance with Rule 6, she would have had ample time to assess the close-quarters situation on radar. However, she assumed that the *Larain* was following, not crossing, the traffic lanes. Similarly, *Larain* failed to slacken her speed in order to take avoiding action, and despite efforts to inform *Papu* that she was on a collision course, she failed to inform the *Papu* of her intention to cross the traffic lanes. In addition, *Larain* attempted to cross the traffic lanes at less than right angles as required by Rule 10. Neither vessel posted a dedicated look-out and sound signals were not heard.

(vii) Summary of collision reports

The re-occurring theme of collisions involving excessive speed for the conditions of low visibility, high traffic density or both is plain. It is also clear that the study area is characterized by conflicts among fishing vessels, through traffic and naval ships on exercise. Evidently, VTS regulators either had difficulty discerning the developing close-quarters situations where numerous radar contacts overloaded their ability to track vessels, or they hesitated in providing advice necessary to arrest the escalating risk of collision.

6. Speed

One would expect that higher vessel speeds would be a contributory factor in collisions. When comparing the mean speed of vessels which have collided to mean transit speed through the study area a finding of similar vessel speeds may indicate that speed is not a factor. However, just the opposite would be true if the conditions during a collision differed from those encountered during an average vessel transit and warranted a reduction in speed.

An examination of the frequency distributions of transit speed for vessels in collision and the one percent sample of vessel transits revealed that the speed of traffic not involved in collisions ranged from one to 23 knots, with a mean speed of 12.45 knots. The average transit speed of vessels that were involved in a collision was 12.8 knots, only .35 knots higher than mean traffic speed (Figure 12).

A t-test was performed to determine if average speeds prior to collisions are similar to average transit speeds (Table 5). Because it is reasonable to expect a higher average speed in a collision, a one-tailed significance value of $p=.301$ is used. If both distributions had the same expected value there would

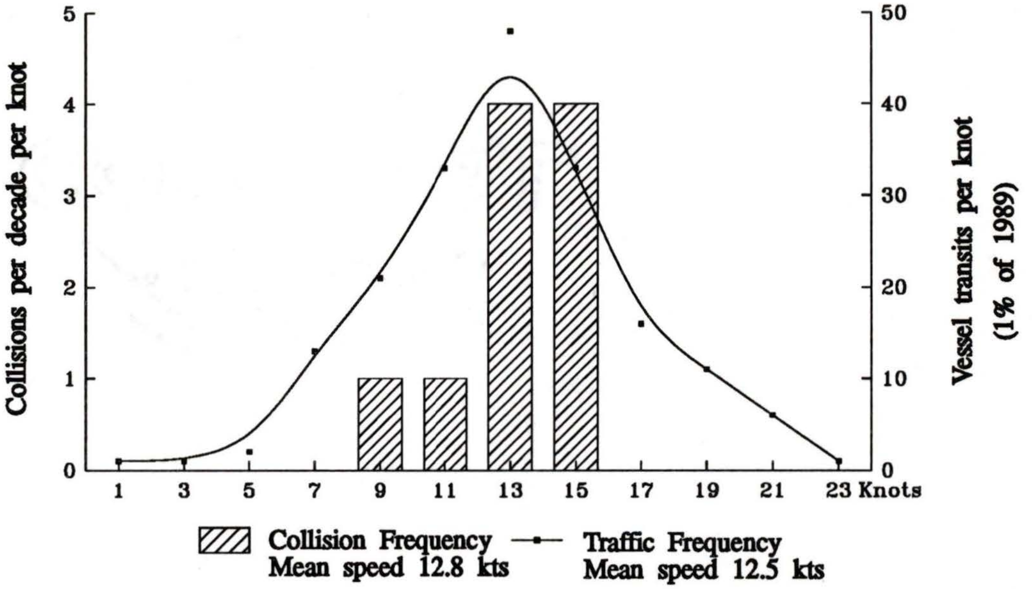

Figure 12. Vessel speed histogram

Table 5. Prevailing speed in transits and collisions

	Number of Cases	Mean Speed (knots)	Standard Deviation	Standard Error
Transits	186	12.45	3.69	.271
Collisions	10	12.80	1.87	.593

			Separate Variance Estimate	
F Value	1-Tail Prob.	t Value	D.F.	1-Tail Prob.
3.88	.015	-.53	13.12	.301

be a 30 percent chance that the average sample speed from ten collisions would be 0.35 knots higher than the average speed from 186 other vessel transits. Even though eight out of ten collisions involved speeds in excess of the average transit speed of 12.45 knots, one must conclude that there is no significant difference between the average speed of traffic and of those vessels which have become involved in a collision. It is suggested that it was not prudent to proceed at an average speed of 12.8 knots if the conditions encountered at the time of collision required a lower speed.

Ships involved in a collision may not initially be proceeding at an unsafe speed. However, if two vessels collide, their collision speed was excessive because there was insufficient time to avoid collision. The inspection of Coast Guard records revealed the incidence of excessive speed during collisions. Recall that, with an average speed in excess of 13.4 knots, the *Alisher Navoi* collided with the *Beagle* in a visibility condition of 550 metres. Similarly, the *Ocean Fame,* proceeding at 13 knots in one mile visibility collided with the *Irtyshsk.* Considering that speed was assessed to be unsafe or excessive for the conditions in four of six collision reports described above, the absence of a difference between mean traffic and collision speed is a significant finding.

Prior to investigating whether there is a significant difference between the conditions present during a collision and those encountered during an average transit, the factor of speed is explored further by comparing mean speeds in several different conditions where a prudent mariner would consider a reduction in speed (International Maritime Organization, 1990).

7. Comparison of mean speeds by risk factors

The finding that average vessel speed prior to a collision is not significantly different from the average transit speed necessitated the exploration of average vessel speed under various conditions where compliance with international regulations would require an appropriate reduction in speed.

What is an appropriate speed? While factors such as a poor lookout or wrongful action may be more probable causes of collisions in clear visibility, high speed is clearly a problem in restricted visibility (Cockcroft, 1987). Proximity to other vessels, or traffic density is another important factor to be considered in the assessment of a safe speed. "In the open sea, with little or no traffic in the vicinity, a relatively high speed may be appropriate for the prevailing circumstance and conditions" (Cockcroft, 1987, p. 136). However, a considerable reduction of speed is necessary under conditions of low visibility and high traffic density.

Cockcroft cites an example of expert testimony of safe speed accepted by the High Court of London in 1972. It was suggested that a radar equipped, diesel powered ship of 108 metres (a similar configuration to the *Tenyo Maru*) should reduce her speed to eight or nine knots in a high traffic area with a visibility of 6 cables (0.6 miles) and that a further reduction is appropriate upon entering dense fog when a close-quarters situation is developing. Other authors present similar accounts illustrating the relative nature of a safe speed (Mankabady, 1987, Holdert and Buzek, 1984). Since over 76 percent of vessel traffic in the Tofino VTS zone includes freighters, tankers and government vessels, one can assume that their similar manoeuvring configurations would necessitate similar safe speeds given the same navigational constraints. Therefore, it is these navigational constraints or risk factors which were examined.

Prior to statistically testing the significance of contributing factors to collisions, factors considered when assessing safe speed were selected. These included visibility, traffic density, windspeed and time of day. Collisions were compared with through traffic in terms of each factor. Table 6 lists the categories of factors for which mean speeds were calculated. The results are presented in Table 7 and illustrated in Figure 13.

Table 6. Selected safe speed factors

Category	Definition
High visibility	Greater than two miles
Low visibility	Less than/equal to two miles
High density	Greater than/equal to 1 per 16 square miles
Low density	Less than 1 per 16 square miles
High windspeed	Greater than/equal to 8 knots
Low windspeed	Less than 8 knots
Night	2000 to 0800 hours, or first (2000-2400), middle (0000-0400) and morning (0400-0800) watches
Day	0800 to 2000 hours, or forenoon (0800-1200), afternoon (1200-1600) and dog (1600-2000) watches

The relative magnitude of each factor was chosen to reveal any significant variation in mean speed that would be likely under adverse conditions. For example, it is possible that a mariner would not consider a reduction in speed necessary for a visibility of three miles if equipped with a highly manoeuvrable ship, sophisticated radar and dedicated radar operators, however, this is unlikely. Nevertheless, "low visibility" was defined as less than or equal to two miles, in order to increase the likelihood that a difference in speed would become apparent.

It was assumed that low visibility would require radar navigation which may not reveal all traffic; high traffic density would necessitate a higher level of attention and anticipation of manoeuvring; windspeeds of over eight knots may degrade radar performance because of sea clutter on the display concealing small contacts, as well as hindering manoeuvrability; and navigation at night may be hampered by back scattering of light interfering with vision, as well as the possibility of confusion when identifying navigation lights or vessel movements.

Figure 13 shows that, on average, mariners proceeded through the study area without any prudent reduction in vessel speed. Of the sixteen groups compared in Table 7, no two groups varied significantly at the .05 level. Since vessel speed did not vary, excessive speed is a persistent factor which can not be solely associated with collisions. Excessive speed is incessant

Table 7. Mean vessel speed by selected safe speed factors

	Mean Transit Speed (knots)	Standard Deviation	Number of Cases
High visibility	12.46	3.55	169
Low visibility	12.25	5.18	16
High density	13.11	4.56	36
Low density	12.29	3.45	150
High winds	12.71	3.68	65
Low winds	12.33	3.72	120
Night	12.95	3.57	121
Day	11.52	3.76	65

	Mean Collision Speed (knots)	Standard Deviation	Number of Cases
High visibility	12.00	2.94	4
Low visibility	13.33	0.51	6
High density	12.28	1.98	7
Low density	14.00	1.00	3
High winds	13.50	0.71	2
Low winds	12.62	2.07	8
Night	12.85	1.77	7
Day	12.67	2.52	3

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob.
Between Groups	3	87.37	29.12	2.26	.08
Within Groups	192	2467.44	12.85		
Total	195	2554.82			

Multiple Range Test–Tukey-B Procedure Ranges for the .05 level: 3.24 3.51 3.67
No two groups are significantly different (.05 level)

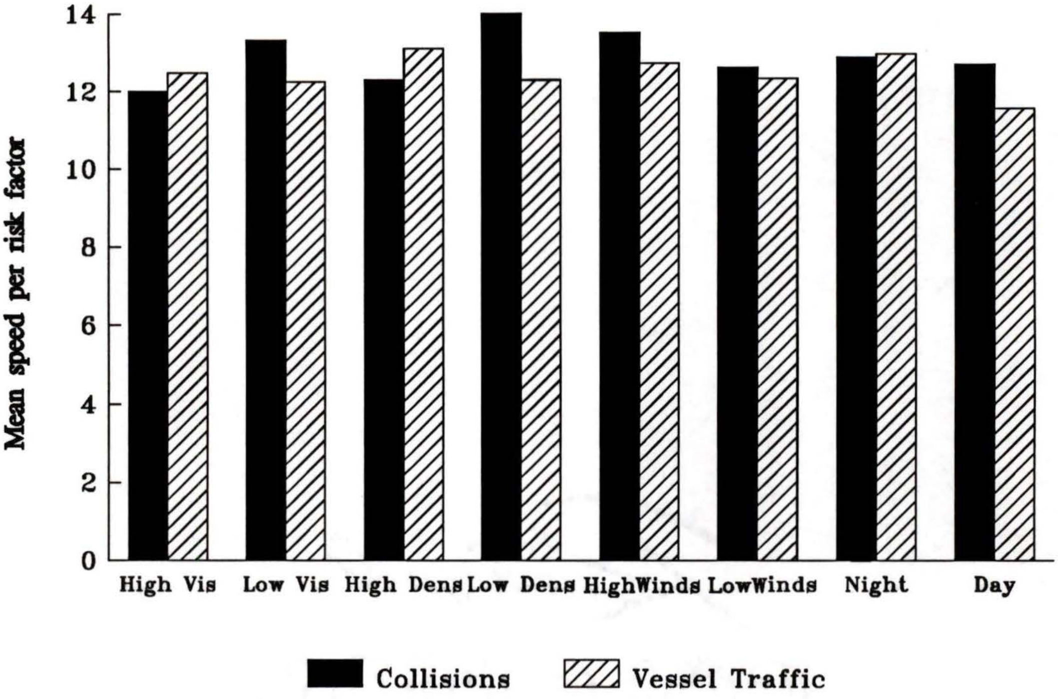

Figure 13. Mean vessel speed by risk factors

if one accepts the assumption that a reduction of speed is necessary during the conditions examined. This finding supports conclusions reached elsewhere that mariners accept a level of risk beyond any reduced risk associated with on-board technological improvements in navigation equipment. As a minimum, the extent of this problem demands intervention to increase awareness. However, in the absence of traffic controls, vessels will continue to exercise their right to free passage, with life, property and the environment at risk.

8. Visibility

The extensive documentation outlining the distinction of visibility as a key factor in collisions would implore its acceptance. However, the unknown magnitude of this factor and the variation in local conditions necessitated the comparison of mean visibility during collisions and mean visibility encountered during transits to establish, without question, its significance. In this analysis the occurrence of climatological factors is weighted by traffic frequency, rather than actual daily occurrence, since the intention is to analyze the environmental conditions encountered by mariners, not describe the climate of the study area.

A frequency distribution of collision visibility is predictably biased to the left, whereas average transit visibility is biased to the right (Figure 14). Greater than 90 percent of traffic proceeded through the study area with a visibility greater than two miles. Although the area cannot be characterized as excessively foggy, six out of ten collisions occurred in restricted visibility which suggests that it is certainly a contributing factor. This finding is further supported by a t-test of means (Table 8). This test confirmed the significantly different mean visibility of 4.6 miles for collisions and 11.2 miles for an average vessel transit, with a .001 probability that as large or larger a difference would occur with these sample sizes if the two populations had the same expected value (Table 8).

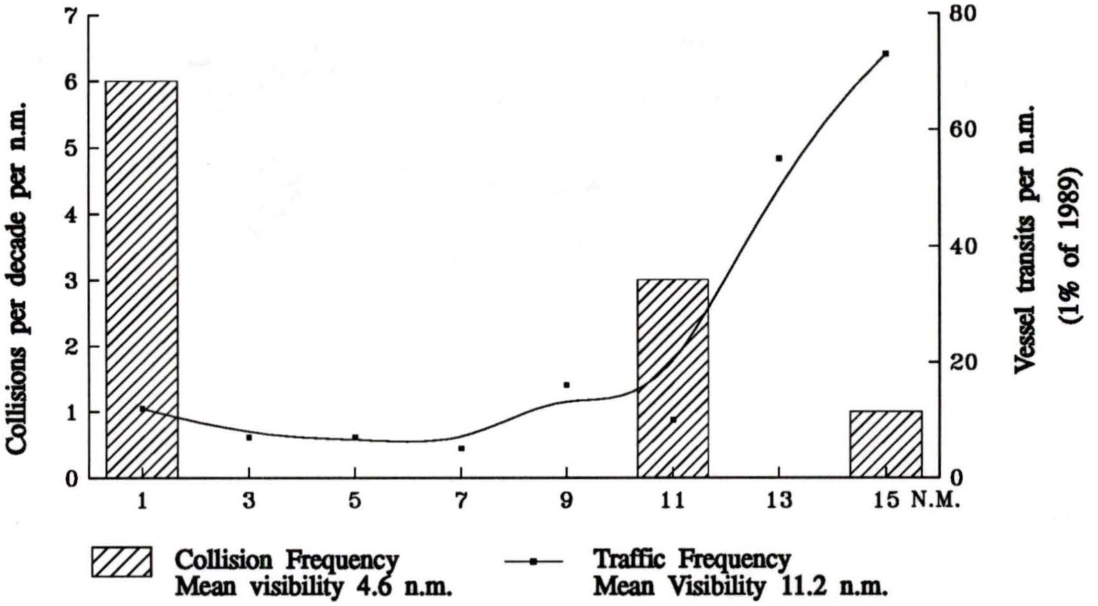

Figure 14. Visibility histogram

Table 8. Prevailing visibility in transits and collisions

	Number of Cases	Mean Visibility (miles)	Standard Deviation	Standard Error
Transits	185	11.16	4.47	.329
Collisions	10	4.64	5.88	1.858

		Pooled Variance Estimate		
F Value	1-Tail Prob.	t Value	D.F.	1-Tail Prob.
1.73	.08	4.42	193	.001

9. Windspeed

Windspeeds encountered by vessels in the study area are moderate, as weighted by the higher frequency of traffic during the summer months. Over 76 percent of vessel traffic experienced windspeeds of less than 11 knots (Figure 15). While the frequency distribution of windspeed is positively skewed with a mode of five knots and a mean of 7.2 knots, the histogram for collisions is bimodal at one and nine knots with a mean of 4.7 knots.

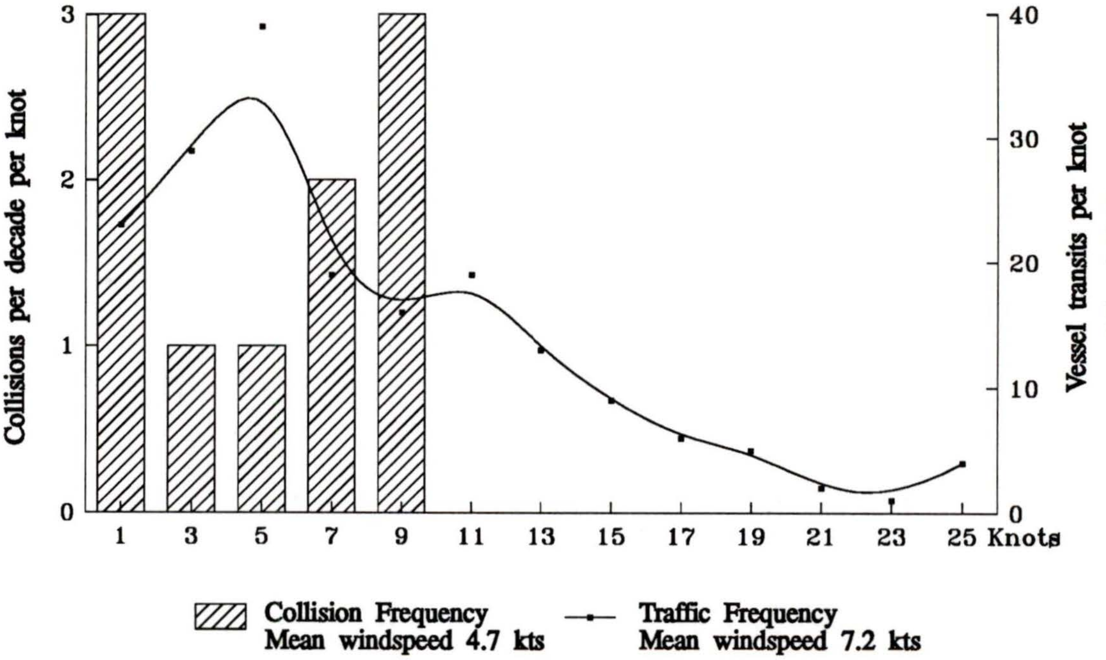

Figure 15. Windspeed histogram

That low windspeeds are associated with low visibility is not very enlightening, however, the second mode of nine knots during collisions could be associated with radar impairment by sea clutter. The detection of small vessels is degraded when obscured by sea clutter which is quite apparent when wave crests begin to break. Beaufort wind scale and correlative sea disturbance data indicate the formation of large wavelets and white caps with a mean height of .9 metres at a wind velocity of seven to ten knots (United Kingdom Ministry of Defence, 1977, p. 622).

A t-test was performed to measure the significance of the different mean windspeeds which showed a difference at the .08 level (Table 9). However, because of the association of low windspeeds with reduced visibility, it cannot be suggested that low windspeeds contribute to collisions.

Table 9. Prevailing windspeed in transits and collisions

	Number of Cases	Mean Windspeed (knots)	Standard Deviation	Standard Error
Transits	185	7.21	5.72	.420
Collisions	10	4.70	3.89	1.230

		Pooled Variance Estimate		
F Value	1-Tail Prob.	t Value	D.F.	1-Tail Prob.
2.16	.10	1.37	193	.08

10. Traffic density

(i) Spatial distribution of traffic density, fishing banks and collision occurrences

Traffic density was greatest on the fishing banks and reached a maximum mean yearly density of .125 vessels per square mile[17] on Soquel Bank (Figure 16). Mariners are warned in VTS and Canadian Hydrographic Service publications that large numbers of fishing vessels may be encountered inside the fifty fathom (100 metre) line in the approaches to Juan de Fuca Strait and that ships should not pass unnecessarily close to vessels engaged in fishing (Canadian Coast Guard, 1990, p. 40 and Canadian Hydrographic Service, 1987, p. 9).

The spatial correspondence between the location of collisions and the fishing banks, as indicated by the 100 metre depth contour, is most visible in Figure 16. The approximation of the limits of the fishing banks by the 100 metre depth contour reduces the uncertainty associated with estimates of traffic density which required the plotting of some fishing vessel data by either a general location on a particular fishing bank, such as Finger Bank, or a specific location estimated by observers.

Areas of higher traffic density, such as fishing banks, require a continuous assessment of the risk of collision. Whether or not the mariner is using visual or radar navigation techniques, the greater the number of vessels, the greater the chance of error or information overload. While it is not surprising

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[17] Values were converted from grid cell density (per 16 square miles) to per one square mile for Figure 16.

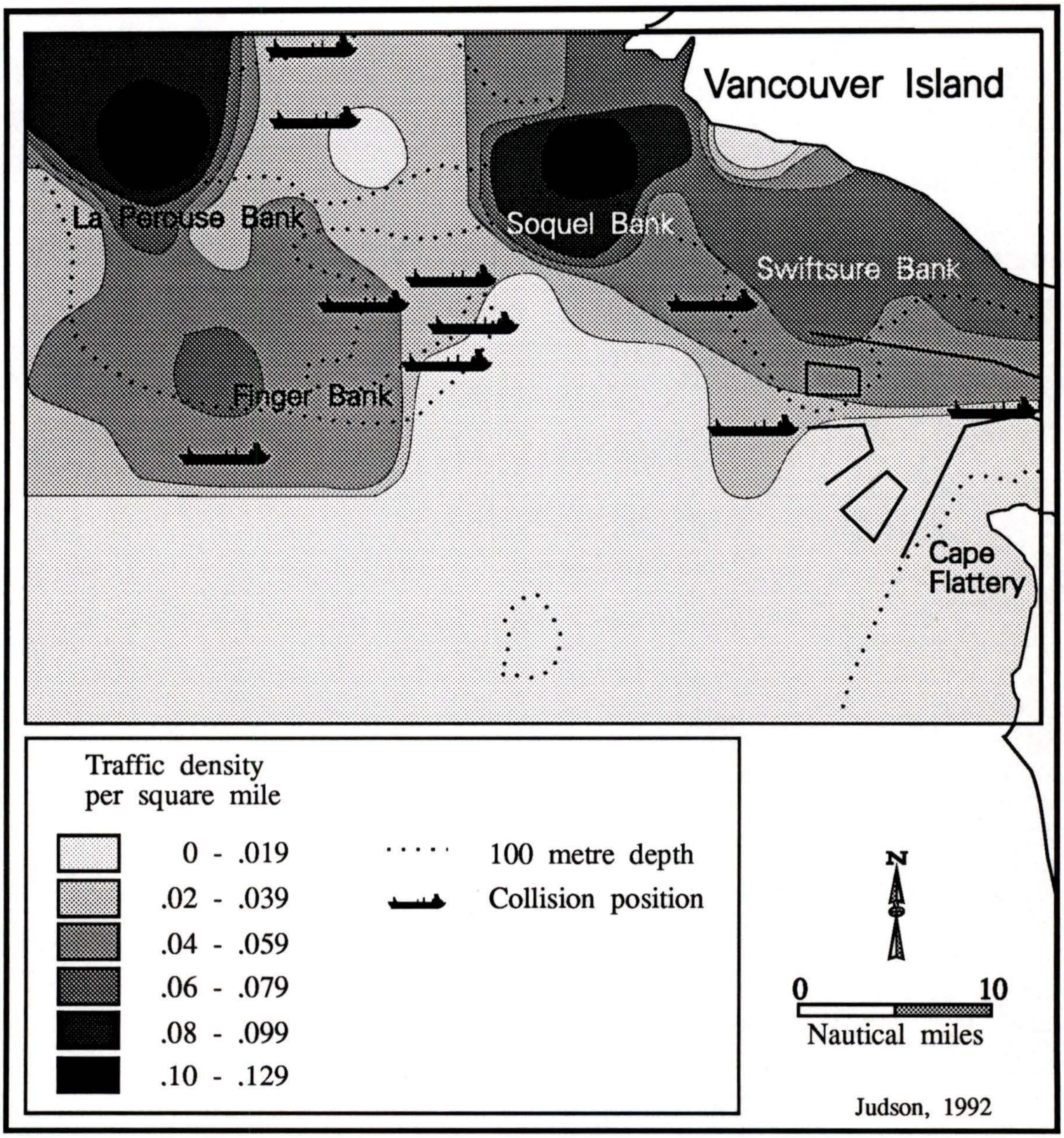

Figure 16. Traffic density, fishing banks and collision positions

that all collisions occurred on or near fishing banks, the proximity to the extremity of the fishing banks suggests that this pattern is the result of the mariner's attempt to avoid the heaviest concentration of fishing vessels and reduce distance overall by navigating too closely to a group of fishing vessels. This finding is further supported by comparing mean traffic density between collisions and through traffic, as well as comparing the seasonal correspondence of traffic density and the collision rate.

(ii) Collision and mean vessel densities encountered

The comparison of mean traffic density encountered by vessels involved in a collision and mean traffic density encountered by transiting vessels confirms density as a very strong factor related to collisions. Figure 17 indicates that transiting vessels experienced a mean traffic density of .67 per grid cell (4x4 miles) or 6.03 per 144 square miles. At a mean speed of 12.5 knots a mariner could expect to encounter six vessels within a six mile range every 19 minutes. By comparison, vessels involved in a collision encountered an average traffic density of 2.16 per grid cell, or 19 vessels within a six mile range. A T-test comparison of means clearly indicates the mean collision density of 2.16 is significantly greater (Table 10).

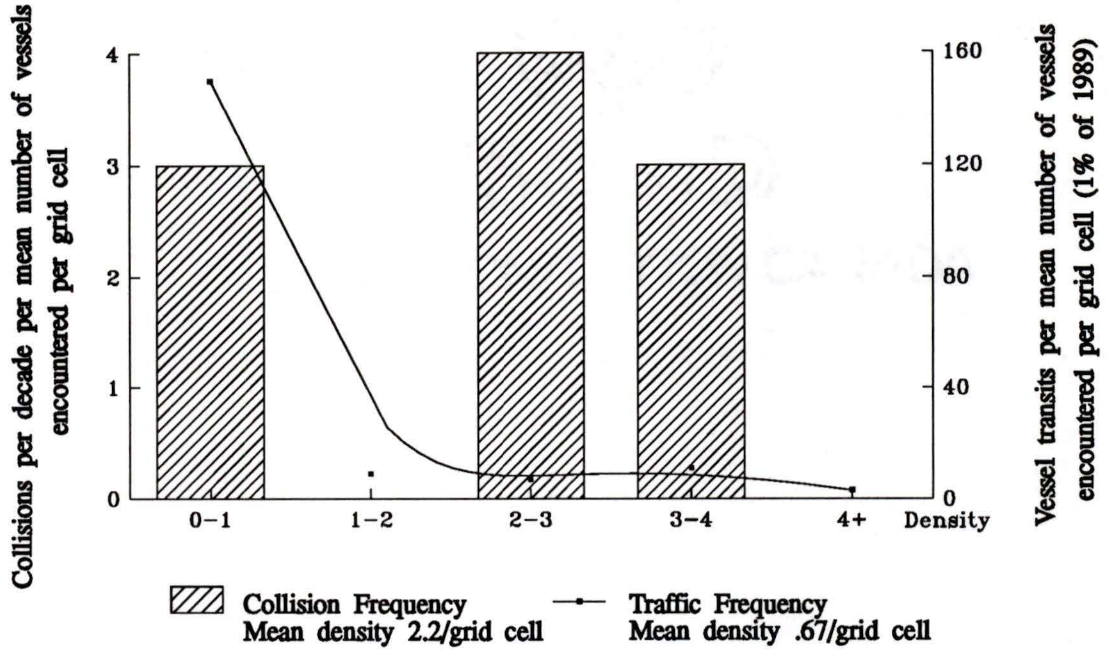

Figure 17. Traffic density histogram

Table 10. Prevailing traffic density in transits and collisions

	Number of Cases	Mean Traffic Density (per grid cell)	Standard Deviation	Standard Error
Transits	186	.67	1.06	.078
Collisions	10	2.16	1.45	.460

		Pooled Variance Estimate		
F Value	1-Tail Prob.	t Value	D.F.	1-Tail Prob.
1.89	.05	-4.24	194	.001

11. Seasonal variation in factors

An examination of monthly data revealed little variation in transit speed and visibility and a high degree of variation in the average monthly traffic density encountered by transiting vessels (Figure 18 and Table 11). Mean vessel speeds of 14.6 and 14.2 knots in April and July, respectively, were significantly higher that of 10.3 knots in September (Table 11). Given that vessels proceeded at an average speed of 12.5 knots despite the conditions, no explanation can be offered for this pattern in terms of safe speed factors. Similarly, the variation of visibility was considerably less than that of traffic density. Visibility was reduced to an average of 7.9 miles in December compared to 13.6 miles in April. This is significant at the .05 level, and is consistent with climatological records which indicate a restriction in visibility for an average of 23 percent of reports year round, with up to a 10 percent improvement in visibility during spring (Canadian Hydrographic Service, 1987, Appendix D).

Mean monthly traffic density was derived by first taking the average of traffic densities encountered by a vessel as it transited the study area (method was described in Chapter 4, Section 8), and second, by averaging all those mean values. For example, in July, 1989, a representative sample of 23 vessel transits proceeded through the study area. As each vessel encountered varying traffic densities these were summed and divided by the total number of grid cells passed through. Mean traffic densities encountered by each of 23 vessels were then averaged, resulting in a mean monthly traffic density encountered of 1.92

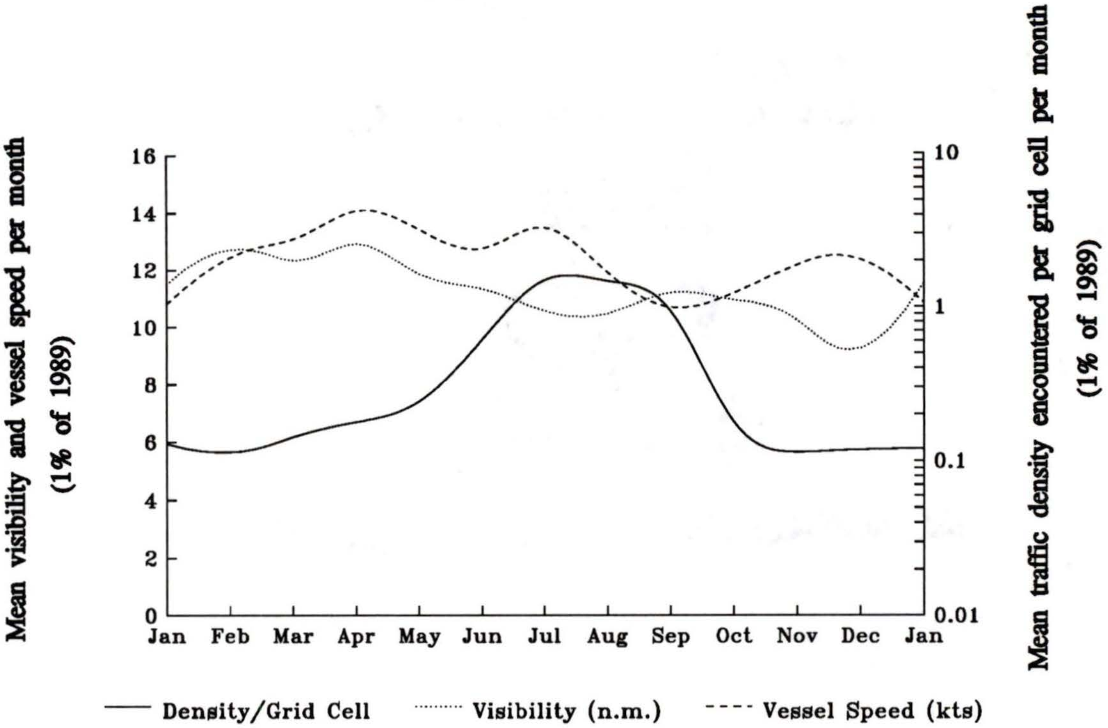

Figure 18. Monthly variation in factors

vessels per grid cell. This method of measurement was consistently applied to all 186 vessels in the sample, and the unit chosen for comparison was vessels per grid cell.

Mean monthly traffic densities of 1.92, 1.41 and 1.43 in July, August, and September were significantly higher than those of all other months (Table 11). The average number of collisions per month was compared with traffic volumes per month, as well as the product of encountered traffic density and ship-miles.

The average number of collisions per month, derived over the ten year study period, was compared with traffic volumes estimated for 1991 (Figure

Table 11. Monthly variation of factors

Summary of factor means

Month	Sample size (1989)	Mean Speed in knots (Std Dev)	Mean Density Encountered/Grid (Std Dev)	Mean Visibility in n.m. (Std Dev)
January	13	10.8 (2.9)	0.13 (0.04)	11.5 (3.5)
February	11	12.9 (3.7)	0.10 (0.04)	13.5 (2.1)
March	13	12.6 (3.0)	0.15 (0.06)	11.5 (2.8)
April	15	14.6 (3.2)	0.18 (0.09)	13.6 (2.5)
May	16	13.4 (3.1)	0.21 (0.06)	11.5 (5.0)
June	17	12.2 (3.1)	0.61 (0.81)	11.5 (2.9)
July	23	14.2 (3.4)	1.92 (1.68)	10.4 (5.1)
August	21	11.7 (4.1)	1.41 (1.05)	10.2 (4.7)
September	18	10.3 (4.3)	1.43 (1.19)	11.5 (5.4)
October	13	11.1 (2.4)	0.12 (0.05)	10.8 (5.4)
November	13	12.2 (3.5)	0.11 (0.06)	10.8 (5.2)
December	13	12.9 (5.0)	0.12 (0.05)	7.9 (5.1)

Analysis of variance

Multiple Range Test–Tukey-B Procedure ranges .05 level: 3.75 4.02 4.18 4.29 4.38 4.45 4.51 4.56 4.61 4.65 4.68

	Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob.
Variation in mean speed	Between Groups	11	319.06	29.01	2.29	.01
	Within Groups	174	2203.01	12.66		
	Total	185	2522.06			
Variation in mean visibility	Between Groups	11	335.32	30.48	1.58	.10
	Within Groups	173	3338.59	19.30		
	Total	184	3673.91			
Variation in mean density	Between Groups	11	87.78	7.98	11.64	.00
	Within Groups	174	119.26	.69		
	Total	185	207.04			

Mean vessel speeds in April and July are significantly different from September (.05 level).
Mean visibility in April is significantly different from December (.05 level).
Mean vessel densities encountered in July, August and September are significantly different from all other months (.05 level).

Table 12. Encountered density, ship-miles and the collision rate, 1991

Month	Mean Traffic Density Encountered	Number of Transits	Ship-miles	Density x Ship-miles	Observed Number of Collisions	Expected Number of Collisions
January	0.14	1442	49850	6869	0.0	0.01
February	0.11	1349	46645	4944	0.0	0.01
March	0.16	1577	54522	8669	0.0	0.02
April	0.19	1687	58345	11132	0.1	0.02
May	0.22	1769	61164	13615	0.1	0.02
June	0.65	1949	67381	43568	0.1	0.08
July	2.04	2598	89854	182870	0.3	0.32
August	1.50	2346	81127	121252	0.3	0.21
September	1.52	1985	68655	104067	0.1	0.18
October	0.13	1583	54754	6965	0.0	0.01
November	0.12	1436	49657	5790	0.0	0.01
December	0.13	1420	49116	6248	0.0	0.01

19 and Table 12). Monthly traffic volumes were estimated by proportioning the annual volume of 21 141 vessels (estimated by an annual increase of 627 vessels since 1989) according to the 1989 monthly distribution. This comparison resulted in a correlation of r=.96 between the monthly collision rate and traffic volumes which implies a higher collision risk per ship during months with high traffic volumes.[18] This relationship is of limited use because it does not show what collision frequencies could be expected if traffic patterns, other than volume, were to change.

Cockcroft (1976, p. 217) has suggested that the collision rate increases with the square of the traffic density. Average traffic densities encountered by transiting vessels and vessels in collision were used in this study to enable comparisons of encountered traffic density which were independent of

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[18] Traffic volume correlation .96, R squared .92, S.E. Est. .03, significance .0000.

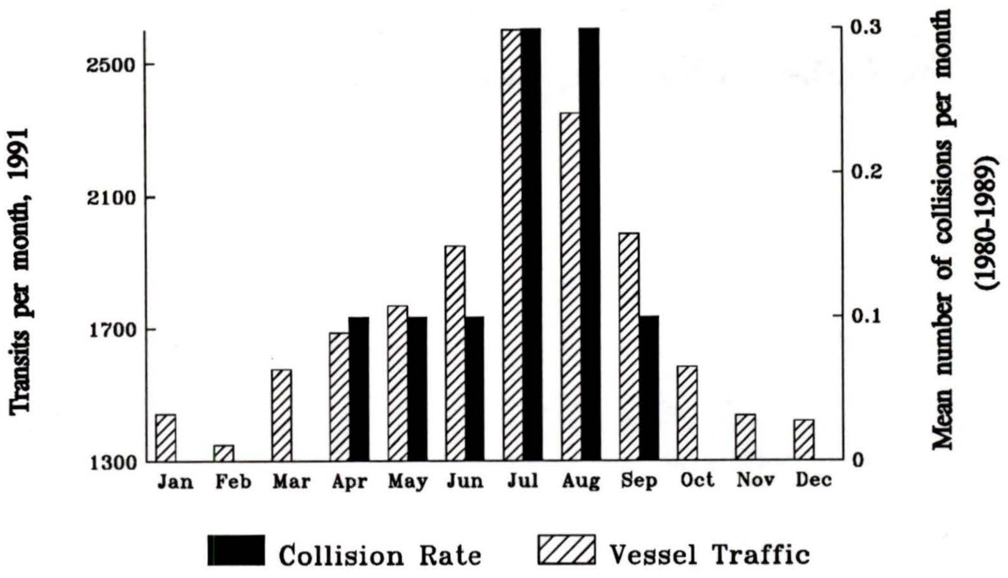

Figure 19. Traffic volume and collision rate correlation

route length, since route lengths through the study area varied. Nevertheless, the distance travelled by all vessels through the study area must be considered in the design of an alternate routing scheme. Changes in traffic routes could affect route lengths and traffic densities encountered. Therefore, rather than just explore the relationship between traffic density and collisions per month, a causal relationship was examined by the inclusion of traffic mileage through areas of varying density via routes identified in Figure 5 and Table 13.

The parameters used in regressing collisions per month with average encountered density per month and ship-miles per month are listed in Table 12. The collision rate was defined as the number of collisions per month averaged over a ten year period. A three percent growth in traffic and fishing activity is assumed which is based on findings indicated previously. Accordingly, traffic densities and transit volumes for 1989 were increased by three percent (Table 12). The collision rate per month over the ten year period is used as an estimate of the collision rate per month for 1991. This estimate does not affect the correlation, but it does illustrate a degree of uncertainty associated with an assumption that fishing vessel counts did not vary significantly over the ten years and the fact that traffic volumes vary from year to year. The fishing vessel counts were the principal factor affecting the traffic density estimates.

The method of determining ship-miles per month is the equivalent of the sum of total distance travelled by all vessels transiting in a month. The method of calculation is indicated in Table 13. The traffic patterns depicted in Figure 5 appear to exhibit an equal dispersion of courses within each distinct arc.

Table 13. Calculation of total ship-miles per month

	Mean course	Median	Frequency	Course length
Inbound	101°	100°	66	52 n.m.
	022°	020°	38	18 n.m.
	142°	130°	4	28 n.m.
Outbound	292°	300°	40	38 n.m.
	201°	200°	38	18 n.m.

January 1991 ship-miles = (1442/186)x6432 = 49865

Note that Table 12 indicates January ship-miles to be 49 850. The discrepancy is due to rounding of estimated monthly transits.

Table 13 indicates that the median courses are within 10° of mean courses for each arc, except the inshore traffic route of 142° which represents only four out of 186 vessels. Therefore, the route lengths of mean courses were used in the calculation of monthly ship-miles. Since it is assumed that the monthly traffic pattern other than volume does not vary between months, total ship-miles per month is equivalent to the product of the number of transits and the average route length of 6432/186 or 34.6 miles.

To ensure that a nonsensical collision rate would not be estimated for an independent variable value of zero, a regression through the origin was performed on the collision rate with encountered traffic density times ship-miles such that,

$$\hat{Y}=.00000176X$$

where $\hat{Y}$ is the estimated collision rate per unit of vessel traffic density times ship-miles and X is the estimated monthly traffic density (vessels encountered per grid cell) times ship-miles.

Figure 20 illustrates this relationship which indicates an R^2 value of .87 (D.F. 11, S.E. Est. .05, Sig. .0005, S.E. Slope $2.05\text{x}10^{-7}$). Expected and observed numbers of collisions per month are presented in Table 12. This finding is consistent with the nature of collisions in the study area which were shown to involve concentrations of fishing vessels and through traffic. During the peak traffic months of July and August six out of ten collisions occurred. During an entire fishing season from June through September 42.5 percent of yearly traffic transited the approaches during which eight out of ten collisions occurred. This finding provided the basis to test the hypothesis that the rare event of a collision occurs as a Poisson distribution in relation to vessel traffic frequency and time.

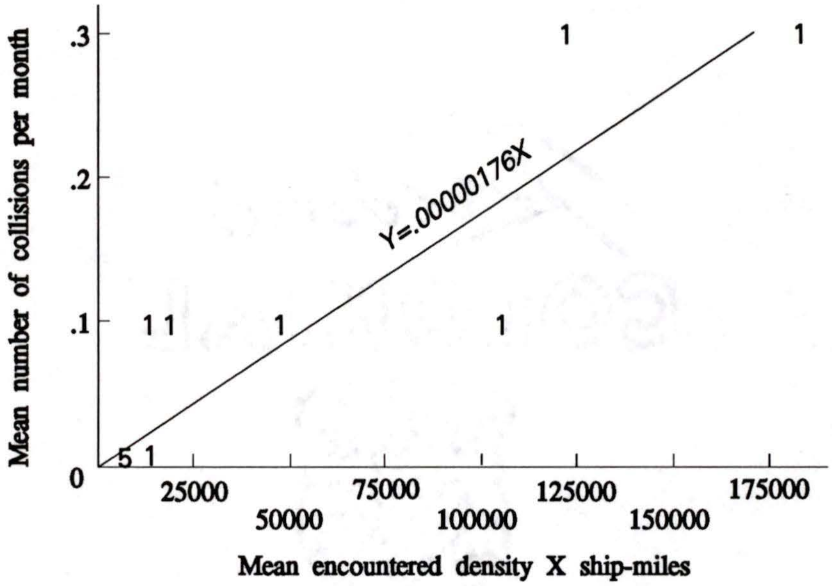

Figure 20. Plot of collision rate with density x ship-miles

12. Diurnal variation in factors

Diurnal variation might be lost in the analysis of an entire year's climatological and traffic data. In order to minimize this dilution of information yet maintain a database capable of supporting the analysis of a diurnal pattern of collisions and factors, only those months during which collisions occurred were selected (April through September inclusive). Factors selected for comparison to the time of collision included visibility, vessel speed and traffic density which were shown to contribute to collision risk. Daily time periods were chosen to correspond to four hour watches.

To enable a comparison between these variables and collisions which is unrelated to transit frequency per watch, the mean annual number of collisions per watch was divided by the sum of the estimated number of transits per watch from April to September (Table 14 and Figure 21).

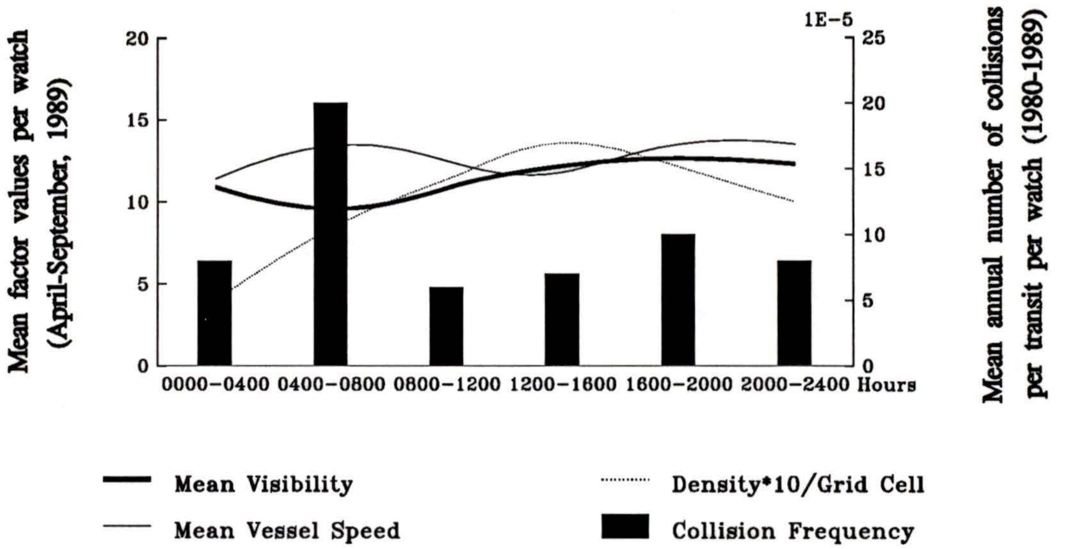

Figure 21. Diurnal variation in factors

A oneway analysis of variance revealed no significant variation in either traffic density, speed or visibility. However, visibility was lowest during the morning watch from 0400 to 0800 hours when collision frequency was highest (Table 14 and Figure 21). While not conclusive, this finding confirmed the expectation of a lower visibility during this period due to fog formation in the early morning and further supports the association of poor visibility and collisions.

Table 14. Diurnal variation of factors

Summary of factor means

Watch	Number of Cases (Apr.-Sep.,1989) (x100 = transits)	Mean Speed (knots) (Std Dev)	Mean Density Encountered/Grid (Std Dev)	Mean Visibility (n.m.) (Std Dev)
Middle	13	11.4(3.9)	0.4(0.4)	10.9(4.2)
Morning	15	14.5(3.6)	0.9(1.3)	8.6(5.8)
Forenoon	34	12.4(3.1)	1.1(1.3)	11.1(4.9)
Afternoon	15	10.7(4.7)	1.5(1.4)	12.3(4.0)
Dogs	7	14.4(2.7)	1.2(1.7)	12.9(3.3)
First	26	13.5(3.9)	1.0(1.2)	12.3(3.3)

Analysis of variance

Multiple Range Test–Tukey-B Procedure ranges for the .05 level: 3.46 3.74 3.90 4.02 4.11

Factor	Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob.
Mean speed	Between Groups	5	173.12	34.62	2.55	.03
	Within Groups	104	1414.70	13.60		
	Total	109	1587.82			

No two groups are significantly different (.05 level)

Factor	Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob.
Mean density	Between Groups	5	8.87	1.77	1.16	.33
	Within Groups	104	158.98	1.53		
	Total	109	167.85			

No two groups are significantly different (.05 level)

Factor	Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob.
Mean visibility	Between Groups	5	177.04	35.41	1.79	.12
	Within Groups	104	2053.70	19.75		
	Total	109	2230.75			

No two groups are significantly different (.05 level)

It is interesting that during the middle watch density fell to 0.40 vessels per grid cell even though it remained higher than the annual mean density of 0.67 throughout the day. Despite this probably insignificant variation, a lower density during darkness may indicate a tendency of mariners to limit passage through fishing areas at night, since density is largely a function of the fishing vessel count, which was assumed to be a monthly constant.

13. Factor weighting

It was shown in the literature review that a problem exists in determining what is a cause of collisions and what is a contributing factor. In all cases examined in this study human error caused the collisions and other factors contributed to human error. The weighting of contributory factors using the method of coincidence is an appropriate procedure if only those factors that were found to be significant are included. This is presented as a means of indicating the relative importance of the factors in question so that appropriate recommendations can be made. It is recognized that human error can exist in the absence of a specific contributing factor, however, this has not been the case in the collision records examined.

Possible social factors such, as lack of sleep, alcohol consumption and competency were purposely excluded, in order to limit the scope of this study to the improvement of traffic management and VTS, rather than improvement of the mariner. Dickins has indicated that 96 percent of human errors which resulted in marine casualties were operational mistakes unrelated to alcohol or substance abuse (Dickins, *Review of Tanker/Barge Safety*, p. 54).

In order to avoid duplication of factors, windspeed, diurnal and seasonal factors were excluded. The seasonal factor was demonstrated to be simply a function of higher density which peaks during the summer months; density is a function of higher traffic volume and fishing activity. Similarly, the only significant diurnal factor was visibility. Despite the finding that mean windspeed was significantly lower during collisions, it was excluded because of its association with low visibility. Speed, density and visibility remained as key contributory factors for inclusion.

The frequencies of occurrence of the contributory factors of excessive speed, high density and low visibility during collisions are presented in Table 13.[19] Speed is of greatest concern, followed closely by density and visibility. Consequently, consideration should be given to these three factors when

Table 15. Contributing factor weighting

Factor	Frequency	Weighting
Speed	8	.38
Density	7	.33
Visibility	6	.29
Total	21	1.00

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[19] High density is greater than or equal to one vessel per grid cell. Visibility is equal to or less than two miles. Speed is considered excessive where it is in excess of the mean traffic speed or where Coast Guard records state that speed was excessive. More than one factor can contribute to a collision.

identifying and evaluating risk reduction measures. The following section presents the results of an estimation of base line collision risk from which risk reduction measures were evaluated.

14. Probability of collision.

Since the collision rate is correlated to vessel traffic frequency, the mean number of collisions is expressed as a ratio of the number of collision incidents to the total number of periods during which 5 000 vessels transited the study area.

Recall that the collision rate per 5 000 transits was used to estimate using the mean or expected value,

$$\lambda = \frac{i}{n}$$

where n is the number of periods during which there were 5 000 vessel transits and i is the total number of collisions. Therefore,

$$\lambda = \frac{10}{34}/5000 = .29/5000$$

According to the Poisson distribution, the probability that there will be r collisions is

$$P_{(r)} = \frac{\lambda^r e^{-\lambda}}{r!}$$

where λ equals 0.29, *e* = 2.7183..., and *r* !, called factorial *r*, is equal to *r* (*r*-1)(*r*-2)...1. A Kolmogorov-Smirnov goodness of fit test comparison of observed collision frequencies with estimated Poisson probabilities confirmed a strong degree of correspondence with a probability greater than .995 that the collision rate is Poisson distributed (Table 14 and Figure 21). Therefore, the probability of at least one collision is .25 per 5 000 transits.

Table 16. Observed and expected collision frequencies per 5 000 transits

Number of Collisions	Observed Frequency	Expected Frequency	Poisson Probability
0	27	25.40	.7483
1	4	7.40	.2170
2	3	1.10	.0315
3	0	0.01	.0003

Most Extreme Absolute Difference .05350 K-S Z=.312 2-tailed P=.995

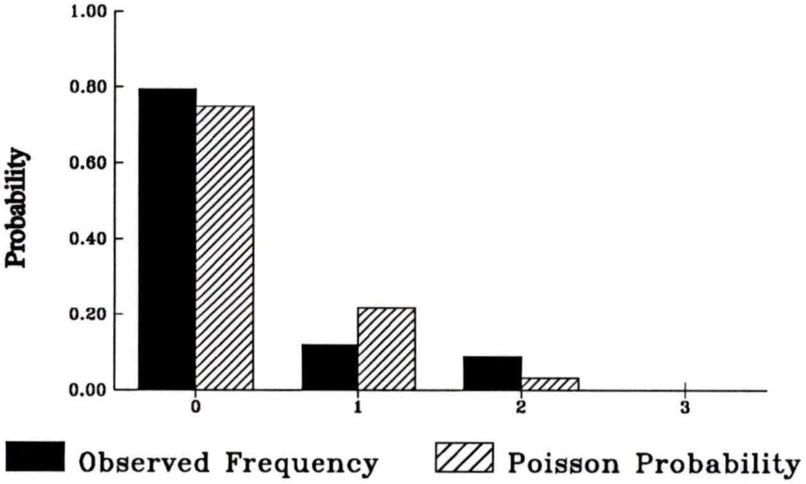

Figure 22. Collision rate per 5 000 transits

Accepting that collision frequency can be approximated by a Poisson distribution and predicted from encountered traffic density, a risk model was developed from which risk reduction can be estimated. This relationship provided a method of predicting the collision rate based upon traffic density which is a factor which can be modified by traffic routing measures. This was accomplished by using the regression function of collision rate on traffic density x ship-miles as an estimate of λ in the Poisson model. Estimated collision rates for each month then were substituted for λ in the Poisson function such that,

$$P_{(r)}=\frac{1}{r!}[.00000176X^{r}e^{-.00000176X}]$$

and the probability of at least one collision is calculated for each month of 1991 (Table 17 and Figure 23).

Table 17. Monthly collision probability, 1991

Month (1991)	Estimate of lambda $\hat{Y}$ or λ	Probability of at least one collision 1-P(0)
January	.01	.01
February	.01	.01
March	.02	.02
April	.02	.02
May	.02	.02
June	.08	.07
July	.32	.28
August	.21	.19
September	.18	.17
October	.01	.01
November	.01	.01
December	.01	.01

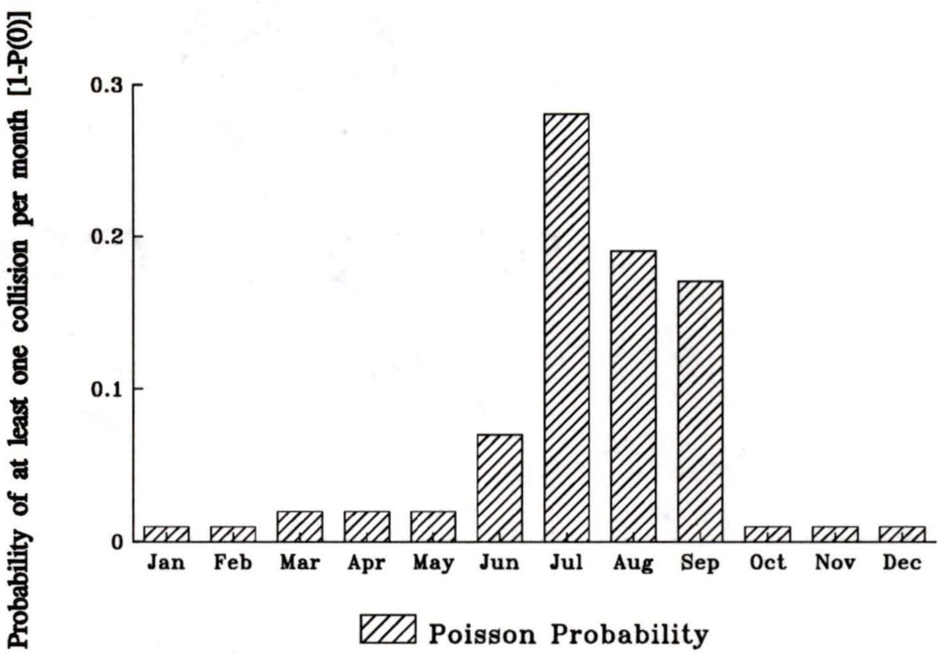

Figure 23. Monthly collision probability, 1991

This figure illustrates monthly collision probabilities of at least one collision (1-P(0)) as a Poisson function derived from the regression estimate of lambda. Collision probability is estimated to peak in July with a 28 percent chance of at least one collision occurring.

Prior to evaluating possible risk reduction effects of a modified traffic scheme or any other measure, one must pause to compare these results with those found in other research.

15. Comparison of estimated risk with other research

The results of this analysis can be compared to research estimating either a collision probability based on transits or traffic density, or a simple collision rate based on time or ship-miles.

Tanker collision risk in the Port of Vancouver was estimated by Sandwell using a Poisson probability function to be one collision per 10 000 port calls (Sandwell, 1991, Section 6, p. 47). This is equivalent to one collision per 20 000 movements through First Narrows, the entrance to Vancouver Harbour, which is comparable to the probability of .25/5 000 or at least one collision per 20 000 transits estimated by this author for the approaches to the Strait. This similarity also demonstrates that areas other than harbours can equally be considered "hot spots."

The European COST 301 project estimated the collision rate for the entire European waters, extending 200 miles off the European states including the Baltic and Mediterranean seas, as .495 per 10^6 ship-miles (Commission of the European Communities, 1988, p.73). Ships over 100 gross tons were included in the estimate. A comparable collision rate in the approaches to the Strait was calculated by determining the total ship-miles during which ten collisions occurred. This was measured by using the distance and frequency of mean transit routes for the sample of 186 vessel transits in 1989 (indicated in Table 13 to be 6 432 miles per 186 transits) to determine the total ship-miles per 171 130 transits. The resulting rate of ten collisions per $5.96\text{x}10^6$ miles is equivalent to 1.69 per 10^6 ship-miles–over three times the rate in European waters. Clearly, the estimation of a collision rate or spill rate for a large geographic region such as North Europe, or even the Pacific Northwest, provides a bench mark for comparison, but would be a generalization which would not give prominence to the high risk areas. Different geographic areas require site-specific prevention and response measures which must be identified by a traffic survey and analysis of cause.

Cohen estimated the tanker spill risk for Vancouver Harbour to be .004 spills per year (greater than 1590 cubic metres), which Sandwell suggests is twice the world average and implies a casualty rate five times the average for United States ports (Cohen and Aylesworth, 1990, p. 30, Sandwell, 1991, Section 6, p. 79). Sandwell does not suggest a reason for this discrepancy, but further examination of the derivation of Cohen's navigation risk figures revealed significant omissions or errors, in addition to the unresolved problem with risk factor weighting. A spill risk of .006 per year was estimated by Cohen for the entrance to the Strait, however, this figure is not comparable to the findings of this thesis because it was developed from a navigational risk value for shipping density which did not include commercial fishing vessels and indicated incorrectly that less than 1 001 deep sea vessels transit the entrance area annually (Cohen and Aylesworth, 1990, pp. 11-13, 30).

5 Evaluation of risk reduction

1. Risk control measures

Two approaches to risk control are apparent in the literature which apply equally to spill prevention, or the mitigation of the effects of spills. The human approach to marine safety involves safety education, rest, drug testing and similar preventative measures, and the engineering approach includes both preventative and loss reduction measures. While it was acknowledged previously that safety education and risk perception are partners in risk reduction, the measures to be considered for evaluation here can be classified as part of the engineering approach.

Government and industry have tended to classify risk reduction measures into two groups, prevention and response. It has been argued repeatedly that response, a means of loss reduction, is inadequate and not cost-effective and that prevention is the key (*Seattle Post-Intelligencer*, August 3, 1991, pp. 1, 4). Others have argued that all risk reduction methods require further study (Anderson, 1989, Branders-Smith, 1990). However, the prevention versus response classification does not lend itself well to an economic appraisal. When considering cost-effectiveness, both preventative measures and loss reduction in the event of a casualty are considered. For example, speed limits could arguably both prevent collisions and in the event of a collision reduce impact velocity, thereby reducing the severity of hull disruption and conceivably lessening the spill probability. Similarly, double-hulls are used to both prevent spills and reduce the severity of a spill should it occur. Salvage and clean-up actions may reduce the loss, depending, of course, on how loss is defined.

This study indicates that vessel speed, traffic density, and visibility are factors to be considered in any risk reduction evaluation. Measures that accommodate these factors include navigational assistance to mariners, coordination of traffic and acceptable restrictions on navigation. Such measures are interrelated and will both prevent losses and reduce the impact of a loss. They include, but are not limited to, VTS, speed control and traffic routing.

2. VTS and speed control

Presently, speeds are limited in a passive sense to those considered appropriate by each mariner in accordance with Rule 6. Rarely will a vessel traffic control authority risk the potential legal consequences of giving compulsory course and speed direction to a vessel when the comparative liability for negligence is considered (Corbet, 1987, pp. 138-139).

> It is not surprising that pilots often put forward the view that port navigation officers (marine traffic controllers) providing active marine traffic control are in a less onerous position than they are themselves as a result of a casualty to their ship which the port navigation officer is advising or 'controlling'. Pilots therefore feel that any advice or directions which they receive from marine traffic controllers might not be given with the same commitment of care as they themselves exercise under the duress of punitive legislation (Corbet, 1989, p. 282).

Canadian VTS is similarly burdened by the difficulty of not appearing to restrict or direct traffic when trying to improve traffic safety. The *Guide to the VTS Regulations* (1988, p. 1) clearly indicates this awareness:

> The *VTS National Study* states that 'VTS is designed to identify potential conflicts and, through an interactive exchange of information with vessels, to reduce marine risk'; however, Coast Guard ensures [*sic*] the marine industry that interaction would not mean that Coast Guard would attempt to navigate or manoeuvre ships from a shore station.[20]

In practice, Tofino marine traffic regulators frequently offer and respond to requests for courses to avoid dense fishing activity, but do not give speed recommendations nor warnings of excessive speed to rogue vessels, or those vessels not operating safely or in violation of international collision regulations.[21] At present, speed recommendations are only implied in the nature of information given to mariners regarding weather and vessel activity. Warnings of the presence of rogue vessels are given to all vessels monitoring VTS radio broadcasts, but policing activity is limited to the registering of formal complaints for investigation.

Collision reports indicated that VTS at Ucluelet cannot track the volume of fishing vessels present during the summer, and even if it were possible course and speed estimates would be inaccurate, given that these vessel manoeuvre continuously. Furthermore, collision situations developed without the intervention of vessel traffic controllers. It appears that VTS at Ucluelet is very effective when it can re-route traffic clear of fishing areas, however, it breaks down when a rogue vessel steams through undaunted, despite the density of

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[20] The study quoted in the VTS Guide refers to Bureau of Management Consulting, *VTS Final Report–National VTS Study*. Ottawa: Canadian Coast Guard, 1984.

[21] Personal communications with Mr. L. Pokeda, Officer in Charge of Tofino Vessel Traffic Services.

vessels or restriction of visibility. Simply put, traffic that is managed only by international regulations is difficult to control.

In addition to the legal complications of speed limits or active direction of traffic, it is argued that a shore station is limited in its ability to navigate a ship in a close-quarters situation. However, a shore radar station's ability to detect rogue vessels is greatly enhanced by its superior radar coverage area and knowledge of the activity of other vessels. Although this "heads-up" advantage is limited in its ability to detect and communicate with all vessels, it enables a shore station to make recommendations to shipping and offer navigational information when requested. Furthermore, if a rogue vessel is not responsive to radio, it can be intercepted and identified. This could be accomplished with light aircraft under contract to be on call, as it is done in the Strait of Dover,[22] or by an all-weather fast patrol boat or hovercraft based in Ucluelet.

Because speed is recognized as a particular problem in the Strait speed limits are one of several navigation safety initiatives being considered by United States Coast Guard. However, speed criteria are only being considered for tankships and chemical carriers under escort by tug, such that the speed does not exceed the operational speed of the escort (United States Coast Guard, *Navigation Safety Initiatives*, 1990, p. 4). This proposal is limited in its scope because it does not consider all vessels, nor the approaches to the Strait.

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[22] Personal communication with Officer in Charge, Channel Navigation Information Service (Dover VTS), May 1990.

This thesis has shown that there is no significant variation in vessel speed in situations where a speed reduction would be considered prudent. This finding precludes any attempt to correlate vessel speed with the collision rate and limits the ability to quantitatively predict risk reduction as a result of speed reduction. This notwithstanding, compliance with international collision regulations is imperative, and excessive speed criteria should be established for situations where VTS controllers must give information on conditions which warrant a speed reduction to a particular vessel. Non-compliance would necessitate a timely recommendation to reconsider the prudence of one's actions. It would be understood that liability could weigh heavily on a vessel that became a casualty after failing to react to a VTS recommendation.

3. Evaluation of traffic routing

The world-wide prevention of collisions by establishing "traffic separation schemes" and "areas to be avoided" has been effective since traffic separation in the Strait of Dover was conceived in the 1960's. The IMO describes the purpose of ship's routing as the improvement in "the safety of navigation in converging areas and in areas where the density of traffic is great or where freedom of movement of shipping is inhibited by restricted sea-room, the existence of obstructions to navigation, limited depths or unfavourable conditions" (International Maritime Organization, 1989, p. 2). Several specific objectives of the IMO's guide, *Ship's Routeing,* indicate traffic circumstances similar to those found in the international and domestic waters of the approaches to the Strait of Juan de Fuca. These objectives include:

(1) the separation of opposing streams of traffic

(2) the organization of traffic flow in or around areas where navigation by all ships or by certain classes of ship is dangerous or undesirable

(3) the guidance of traffic clear of fishing grounds or the organization of traffic through fishing grounds

However, before any modification to the existing routing scheme would be accepted, the IMO Subcommittee on Safety of Navigation must be convinced of the localized collision risk and the special trans-boundary environmental concerns in the Washington and British Columbia coastal zone.

In the past, proposals in other areas to establish "areas to be avoided" coincident with fishing grounds have been rejected because of the seasonal nature of fishing, and the precedent that would be set (Cockcroft, 1986, p. 223). However, several "areas to be avoided" exist for reasons of environmental protection, danger of stranding, conservation of wildlife or risk of pollution due to an accident. One such area is in the region of Nantucket Shoals which extend 42 miles southeast of Nantucket Island. The shoals are afforded protection by traffic separation schemes in the approaches to Boston and New York and a designated "area to be avoided" (International Maritime Organization, 1989, Section 9, p. 5.4)

Prior to consulting user groups which may be affected by modifications to existing routing schemes, these groups must be identified and past areas of interest or conflict should be considered. Potential interests are outlined in IMO's *Traffic Routeing* design criteria (International Maritime Organization, 1989, pp. 2-15). In the study area, organizations with a vested interest in improving safety in this area of the coastal zone would include:

(1) United States and Canadian departments of National Defence
(2) Company of Master Mariners
(3) British Columbia Pilotage Authority
(4) Canadian Mariners Advisory Committee
(5) Shipping companies
(6) Deep Sea Trawlers Association
(7) United Fishermen and Allied Workers' Union
(8) Government agencies
(9) Citizen's Advisory Committee on Marine Oil Spill Prevention and Response

Fishing organizations are one of several groups with a prominent economic and environmental interest in the approaches to the Strait. In the past, the Canadian fishing community has opposed any restrictions on its activity resulting from the implementation of mandatory traffic routing schemes. Routing schemes through fishing areas should reduce the risk of collision by restricting the movement of fishing vessels within the traffic lanes (Cockcroft, 1986). However, opposition to any restriction on fishing vessel navigation resulted in a Canadian modification to Rule 10 which outlines the international rules applicable to traffic separation schemes. Despite the restriction that "a vessel engaged in fishing shall not impede the passage of any vessel following a traffic lane", a vessel fishing in Canadian waters or fishing zones is exempt from the following rules (Canadian Coast Guard, *Collision Regulations*, 1989, pp. 10-11):

> (1) 10(b) A vessel using a traffic separation scheme shall:
> - (i) proceed in the appropriate traffic lane in the general direction of traffic flow for that lane,
> - (ii) so far as practicable keep clear of a traffic separation line or separation zone,
> - (iii) normally join or leave a traffic lane at the termination of the lane, but when joining or leaving from either side shall do so at as small an angle to the general direction of traffic flow as practicable.
>
> (2) 10(c) A vessel shall so far as practicable avoid crossing traffic lanes, but if obliged to do so shall cross as nearly as practicable at right angles to the general direction of traffic flow.
>
> (3) 10(h) A vessel not using a traffic separation scheme shall avoid it by as wide a margin as is practicable.

The effect of these exemptions is that fishing vessels may continue their normal activity, which often involves unpredictable manoeuvring, as long as the passage of vessels following the traffic lane is not impeded. The freedom enjoyed by fishing vessels in traffic lanes in Canadian waters is a potential source of conflict for commercial shipping if free navigation in the approaches to the Strait is restricted within a routing scheme extending into international waters. The Canadian modifications to Rule 10 suggests that fishing vessels are not required to keep clear of traffic lanes in Canadian fishing zones. Since the existing routing scheme does not extend beyond Canadian territorial waters into Canadian fishing zones, the privilege afforded fishing vessels by the Canadian modifications to

Rule 10 has not been challenged by international authorities. However, one would expect that the fishing industry would not object to the placement of traffic lanes clear of the major fishing grounds if it were in their interest.

Traffic safety concerns were acknowledged by the local United Fishermen and Allied Workers' Union after the sinking of the *Tenyo Maru* (*Vancouver Sun*, July 24, 1991, p. A2). However, it seems that the union is not yet convinced of the necessity of improving traffic routing.[23] The sole change suggested by the union after the sinking of the *Tenyo Maru* was the improvement of communications which appeared to be reactive to events–the *Tenyo Maru* did not respond to radio warnings by local fishermen (*Vancouver Sun*, July 23, 1991, pp. A1, A2, A6). On the other hand, the British Columbia Deep Sea Trawlers Association have expressed a concern about traffic congestion and the need to change routing in the approaches:

> We have talked about it over the years, it's always been a Catch-22. We want to divert the shipping, but we don't want to lose the fishing area. It's a small area, but very productive for us (*Seattle Post-Intelligencer*, July 24, 1991, p. A1).

Other fishermen have expressed similar concerns (*Seattle Post-Intelligencer*, July 31, 1991, p. B2).

The Vancouver Division of the Company of Master Mariners of Canada is in favour of a review of the traffic routing scheme:

> The group agrees that environmental impact of breakups should be considered in the routing of tankers where practicable. There is agreement in principle for the concept of "Special Area" status but this may be impractical or difficult to

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[23] The union was informed, without acknowledgment, of this author's concern for the safety of fishing vessels in the approaches to the Strait, and the preliminary results of this thesis, one month prior to the sinking of the *Tenyo Maru*.

> achieve through IMO. There is agreement in principle with the review of the traffic scheme at the entrance to Juan de Fuca Strait (Company of Master Mariners of Canada, 1991, p.7).

The Canadian Department of National Defence has an interest in the United States maintaining W601 as a surface and air gunnery exercise area, but a recent decision by the United States military has promulgated its removal (Figure 24). However, the location of W601 for the purpose of anti-submarine warfare exercises seems irrelevant, considering that the Canadian Navy regularly operates outside of this area. Therefore, it seems likely that the shifting of W601 to a less central area, or its elimination and substitution by the use of W237N to the south, would reduce traffic conflict, but it would not eliminate the possibility of a collision, such as occurred with the *Kootenay*. By using W237N instead of W601, military ships and aircraft would be required to relocate only 20 miles to the southwest of the centre of W601. If W601 were to be re-established elsewhere, air and submarine corridors may require additional examination.

Given that discussions with user groups should be conducted with achievable and effective options in hand prior to proposing any changes to IMO, an optional traffic routing scheme is provided and evaluated for its ability to reduce the collision risk probability that was presented in the previous chapter. This routing evaluation method is suggested as a model for the analysis of any congested marine environment where it can be shown that collision risk is largely a function of traffic density encountered.

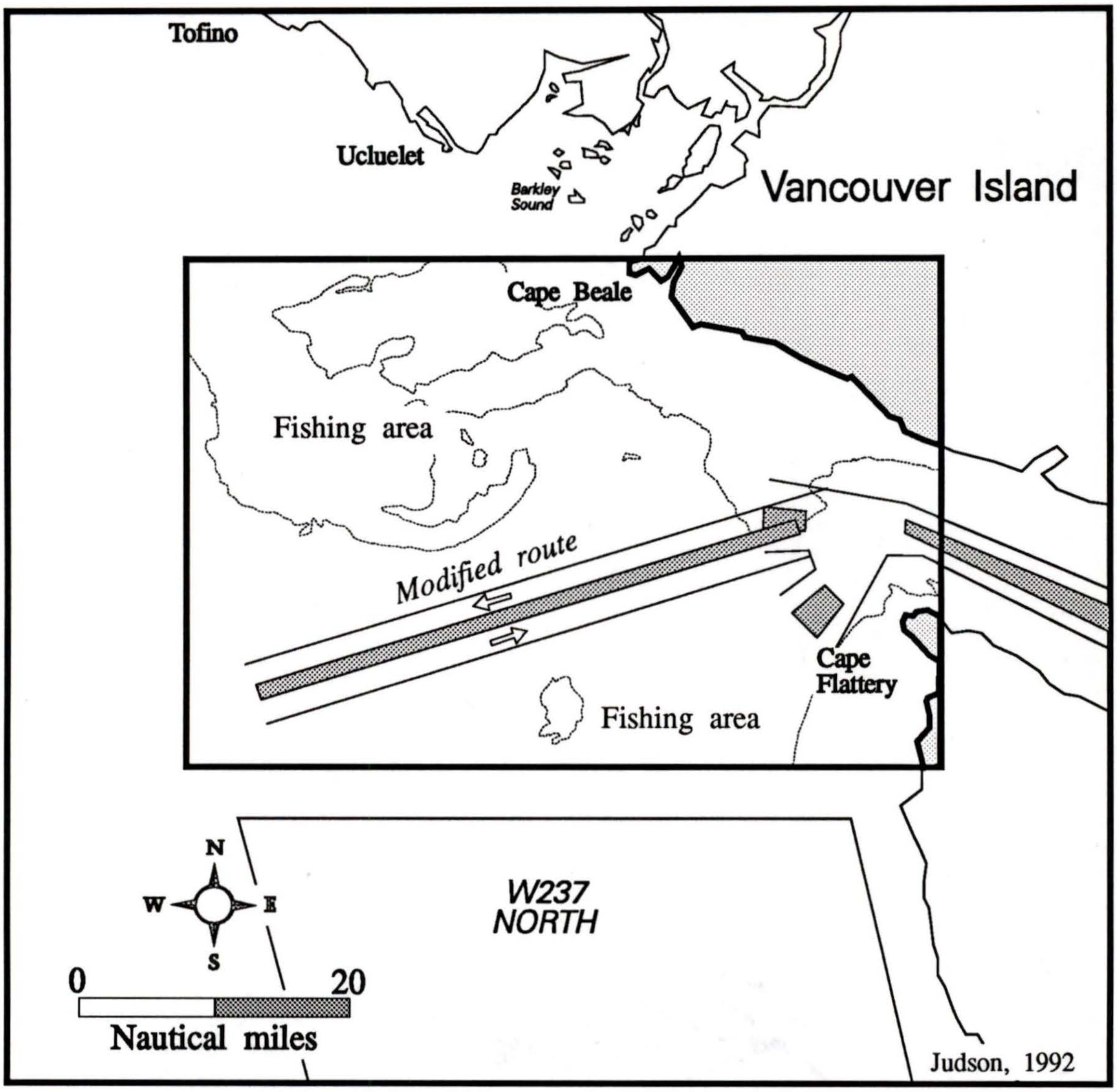

Figure 24. Proposed alternate routing scheme

4. Effectiveness of an alternate routing scheme

Figure 24 illustrates this author's proposed location of traffic separation lanes intended to re-route traffic south of La Pérouse Bank. The lanes extend 40 nautical miles southwest of Buoy J which marks the entrance of the Strait. The requirement for all traffic, except as exempted in Rule 10, to use the separation scheme is expected to result in an increase in traffic density within the lanes. This would be minor relative to the near elimination of overseas traffic from the fishing grounds.

The proposed traffic lanes and separation zone are designed to accommodate overseas traffic and the accuracy of position fixing. Several methods of position fixing are used in the approaches to the Strait. In addition to visual and radar fixing methods, radio fixing aids, including direction-finding, Global Positioning Systems, Omega and Loran C are commonly used. While Global Positioning System equipment is increasingly used, which gives a position accuracy of at least 100 metres, the use of the Loran C system is widespread and will give a fix accuracy of 18 to 90 metres (Canadian Coast Guard, *Canadian Marine Radionavigation Statement,* 1991, pp. A5-A25). Therefore, the designed lane width of 1.5 nautical miles accommodates a separation zone of one nautical mile which is over eighteen times the accuracy of Loran C. This exceeds the fixing requirements of IMO's separation scheme design criteria (International Maritime Organization, 1989). Therefore, a mariner should have no difficulty navigating within the lanes and any difficulties occurring would be apparent immediately to radar controllers at Tofino VTS.

In the estimate of traffic densities in the proposed scheme it is assumed that all traffic proceeding to and from the west and northwest, within a 113° arc from 247° Buoy J to 000° Buoy J, is concentrated within a four mile wide corridor representing the lanes. If the fishing vessel count within the proposed lanes were assumed to be zero then the net effect would be a modification of the traffic density encountered by the sample of 110 vessels which transited to and from the northwest (Table 18). Vessel transit mean density calculations then are simplified, as follows, for all traffic confined to the traffic lanes where G is the estimated traffic density encountered by each vessel within the proposed lanes during month *k*:

$$G_k = F_k + V[\frac{(\frac{d}{S})}{H}(\frac{n_k}{N})(\frac{T}{N})]$$

and

F is the fishing vessel count (assumed to be zero),
V is the total sample transiting vessel count for the proposed lanes in a sample year,
d is the mean distance through a grid cell in miles,
S is the sample mean transiting vessel speed in knots,
H is the mean number of hours per month (365.25/12x24=730.5),
n_k is the number of transiting vessels sampled in month *k* in 1989,
N is the number of transiting vessels in a one percent sample of those vessels transiting the study area in 1989, and
T is the actual number of transits in 1989.

Table 18. Calculation of total ship-miles per month, modified route

	Mean course	Frequency	Course length
New route	073°/253°	110	51 n.m.
Unchanged routes	022°	38	18 n.m.
	201°	38	18 n.m.

January 1991 ship-miles = (1442/186)x6978 = 54098 (discrepancy in Table 19 due to rounding of estimated monthly transits)

Average monthly traffic density values were re-calculated and increased by an annual rate of approximately three percent. The increase in traffic density caused by the proximity of transiting vessels in the proposed lanes is more than offset by the reduction of traffic density associated with the absence of fishing activity (Table 19).

The products of density and ship-miles (listed in Table 19) were multipled by the slope of the collision rate regression function to derive the expected number of collisions per month. These values were used as an estimate of lambda in order to provide collision probability estimates for each month in 1991. The probability of at least one collision per month for the status quo is compared with that of the proposed routing modification for 1991 (Figure 25). The highest collision risk probability of 0.28 in July 1991 (Table 17) is reduced by 68 percent to 0.09, and the annual collision probability is reduced by 40 percent.

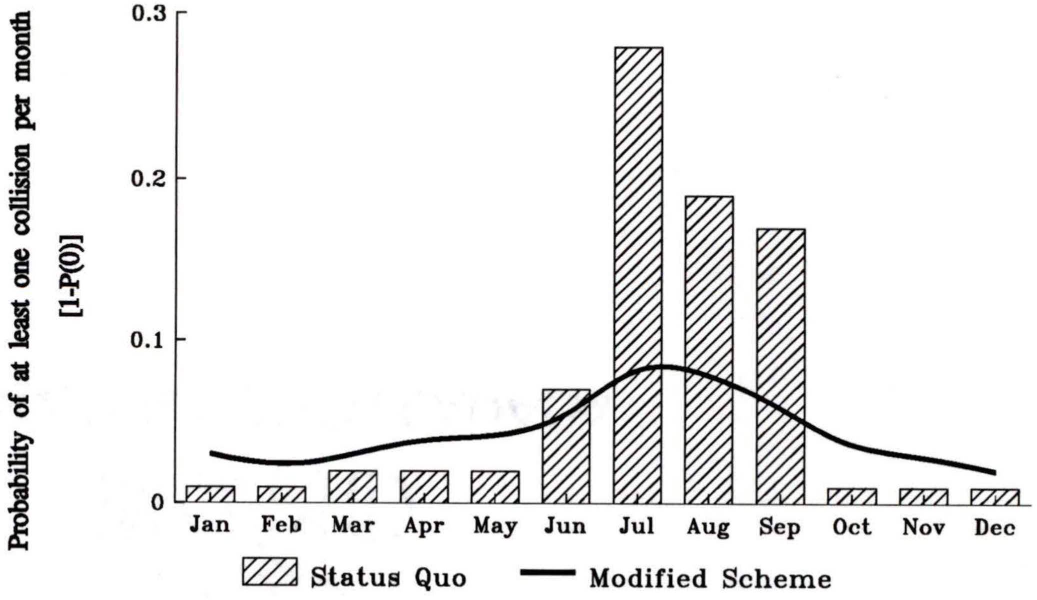

Figure 25. Monthly collision probability, 1991, alternate routing

Table 19. Encountered density, ship-miles and the collision rate, modified route, 1991

Month	Mean Traffic Density Encountered	Number of Transits	Ship-miles	Density x Ship-miles	Expected Number of Collisions λ	Probability of at least one Collision [1-P(0)]
January	0.33	1442	54190	18094	0.03	0.03
February	0.27	1349	50706	13491	0.02	0.02
March	0.30	1577	59269	17591	0.03	0.03
April	0.35	1687	63425	22455	0.04	0.04
May	0.32	1769	66489	21496	0.04	0.04
June	0.37	1949	73247	27252	0.05	0.05
July	0.52	2598	97677	50733	0.09	0.09
August	0.53	2346	88190	46273	0.08	0.08
September	0.47	1985	74632	35125	0.06	0.06
October	0.28	1583	59521	17098	0.03	0.03
November	0.27	1436	53980	14476	0.03	0.03
December	0.19	1420	53393	9961	0.02	0.02

5. Discussion

The "right to free passage" must be coordinated with other uses in the coastal zone, such as the public interest in preserving the environment–it is inconceivable that it still must be said that this coastal zone area must be managed as a common property resource. There is no doubt that international collision prevention regulations in conjunction with VTS have minimized the collision rate in the study area, however, the extension of traffic routing would enable VTS authorities to recognize and act on an infringement of international regulations. Had a routing scheme through international waters been in place when the *Tenyo Maru* was sunk in July of 1991 both the fouling of United States coastal zone beaches and estuaries as far south as California, and the death of a seaman may have been prevented.

Ross (1973) recognized that regionally centred crises seldom move governments to action, but had hoped that regional preventive measures might be instituted by the national governments in response to a catastrophic oil spill. The oil spill caused by the sinking of the *Tenyo Maru* prompted a resurgent interest in marine safety by the North American media and by governments. Interest in the cause of the collision resulted in this thesis receiving national attention on Canadian Television News and in local newspapers in Vancouver and Seattle (Canadian Television News, July 23, 1991, *Vancouver Sun,* August 3, 1991, pp. B1, B8 and *Seattle Post-Intelligencer,* August 1, 1991, pp. A1, A5). The United States government responded to public concern when Washington State Senator Slade Gorton introduced legislation on July 30, 1991 directing the United States Coast Guard, the Department of Transportation and the State Department to work with Canadian agencies to improve marine safety in the international waters of the approaches to the Strait of Juan de Fuca by reducing congestion, possibly through traffic separation (*Seattle Post-Intelligencer,* July, 31, 1991, p. B2). This legislation, amending the United States Coast Guard budget, was passed the same day.

While it is encouraging that regional environmental issues finally are receiving national attention, it remains to be seen whether the United States response to the collision and oil spill will be followed by attention to preventative action by both governments. The United States has taken the initiative, now it is up to Canada to participate fully to institute the preventative measures which are absolutely essential–especially a traffic separation scheme and speed restrictions.

5 Conclusions and recommendations

1. Conclusions

The problem of marine collisions in the approaches to the Strait of Juan de Fuca was investigated with the purpose of identifying causal and contributory factors and reducing casualties that frequently result in property loss, toxic spills and loss of life. Oil spills have been emphasized because of their persistent impact and frequency of occurrence. Oil spills illustrate the potential severity of impact from accidental spills of any hazardous liquid, an important concern when evaluating risk reduction in the coastal zone.

An attempt was made to improve upon existing methodologies used to study marine traffic in Canada through the use of a survey of marine traffic patterns and the estimation of a geographic collision risk. Initially, the causal and contributory factors to marine collisions in the study area were identified to direct the investigation towards practical and applicable solutions to the specific problems encountered. The benefit of traffic routing in the approaches to the Strait was demonstrated by a quantitative reduction in absolute risk and marine traffic safety was examined.

It was found that the existing literature in Canada in the field of prevention of marine casualties and spills was of limited use for risk reduction because researchers have tended to reach conclusions drawn from questionable casualty data sets without considering the relative importance of causal factors. Had the States/British Columbia Task Force examination of risk in broad geographic regions included a spatial distribution of casualties it would have been useful for the identification of "hot spots" requiring specific investigation and action.

Despite these inadequacies, microwave imagery, conventional radar and related data are available in a form which can be used to reconstruct traffic patterns. This was done by using GIS to plot traffic positions and calculate traffic density, courses and speeds. This provided a more accurate depiction of traffic flow than simple traffic volume data which is commonly used. Through vessel traffic nearly doubles in frequency during summer months, the same period of intense fishing activity (Figure 8). While vessel traffic tends to separate into inbound and outbound sectors, average traffic routes pass through the most active fishing areas (Figure 5).

Traffic density and reduced visibility were demonstrated to be the most significant factors contributing to ten collision incidents (Tables 8 and 10). Excessive speed was found to be prevalent in restrictive navigating conditions in the study area (Table 7). This result precluded finding statistically higher speeds associated with collisions. However, eight out of ten collisions involved excessive speed, seven occurred in areas of high traffic density and six occurred during restricted visibility (Table 15).

It must be concluded that the passage of traffic through the fishing grounds and the central location of military exercise area W601 at the southern limits of La Pérouse Bank are inappropriate. Because traffic tends to remain clear of W601 and is free to choose any route outside of the present routing scheme, traffic on the banks is unnecessarily concentrated. Moreover, Canadian Hydrographic Services publications provide routes to and from Japan without an appropriate indication that these routes should converge beyond the fishing banks, not at Buoy J at the entrance to the Strait. This is in conflict with recommendations that traffic remain clear of fishing areas while transiting the approaches to the Strait.

A regression of collision rates with the product of encountered traffic density and ship-miles resulted in an R^2 value of .87 (Figure 20). This relationship was anticipated, as the literature supports, in theory, an association between traffic density and collisions. The correlation of .96 with traffic volumes also supports this finding (Figure 19).

A Poisson distribution was used to derive collision probabilities from collision rates estimated from traffic density and ship-miles. This model was shown to compare well with observed collision frequencies in the study area (Table 16). It was found that, by routing traffic clear of the fishing banks, the probability of collision during the peak traffic month of July was reduced by 68 percent and the annual collision risk by 40 percent.

2. Recommendations

Inadequacies are apparent in both the definition and recording of causal factors and near-collisions by the Canadian and United States coast guards.

It is likely that there are many near collisions for every collision. The systematic use of a checklist to record contributing factors during collision risk situations would simplify the periodic review of traffic schemes. An explanatory comment on the Rules of the Road situation involved during a collision should be noted in casualty databases. Alternatives, such as "overtaking", "crossing", "head-on" or "restricted visibility" situations, should be indicated on the database, as these categories would enable analysis of possible infractions of the collision regulations. The summation of investigation reports into casualty databases could be improved by consistently distinguishing between causal and contributing factors—an environmental factor should not be cited as a primary cause where human error is suggested to be a secondary factor.

Because mariners proceeded through the approaches to the Strait uncontrolled at an average speed of 12.5 knots, and without a significant reduction in vessel speed where prudent, it can be assumed an inappropriate level of risk was accepted. Studies that recommend the improvement of the mariner through higher training or certification standards because human error is the cause of most marine casualties ignore the obvious fact that most mariners do not have accidents. While most mariners are capable of navigating at high speeds, unrestricted traffic includes those vessels that either disregard or excessively risk the safety of other vessels. The threat posed to life, property and the environment, therefore, requires that the current level of risk be addressed. Criteria for the determination of excessive speed should be established by the

Canadian and United States coast guards. The definition of excessive speed would vary in accordance with the prevailing environmental and traffic conditions. This would be a far superior means of controlling speed than a single speed limit which could not be low enough to be considered appropriate in all circumstances. VTS regulators would be required to recognize rogue vessels and enforce safety regulations through the use of an all-weather, fast patrol boat or hovercraft based in Ucluelet. If these measures were applied in conjunction with a routing scheme VTS effectiveness would be enhanced by the authorization of the power to give direction to vessels infringing upon the rights of other ships using the traffic scheme.

The IMO recommendation to review, re-survey and adjust routing schemes to maintain their effectiveness and compatibility should be adopted by the United States and Canadian coast guard services. However, future study of casualties in North American waters must not be limited to areas which have experienced marine crises. Coastal shipping routes and harbours throughout North America must be systematically surveyed to investigate traffic patterns, potential conflicts, casualty risk and impacts. In particular, Canadian studies have identified that hazards exist, but the risk of marine casualties in areas such as the Beaufort Sea, Lancaster Sound, the Grand Banks, the Great Lakes, the Maritimes and the rest of the West Coast requires intensive study.

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Appendix A

Study area database

Codes

Column		Value	
A	Collision	1	Collision
		0	Non-collision
B	Visibility	Nautical miles	
C	Mean Density Encountered	Vessels per four sq.mi. grid cell per 19 minutes	
D	Windspeed	Knots	
E	Average Speed	Knots (highest for collisions)	
F	Month	1=January...12=December	
G	Time	24 Hours	
H	Vessel Type	1	Freighter
		2	Tanker
		3	Tugs/barges
		4	Fishing vessels
		5	Government vessels
		6	Miscellaneous or unknown
I	Year		
J	Course	Course made good in degrees true	

A	B	C	D	E	F	G	H	I	J
1	10	2.959	10	14	4	138	1, 4	80	270,n/a
1	0	2.548	1	13	5	530	1, 4	80	295,210
1	0	3.910	10	13	7	2120	1, 4	84	295,n/a
1	0	2.028	6	14	7	1730	2, 4	84	294,n/a
1	10	0.121	0	15	9	1503	2, 4	87	073,n/a
1	10	3.217	6	9	8	2205	4, 4	88	100,180
1	1	2.204	4	13	8	630	1, 4	89	270,050
1	0	0.492	2	14	6	727	1, 5	89	270,135
1	0	0.177	0	13	7	1112	1, 3	89	095,075
1	15	3.937	8	10	8	913	3, 4	89	135,n/a
0	15	0.109	12	14	1	100	1	89	300

A	B	C	D	E	F	G	H	I	J
0	15	0.205	5	8	1	2230	3	89	125
0	15	0.158	4	6	1	1030	3	89	10
0	5	0.104	15	11	1	1900	1	89	300
0	12	0.151	4	7	1	1900	5	89	200
0	12	0.184	5	8	1	700	1	89	200
0	8	0.104	4	15	1	400	1	89	90
0	8	0.116	26	14	1	1900	2	89	110
0	15	0.079	0	13	1	1300	1	89	80
0	15	0.211	17	11	1	1000	1	89	300
0	8	0.104	24	10	1	1900	1	89	90
0	12	0.099	7	10	1	1600	1	89	300
0	10	0.097	4	13	1	400	1	89	120
0	15	0.156	4	9	2	400	3	89	20
0	15	0.166	3	13	2	700	1	89	20
0	15	0.096	3	16	2	2200	2	89	300
0	15	0.048	2	15	2	400	1	89	80
0	15	0.065	4	6	2	1900	3	89	130
0	12	0.156	0	15	2	1900	1	89	20
0	15	0.096	4	18	2	1600	1	89	300
0	12	0.088	8	16	2	1900	1	89	90
0	10	0.071	18	10	2	700	1	89	130
0	10	0.136	8	14	2	1900	1	89	10
0	15	0.067	3	10	2	400	3	89	120
0	15	0.180	2	13	3	2200	1	89	300
0	12	0.170	16	6	3	1600	3	89	120
0	6	0.093	16	12	3	1900	1	89	90
0	12	0.102	8	17	3	1000	1	89	90
0	12	0.097	10	16	3	2200	1	89	100
0	15	0.172	0	11	3	100	1	89	200

A	B	C	D	E	F	G	H	I	J
0	15	0.102	4	12	3	1900	1	89	280
0	12	0.265	12	13	3	1300	2	89	110
0	10	0.196	0	11	3	400	1	89	200
0	12	0.151	4	17	3	400	1	89	30
0	12	0.196	14	10	3	2200	3	89	20
0	8	0.041	7	13	3	1900	5	89	60
0	8	0.165	7	13	3	1400	1	89	120
0	15	0.142	8	20	4	2000	1	89	300
0	12	0.127	8	12	4	2000	1	89	100
0	6	0.212	9	9	4	200	1	89	200
0	15	0.128	12	12	4	1400	2	89	40
0	15	0.186	0	15	4	800	1	89	20
0	15	0.120	3	19	4	500	1	89	270
0	15	0.120	2	16	4	200	2	89	270
0	15	0.120	12	13	4	1100	1	89	90
0	15	0.182	12	13	4	2000	1	89	10
0	15	0.129	0	14	4	2000	1	89	100
0	12	0.390	14	15	4	500	2	89	110
0	12	0.124	9	20	4	1100	1	89	305
0	15	0.390	5	12	4	800	1	89	290
0	15	0.131	0	13	4	800	1	89	120
0	12	0.128	2	16	4	2300	1	89	40
0	15	0.212	5	12	5	500	2	89	200
0	2	0.186	6	19	5	2300	1	89	210
0	1	0.226	3	12	5	500	1	89	200
0	12	0.198	14	10	5	1700	1	89	10
0	15	0.207	15	15	5	1400	2	89	100
0	15	0.212	2	10	5	800	1	89	200
0	15	0.199	6	12	5	1100	1	89	290

A	B	C	D	E	F	G	H	I	J
0	15	0.277	10	13	5	1100	1	89	100
0	8	0.226	4	10	5	800	3	89	10
0	15	0.137	19	12	5	2300	1	89	300
0	12	0.212	14	11	5	200	2	89	200
0	12	0.282	0	14	5	800	1	89	100
0	15	0.209	6	15	5	1700	1	89	110
0	15	0.226	3	14	5	500	1	89	10
0	4	0.297	18	21	5	2300	1	89	110
0	12	0.061	2	15	5	500	2	89	189
0	12	0.240	6	13	6	2300	1	89	200
0	8	0.292	6	16	6	500	1	89	100
0	12	0.206	7	11	6	1100	2	89	10
0	12	0.257	0	9	6	1100	2	89	200
0	12	0.257	0	11	6	200	1	89	200
0	10	0.240	7	11	6	500	1	89	200
0	12	0.303	8	9	6	2300	1	89	90
0	15	0.290	10	13	6	1700	2	89	110
0	15	2.343	8	11	6	1140	1	89	300
0	12	0.210	5	12	6	1400	1	89	10
0	15	0.284	4	12	6	200	1	89	270
0	12	2.226	10	18	6	2000	1	89	300
0	15	0.206	0	19	6	800	1	89	190
0	10	0.096	6	10	6	200	4	89	40
0	12	0.303	12	13	6	200	2	89	90
0	8	2.350	4	7	6	1400	3	89	130
0	4	0.303	24	13	6	500	1	89	90
0	8	0.347	18	13	7	1100	1	89	20
0	12	0.267	10	16	7	2300	2	89	20
0	4	0.212	2	10	7	800	3	89	80

A	B	C	D	E	F	G	H	I	J
0	12	0.304	3	11	7	200	2	89	200
0	1	4.691	11	21	7	500	1	89	120
0	15	2.514	5	14	7	1100	2	89	100
0	12	0.325	8	15	7	1400	1	89	20
0	15	3.101	5	15	7	1700	1	89	90
0	15	2.866	6	13	7	1100	1	89	90
0	15	0.325	12	13	7	1700	1	89	10
0	15	0.285	6	14	7	1100	1	89	10
0	6	4.382	10	17	7	1700	1	89	300
0	5	4.258	13	11	7	800	1	89	290
0	10	3.832	10	9	7	1100	2	89	305
0	12	0.177	4	18	7	1700	2	89	30
0	15	3.460	18	18	7	2000	1	89	110
0	15	3.521	14	16	7	1400	2	89	305
0	0	0.333	4	11	7	800	1	89	190
0	1	2.342	12	15	7	500	1	89	280
0	12	3.035	0	19	7	1400	1	89	120
0	15	0.279	9	15	7	1100	1	89	10
0	12	0.325	2	7	7	200	4	89	200
0	12	3.037	4	16	7	1100	1	89	100
0	15	2.410	4	13	8	2000	1	89	100
0	15	1.967	10	9	8	2000	2	89	80
0	15	0.038	12	9	8	1400	4	89	180
0	12	2.603	10	12	8	2300	1	89	100
0	12	1.261	6	9	8	200	4	89	300
0	8	1.261	9	21	8	500	1	89	120
0	12	1.967	6	7	8	1400	6	89	80
0	15	0.297	3	12	8	200	1	89	20
0	15	0.297	6	5	8	1400	3	89	200

A	B	C	D	E	F	G	H	I	J
0	15	2.604	0	12	8	800	1	89	100
0	12	1.558	9	16	8	2000	1	89	300
0	8	2.721	3	13	8	1100	1	89	290
0	10	0.297	0	10	8	2300	1	89	200
0	0	0.179	9	6	8	200	3	89	30
0	12	2.418	3	12	8	2300	1	89	90
0	3	0.297	0	12	8	1100	1	89	200
0	12	2.813	10	12	8	1400	1	89	100
0	0	2.608	0	14	8	800	1	89	100
0	8	0.260	2	11	8	2000	1	89	200
0	8	1.531	0	21	8	200	1	89	300
0	8	0.129	16	9	8	1100	1	89	70
0	15	0.203	7	6	9	2000	1	89	30
0	12	1.815	4	8	9	1100	1	89	110
0	1	3.146	5	18	9	1100	3	89	125
0	12	0.755	3	4	9	800	2	89	250
0	15	0.041	0	9	9	500	1	89	90
0	12	3.156	0	9	9	1400	5	89	305
0	15	0.260	0	9	9	1400	1	89	200
0	15	0.894	4	12	9	1400	1	89	90
0	15	0.729	0	13	9	1100	1	89	80
0	15	0.745	0	12	9	800	1	89	260
0	12	3.043	3	14	9	2000	3	89	125
0	15	0.272	8	16	9	2000	6	89	200
0	12	1.441	8	14	9	500	1	89	110
0	12	0.255	2	10	9	2300	1	89	10
0	0	1.881	3	11	9	500	1	89	110
0	15	3.146	5	6	9	2000	3	89	305
0	0	3.062	3	1	9	1400	5	89	125

A	B	C	D	E	F	G	H	I	J
0	15	0.894	3	14	9	2300	1	89	90
0	15	0.022	7	9	10	1700	4	89	250
0	12	0.056	10	8	10	1400	4	89	80
0	2	0.184	5	9	10	200	1	89	200
0	12	0.107	5	11	10	2300	1	89	110
0	4	0.158	5	14	10	500	2	89	10
0	15	0.172	4	15	10	2000	1	89	210
0	15	0.046	11	9	10	800	1	89	125
0	1	0.151	25	14	10	1100	2	89	210
0	15	0.172	10	8	10	1000	2	89	200
0	15	0.104	5	11	10	1900	4	89	100
0	8	0.099	20	12	10	1300	1	89	110
0	12	0.123	5	12	10	100	1	89	300
0	15	0.158	10	12	10	2200	1	89	10
0	12	0.196	0	15	11	1300	1	89	200
0	2	0.044	16	12	11	700	1	89	250
0	15	0.107	14	11	11	100	1	89	305
0	15	0.102	15	19	11	400	2	89	280
0	10	0.184	3	11	11	1000	1	89	200
0	15	0.047	5	9	11	1600	5	89	230
0	8	0.114	13	14	11	2200	1	89	305
0	2	0.100	10	16	11	1900	1	89	100
0	6	0.077	2	7	11	400	1	89	305
0		0.020		11	11	1900	1	89	60
0	15	0.067	5	12	11	1900	1	89	80
0	15	0.158	10	7	11	1300	3	89	190
0	15	0.161	11	14	11	2200	2	89	190
0	3	0.172	17	3	12	1000	3	89	200
0	3	0.132	22	13	12	1900	1	89	10

A	B	C	D	E	F	G	H	I	J
0	6	0.150	12	15	12	1600	1	89	20
0	15	0.104	4	14	12	1900	2	89	90
0	12	0.128	4	23	12	1900	1	89	300
0	12	0.172	4	14	12	2200	1	89	200
0	12	0.100	2	18	12	1900	1	89	210
0	10	0.184	4	16	12	400	1	89	10
0	1	0.047	11	11	12	1900	1	89	230
0	4	0.151	12	12	12	700	1	89	20
0	1	0.054	6	6	12	1000	3	89	40
0	12	0.113	3	13	12	1900	1	89	305
0	12	0.046	20	10	12	2200	1	89	60

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Title of Thesis: Collision Risk in the Approaches to the Strait of Juan de Fuca
An Analysis of Circumstances and Traffic Routing

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2 April, 1992