Methodology for Assessment of Vessel Impact Energy on Bridge Piers and Spans

PETER BEIN

Relevant risk factors are reviewed and a methodology is presented for determination of vessel impact energies and return periods for bridges located over navigable waters. The approach integrates vessel traffic and operating characteristics, bridge geometry, marine environment conditions, and aberrance frequencies of vessels. The method is generic and can be applied to multispan as well as to short bridges located either in a marine environment or over inland waterways. Main and side piers and spans are considered the objects of vessel impact threats. The analysis can be useful in bridge planning and in selection of design criteria for impact loads on bridge elements. The methodology recommends calculation of impact velocities of vessels by the application of mechanistic equations describing the behavior of errant vessels in wind, currents, and waves as a function of the vessels' operating speed and location at the instance of aberrance. The method can also be used if the impact velocity distributions are assumed by judgment. Examples from two Canadian bridge projects are given.

The determination of vessel impact forces is crucial for planning and design of bridges over navigational waters, but it requires extensive data. Some bridge risk assessments mix loss of human life with economic efficiencies (*1*, pp. 24–34). An alternative approach (*2*, pp. 297–306) selects vessel impact design criteria on the basis of socially acceptable risk levels and requires an assessment of possible impact energies and recurrence intervals. Multispan bridges pose special problems in the assessment. Vessels straying from a navigational channel have a high probability of approaching the flanks of a bridge. Often the side elements cannot, for reasons of economy, be designed to the same standards as the main piers and spans. Marine exposure creates additional risk factors, which are not normally present in inland waterways. This paper reviews vessel impact risk factors for a long bridge located in a marine environment and presents a method for assessing impact energy and recurrence. Potential damage to a bridge depends on the striking vessel's kinetic energy and also on dissipation of this energy in the process of deformation and displacement of the vessel, bridge elements, and protective devices. Energy dissipation and impact force generation are not the subject of this paper. The approach is illustrated with two cases: the Northumberland Strait Crossing on Canada's eastern seaboard and the Annacis Channel Bridge in Vancouver, British Columbia.

In this paper, a vessel "casualty" means a collision, grounding, flooding, capsizing, foundering, sinking, fire, explosion, ice damage, or other misfortune. Casualties and near-casualties are "incidents." "Collision" is contact between two or more vessels, whereas "striking" is contact between a vessel and a stationary object. "Aberrance" means that a vessel is out of control or on an error course.

RISK FACTORS AND IMPACT ENERGY

A review of sources on marine and bridge casualties, which is discussed elsewhere (*3*), revealed that the following factors may aggravate the risk of vessel impacts on multispan bridges in a marine environment:

1. Mixed use of the waterway, involving fishing, recreation, and commercial vessels;
2. The presence of towed barges and ships under ballast in the traffic;
3. Tides, currents, winds, floating ice, and reduced visibility;
4. Sabotage and vandalism; and
5. A large number of spans and piers posing an obstacle to safe transit of a large vessel on a stray course.

Casualty Statistics and Limitations

The review also established that casualty statistics cannot be exported uncritically between regions, particularly under conditions of low vessel traffic volume. The statistics are based on past occurrences and reflect marine conditions, ship technology, and navigational aids specific to the time and place of data collection. Human differences between the navigators in foreign waters and at a study bridge site may also be a limitation, because the human factor is the leading cause of incidents.

Computational methods based on mechanistic models and fault-tree analysis of a vessel's systems are not adequate either, because they miss the human error. These limitations pose a dilemma, because strikings of bridges are rare events, and a risk analyst would gladly use any available data. Vessel casualty data banks, such as those operated by marine insurance companies or the Canadian and U.S. coast guards, provide a sound basis to establish statistics reflecting local factors. In North America, the law requires the reporting of all incidents through appropriate channels, but near-casualties would not always be reported. Canadian Coast Guard reports of 77 marine incidents (Table 1) in the Northumberland Strait were analyzed. Although fishing vessels appear accident-prone, they are significantly safer than other vessels if one considers their length of time at sea.

3955 West 14th Avenue, Vancouver, B.C., Canada V6R 2X2.

TABLE 1 CASUALTIES IN NORTHUMBERLAND STRAIT, 1976–1986

	No. of Incidents(a)			No. of Casualties(b)		
Year	Total	Fishing(c)	Other(d)	Total	Fishing(c)	Other(d)
1976	2	0	2	2	0	2
1977	0	0	0	0	0	0
1978	1	0	0	1	0	1
1979	2	1	1	2	1	1
1980(e)	10	4	6	9	4	5
1981	11	10	1	11	10	1
1982	10	7	3	9	7	2
1983	7	6	1	7	6	1
1984	12	9	3	10	8	2
1985	16	8	8	15	8	7
1986(f)	5	4	1	5	4	1
Total	77	49	28	72	48	23

Notes:
(a) Excluding ferries, confined waters, and harbors.
(b) As (a) but multiple vessels involved are counted as one event.
(c) Including trawlers, draggers and seiners.
(d) General cargo, tankers, dredges, towed barges and work boats, icebreakers, tenders, and research vessels.
(e) New reporting procedure introduced.
(f) Incomplete annual report.

Bridge Striking Data

Half the time, the human factor was the main cause in major Canadian bridge strikings. The human factor was a secondary contributor to the environmental factors; thus human error was involved in most of the incidents (*4*). Contrary to conventional design practice, ships choose to ram the side piers and spans more often than the main piers (*5*). Only 6 of 19 serious strikings worldwide involved main piers, and 13 involved side piers and superstructures (*6*). Bridges over waterways may create or aggravate difficult areas of navigation (*7*).

Sea Ice Factor in Casualty Statistics

Ice conditions were found to make a significant contribution to vessel casualties in Canada and in Europe (*3*). In Table 1 most of the incidents involving more than one vessel occurred in ice. In Canada, ice was the primary cause in three major bridge casualties (*4*). Table 2 shows that in Northumberland Strait the risk of vessel casualty in winter is about seven times greater per transit than in the ice-free season. Whether an incident in ice will become a casualty at a bridge depends on the buffer effects and the movement of ice surrounding the vessel.

TABLE 2 RELATIVE HAZARD OF SEA ICE IN NORTHUMBERLAND STRAIT

Season	Vessel Movements	Incidents	Incident Frequency
Ice-free	189	10	0.053
Winter	21	8	0.381
Total	210	18	

Note:
1980-1985 casualty records for Northumberland Strait, Canadian Coast Guard. Number of vessel movements based on 1978-1986 annual average, 10% of which take place in winter.

Impact Energy Equation

The impact energy E_{ij} is given by

$$E_{ij} = 0.5 \cdot k_m \cdot m_i \cdot v_j^2 \qquad (1)$$

where

k_m = added mass coefficient,
m_i = mass of vessel, and
v_j = impact velocity of vessel.

The impact mass includes both the vessel and a water volume surrounding the hull. The coefficient k_m ranges from 1.1 for head-on to 1.4 for broadside strikings in deep water. For a clearance under the keel smaller than the vessel's draft, k_m can exceed a value of 2. Modern laden tankers meet such conditions in many navigational channels. At side piers, which are usually located in shallower water, most of the laden cargo ships will engage a high added mass of water. If a ship is trapped in sea ice, the mass of ice moving with the ship should be included in m_i.

Many factors specific to site conditions and vessel operation determine magnitude and direction of v_j, as follows:

$$v_j = f_i\,(v_o, l_o, S_e, S_i) \qquad (2)$$

where

i = vessel under consideration;
v_o, l_o = vessel's operating speed and location before aberrance, respectively;
S_e = modifying effects of wind, currents, and waves as the vessel closes in on the bridge; and
S_i = vessel's geometric and dynamic characteristics.

It is expedient to determine v_j by simulation with equations describing vessel behavior under wind, current, and wave forces. A range of starting speed and location is assumed from data on vessel operation. Each starting condition is analyzed for the full range of possible environmental conditions that cause the vessel to advance toward the bridge. Advanced hydrodynamic equations can also be used, but then the vessel data inputs may be too demanding. A set of curves as in Equation 2 was developed for laden and empty barges (*2*). Each curve describes v_j as a function of the closing distance, current, and wind speed and direction. One set of such curves is shown in Figure 1.

Environmental Factors and Vessel Behavior

The marine environment can be a powerful determinant of vessel speed and aberrant behavior. Currents may be due to tidal, wind-stress, and storm surge currents, which are independent and add up if superimposed. Currents increase in passages and narrows, where bridges are most often located. The resultant flow depends on the hydrography and bathymetry and on the meteorological conditions in a bridge site area. Currents combined with wind and waves determine drift velocities of disabled vessels and vessel course-keeping on approaches to the bridge. In winter, floating ice interferes

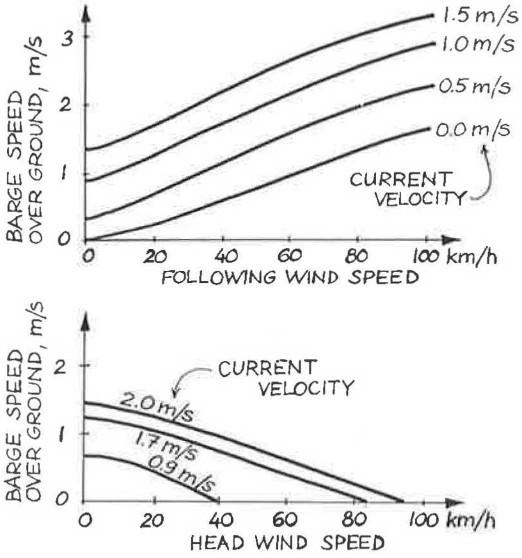

FIGURE 1 Impact velocity curves for laden barges becoming aberrant at 700 m closing distance.

with navigation. More detailed discussions have been presented elsewhere (*3*).

PROBABILITY MODEL FOR STRIKING A MULTISPAN BRIDGE

Three conditions are required for a vessel to strike a bridge:

1. Aberrance: the vessel must either become out of control or disabled or start an erroneous course anywhere on the approach to the bridge.
2. No evasion: the vessel must continue sailing and must reach the bridge location rather than somehow avoid it.
3. Geometry: once at the bridge, the vessel must make contact with some bridge elements.

Besides the probability of striking, mass and impact velocity of the vessel influence the extent of potential damage to the bridge. Thus, three pieces of information are needed to assess the probability of impact energy: (a) probability of striking, P_s; (b) probability of impact mass, P_m; and (c) probability of impact velocity, P_v. For Vessel i, these probabilities are independent and the total probability of impact energy E_{ij} due to mass m_i and velocity v_j is

$$P(E_{ij}) = P_{si} \cdot P_{mi} \cdot P_{vj} \tag{3}$$

Annual basis is used for all three probabilities because the objective of the analysis is to calculate annual probability distributions of impact energy from which return periods can be obtained.

Probability of Striking

The probability of striking is a product of three probabilities:

$$P_{si} = p_{1i} \cdot p_{2i} \cdot p_{3i} \tag{4}$$

where

p_{1i} = annual probability of aberrance of the vessel type under consideration,
p_{2i} = probability of no evasion; and
p_{3i} = geometric probability.

Probability of Aberrance

How far from the bridge a vessel gets out of control is irrelevant from the risk analysis viewpoint, as long as the aberrance is a potential threat to the bridge. The aberrance frequency is specific to type of vessel and local conditions. Barges or other vessels on tow are more prone to get out of control, as are large ships under ballast. Adverse weather and currents, and the presence of sea ice, increase the chance of aberrance of any vessel. Local data on aberrance frequencies account for both the local vessel factor and local site conditions. If available, such data should be used rather than data from foreign waterways, because the specific local environmental and operating conditions are locked into the statistics.

Probability of No Evasion

Evasive actions may be taken on board the stray vessel if the crew realizes the danger. Some possibilities include dropping an anchor, steering away from the bridge, or reversing the engine. Human intervention could also come from outside, for example, by deflecting a stray vessel or stopping it with tugs. Evasion may also occur by chance if the aberrant vessel is stranded, sinks, or is grounded on shallows before reaching the bridge. Depending on incident-reporting practice, vessel aberrance statistics now available may or may not include the effects of human intervention on evasion. In most risk analyses, p_{2i} is assumed to equal 1.0 unless there are vessel-monitoring and tug intervention systems in place at a bridge site. Such systems would make sense for long bridges with low-clearance side spans because the likelihood of striking side spans and piers is high.

Geometric Probabilities

Geometric probability of striking a bridge element depends on the size of the vessel and on bridge dimensions. For piers, the probability is

$$p'_{3i} = (B + w_i)/L \tag{5}$$

where

B = pier base or protective island diameter,
w_i = effective width of vessel, and
L = bridge span center to center.

The vessel's effective width is a random variable equal to the width projected on the longitudinal axis of the bridge. It ranges from vessel breadth for bow-on and stern-on impacts to vessel length for impacts broadside. Ambitious studies with sufficient data can assume a probability distribution for w_i, but generally the following judgmental formula for an average value should suffice:

$$w_i = (l_i + b_i)/a_i \tag{6}$$

where

l_i = vessel's length overall,
b_i = vessel's breadth (beam), and
a_i = judgmental constant greater than 1.0.

The judgmental constant depends on vessel and pier type. Strikings tend to be oblique at a sharper angle at main piers, whereas they would be more broadside at side piers. In the Northumberland Strait study, $a_i = 3$ was adopted for ballasted and for towed vessels, and $a_i = 4$ for all other vessels. Corresponding to relatively sharp angles of vessel attack, these constants are particularly relevant to main piers. Smaller values would be more appropriate for side piers. The constant and the effective width of vessels have a greater effect on Equation 5 when the pier diameter is small compared with vessel size, and for that reason the estimation should then be more careful.

The geometric probability of striking the spans, p''_{3i}, depends on a vessel's superstructure. The topmost "soft" elements, such as antennas and masts, are not necessarily a serious threat, and the height of the vessel can be suitably reduced for risk analysis of spans. At sites with tidal variation of water level, the vertical clearance of a span has a frequency distribution. The same vessel may clear the available height at low tides but not at high tides. The general expression for p''_{3i} is

$$p''_{3i} = P(h_i > H) = 1 - P(h_i < H) = 1 - F_h(H) \tag{7}$$

where

h_i = elevation of uppermost limit of vessel's "hard" elements above water line,
H = span vertical clearance,
P = probability, and
$F_h(H)$ = cumulative distribution function, that is, the probability that vessel height h_i is equal to or less than the available vertical clearance under a span.

The latter distribution can be constructed from the frequency distribution of tidal elevations.

Probability Relation to Closing Distance

All three probability components of bridge striking by a vessel are related to its distance from the bridge. In general, this function is

$$p_k = f_k(d) \tag{8}$$

where k refers to aberrance, evasion, or geometric probability and d is the closing distance from the vessel to the bridge. In most analyses it would be pragmatic to take average values for each p_k.

For long bridges, the geometric probability of striking main piers decreases with the closing distance, whereas for side piers and spans, it increases. A schematic in Figure 2 helps to calculate the geometric probabilities. Assume that each pier is represented by a circle of diameter D equal to the width of the pier base plus a characteristic average vessel dimension, as defined in Equation 5. Diameter D can be different for main and side piers. All errant paths of a vessel are equiprobable straight lines fanning out from the point at which loss of control started. If there are reasons to believe that the errant paths are not equally likely, a different probability distribution can be introduced.

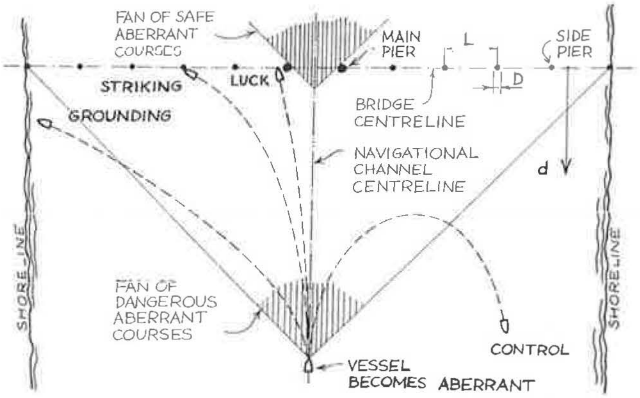

FIGURE 2 Situation graph for probabilistic model.

When the outside of the fan glances the inside of the main pier circles, there are no strikings. When the outside of the fan intersects the bridge approaches at the shoreline, the upper limit of the number of potential strikings is reached. Moving the fan farther away will strand the vessel. Intuitively, between the two limits there are strikings of the bridge, and their geometric probability can be calculated by counting the number of bridge elements swept by the fan placed at successively increasing distances from the bridge.

The geometric probabilities are shown in Figure 3 for the case of a navigational channel centered about the bridge length and all spans of equal length. For aberrance occurring up to about 1.5 span lengths from the bridge, main piers are prime targets. As the distance increases, the likelihood of hitting one of the side piers increases. The results are for a 90-degree fan. For a navigational channel located close to one shore, there will be about 50 percent reduction of frequency of strik-

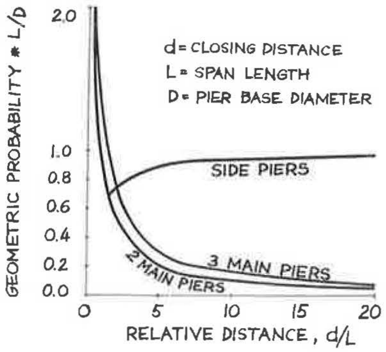

FIGURE 3 Relative likelihood of striking piers when all span lengths are equal.

ing the side bridge element. Similar results can be shown for striking the spans.

The tendency to hit piers and spans will be countered by possible successive evasions. The chance of taking an evasive action diminishes at shorter distances, which do not leave as much time to act compared with longer closing distances. For lack of data, one can assume a probability of no evasion, $p_{2i} = 1.0$ at $d = 0$, decreasing to $p_{2i} = 0.0$ at a large distance, which should be determined by judgment.

The distance to the farthest point of aberrance that could result in striking is large in the case of long bridges. In Figure 2, the distance is equal to about half of the bridge total length, that is, 6 km for the case of the Northumberland Strait Crossing. Published aberrance frequency statistics relate to vessel passage by a critical location, but for long bridges it would be more meaningful to express the frequency in terms of distance traveled by a vessel. It is not a particular location that is critical to aberrance, but rather a certain long distance on both approaches to a bridge. This alternative approach to estimating aberrance frequency requires both vessel incident and travel data from the study area.

Probability of Impact Mass

Probability of impact mass is

$$P_{mi} = f_i \cdot p_{mi} \tag{9}$$

where f_i is the relative frequency of vessel type under consideration in the traffic volume and p_{mi} is the probability of added mass. The total annual traffic volume is classed into a number of typical vessels on the basis of operational characteristics and size. An allowance should be made for traffic growth and for possible introduction of new types of vessels in the future.

Probability p_{mi} is conditional on the same factors that affect the total mass at impact. These factors are the ratio of water depth to vessel draft and the inclination of the striking vessel relative to bridge elements. The ratio depends on vessel loading condition and location at the bridge, and the inclination depends on vessel type, loading, and weather and currents.

It may be too cumbersome to determine p_{mi} conditional on so many factors. Unless Equation 3 proves to be sensitive to this parameter, p_{mi} can be disregarded. The annual traffic volume is then classed on the basis of both vessel operational characteristics and behavior when aberrant in the marine environment, and an average added mass coefficient is used in Equation 1. The Northumberland Strait preliminary study, for example, subdivided all vessels into freighters, tankers, passenger ships, barges, and other vessels. The cargo vessels were classed by size as laden or ballasted to account for the behavioral factor and the depth-to-draft ratio. A total of 14 types resulted, and the fraction of each vessel type in the annual volume was estimated from past traffic statistics and future projections.

Probability of Impact Velocity

Given the relationship in Equation 2, v_j has a joint probability of operating conditions v_o and l_o and environmental factors S_e. In general, the vessel's operating speed depends on S_e, and consequently,

$$P_{vj} = P(v_o|S_e) \cdot P(l_o) \cdot P(S_e) \tag{10}$$

where $P(v_o|S_e)$ is probability of operating speed in a given marine environment. Vessel characteristics S_i are implicit in Equation 10, which is specific to vessel type but not indexed with i for simplicity.

Variables v_o and S_e have those particular values that produce impact speed value v_j. Specifically,

$$P(S_e) = P(u_j|w_j) \cdot P(w_j) \cdot P(c_j) \tag{11}$$

where

u = wave conditions;
w = wind speed, direction, and duration;
c = currents; and
j = specific values resulting in the value v_j of impact speed.

For example, a certain vessel described by a set of characteristics S_i, westbound and becoming aberrant at l_o = (1.5 km east of the bridge) and v_o = (7 m/sec over ground or 5 m/sec through water), and experiencing w_j = (side wind, 40 km/hr), c_j = (westerly current, 2 m/sec; cross-current, 0.5 m/sec at 1-km intervals) could have an impact velocity v_j = 3 m/sec while inclined 60 degrees.

Waves need not always be considered, because they do not affect impact velocity of larger vessels. If considered, their probability is normally conditional on wind, unless other wave sources such as swell occur at a bridge site.

An example of a P_{vj} distribution for barges (*2*) is shown in Figure 4. The impact speed is a function of wind; river and tidal currents; four segments of barge routes, some of which involve turning; variable operating speeds; selected operating hours; and two distinct sources of aberrant vessels, namely, moored barges and towed barges. The complexity of operating conditions was reduced to two variables, v_o and l_o, which were classed into intervals with relative frequencies known from analysis of the operations. Occurrence of currents was determined for the operating hours. Frequency distributions for currents and winds were derived from past statistics. Environmental and operating conditions that drove the vessels away from the bridge or led to $v_j = 0$ were consolidated and their joint probability is shown in Figure 4 at impact speed 0 m/sec.

Return Period of Impact Energy

Calculation of the return periods is trivial once all the steps required to obtain $P(E_{ij})$ in Equation 3 have been completed for all possible impacts. All values of E_{ij} are arranged in descending order, and the probabilities of each event are added to arrive at the annual exceedence probability for a given impact energy. A reciprocal of the annual exceedence probability is the return period of the impact energy.

In some bridge risk analyses, there may be two or more distinct sources of possible strikings of bridge elements by vessels. Examples include a navigational channel and a vessel mooring site; a combination of independent navigational channels; or a combination of different marine activities, such as fishing and navigation. There may also be a number of

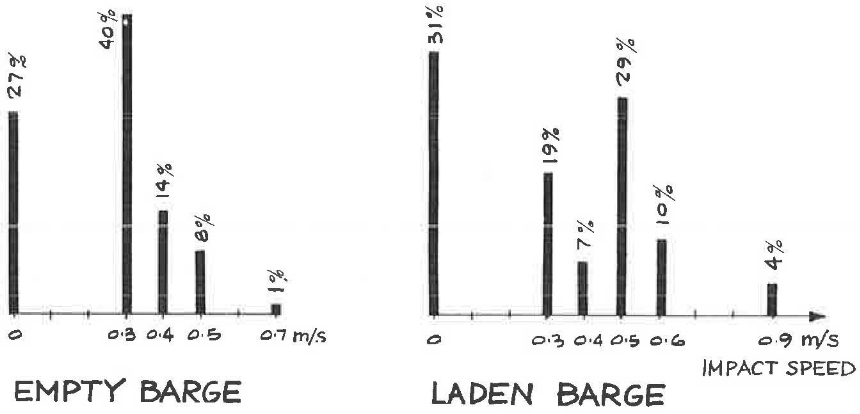

FIGURE 4 Probability of barge impact velocity.

segments within the shipping lanes with different vessel operating characteristics. Regardless of the real-world complexities, it is usually possible to break the problem down so that the energies, the associated probabilities, and the return periods can be calculated.

Such analysis has been done (*2*) for complex conditions. The impact energies associated with 200- and 500-year return periods were of particular interest for design. The bridge supports an urban arterial road, which serves as a lifeline facility in case of earthquake or other emergencies. The highway authority specified the 200-year event for designing structures to the elastic limit. A 500-year recurrence was specified for vessel impacts that can cause permanent structural damage, but without collapse and loss of human life.

Example

The Abegweit Passage of Northumberland Strait between Prince Edward Island and mainland Canada is 13 km wide. In preliminary planning, a number of generic bridge designs were considered. This example refers to an alternative with 43 spans, each 300 m in length (*3*). The navigational channel is located close to one shore. The side spans have a clear height of 14 m, but the main span permits transit of large ships. The main piers are protected by islands 100 m in diameter (including the effect of underwater slope), and the calculated impact energies are applied to design of the berms. Side piers are 15 m at the base.

Environment

Two ebbs and two floods move through the passage each day. The flood rates range from 0.4 to 1 m/sec, depending on the season. Surge currents caused by storms in the Gulf of St. Lawrence occur on 5 days per month on the average. The surges can reach 1 m/sec and last a long time if driven by major storms. Rip currents caused by crosswinds can be a major factor in loss of control of ballasted or towed vessels at the site. Wind conditions are not sufficient to develop Sea State 5 or rougher. Ice conditions are among the most difficult of all approaches to Canadian ports and last 10.5 weeks on the average. Even the most powerful ships may then experience difficulty, and lower-powered vessels become beset by the moving sea ice.

Vessel Traffic

The vessels in the navigation channel range from occasional passenger cruisers and large cargo ships and tankers to fishing trawlers and barge tows. Typical vessels are described in Table 3. The base case traffic volume is 260 vessel movements per year, of which 10 percent occur in ice conditions. Barges constitute 20 percent of the total traffic. The cargo vessels were assumed fully laden in 65 percent of movements and ballasted in 35 percent, and tankers and barges fully laden in 50 percent of movements.

Aberrance frequencies based on "vessel-kilometers" rather than "passing by a geographic point" could not be calculated for lack of vessel travel data.

Assumptions

Data were not available in sufficient detail to warrant determination of relative frequencies of all relevant environmental factors. Instead, P_{vj} was adopted by judgment of site and navigational conditions. The base case assumes a three-point distribution with 2, 4, and 6 m/sec impact speed and probability mass of 25, 50, and 25 percent, respectively. For barges and other vessels, the three points are 1, 2, and 3 m/sec. The low speed represents impacts in head currents, whereas the high speed represents impacts in following currents. To account for the dislocation of stray vessels under wind and current, which were not modeled mechanistically, a "path probability"

TABLE 3 CHARACTERISTICS OF TYPICAL VESSELS IN NORTHUMBERLAND STRAIT

Vessel Type	Displacement, tonnes		Length, m	Beam, m	Air Draft, m	
	Laden	Ballasted			Laden	Ballasted
Freighter	4000-18000	700-5200	91-134	13-20	18-32	20-34
Tanker	10000-16000	2800-3800	119-132	16-20	23-30	25-32
Passenger	3700	NA	98	16	24	NA
Barge	7400	1300	100	20	6	9
Other	1000	NA	46	9	21	NA

Note: NA = not applicable

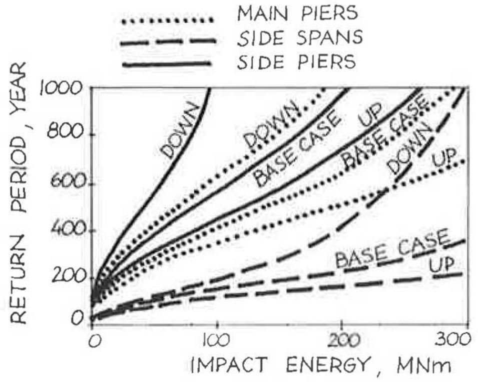

FIGURE 5 Effects of changing impact velocity by 1 m/sec up or down.

was introduced. It refers to the likelihood of an aberrant vessel transit within the main channel and piers. Other paths lead to side piers and spans. In the base case, 50 percent of aberrant courses are within the main channel, except ballasted freighters and ballasted tankers, and all barges are assumed to have this probability reduced to 30 percent owing to their steering difficulties.

Analysis

The analysis was carried out for main piers, side piers, and side spans using a microcomputer spreadsheet. None of the vessels can reach the underside of the main span, even at high tide. The return periods were computed from cumulative probability mass functions of impact energies and the results were smoothed out. The sensitivity of results was tested relative to impact speeds, traffic, aberrance frequencies, path probability, and bridge geometry. The results were graphed with the return period as a function of the impact energy. A graph can be entered with a predetermined return period and the corresponding impact energy can be found.

Results

The most severe loads can be expected on side spans, for which the corresponding curve has the smallest slope (Figures 5 and 6). A 500-year energy is 400 MNm on side spans, but it is only 140 MNm on main pier islands and 60 MNm on side piers in the base case. This agrees with intuition, because the side spans "catch" all vessels that cannot clear the height of the side spans above water level. Side piers receive less energy than main piers for a given return period, owing to higher main channel path probability assigned to the larger vessels, and higher geometric probability of striking the main pier island than the side piers. Changing the range of speeds from low to high doubles or triples the impact energy for a fixed return period (Figure 5). Changing the skewness of the speed distribution from left to right has a similar effect (not shown), because right skew of the distribution implies more frequent occurrences of higher speeds.

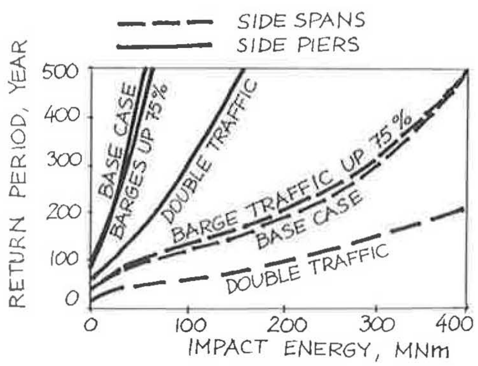

FIGURE 6 Effects on side piers and spans of changing impact velocity.

Doubling the barge traffic (Figure 6) has a negligible effect because the number of barge movements increases at the expense of the other vessel movements, whereas the total number of vessels remains unchanged. This simulates a mode shift from the smaller freighters and tankers to the barge. The small deviations from the base case reflect changes in vessel mass distribution. Doubling annual traffic, however, triples or quadruples the base case energies within the 200- to 500-year range (Figure 7).

Path probabilities have a strong effect (Figure 8), but the example uses extreme cases, which are not very likely in practice. The path effect is not comparable with the effect of aberrance frequencies, which are probably closer to the actual situation. A high probability of main channel path drastically increases the energy corresponding to 200 years, whereas a low probability reduces the impact energies on the protective islands to nil. A weaker effect in the same direction is due to aberrance frequency. The approximate magnitudes of these deviations from the base case vary greatly with the return period because the slope of the graphs is highly variable. For side piers and spans, the opposite trend is true for path probabilities (not shown), while aberrance probability changes have similar effects to those in Figure 7 in percentage terms.

The effect on side piers of changing side span length by 10 percent and of doubling pier base diameter was found to be minor. However, decreasing the 14-m clearance to 10 m (a saving of some 160 vertical m of side pier structures) does not practically change the risk of collisions with the "hard" elements of vessels.

Effect on Planning

As a result of the preliminary risk study, it was decided to relocate the navigational channel closer to the center of the

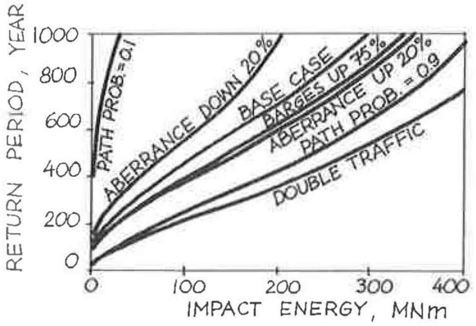

FIGURE 7 Effects on main spans of changing impact velocity.

bridge. The height of the side spans was increased to allow clearance for hard elements of the largest vessels under high-tide conditions. The sensitivity analysis findings pointed to the importance of vessel speed determination for future phases of the project. A 20 percent underestimate of impact velocity, for example, results in a 44 percent underestimate of the energy. Frequency distributions for winds, currents, tidal elevations, and ice conditions will be required to achieve accurate estimates. Due to the complexity of marine elements, vessel operating data from the Strait should be applied in mechanistic simulations of aberrant drift to determine the impact velocities. Aberrance probabilities can be estimated from the Canadian Coast Guard data and vessel travel statistics.

CONCLUSIONS

For bridges in marine environments, selection of design criteria from probability distributions on the basis of publicly acceptable risks is the preferred method because it avoids evaluation of intangibles, such as the worth of human life.

A methodology has been presented for assessing the probability distribution of impacts from bridge geometry, vessel characteristics, marine site data, and local aberrance statistics. The approach draws on models and methods previously developed by others and by the author. It integrates all factors considered relevant in such risk analysis and can also be applied to shorter bridges and to inland waterways, because it is generic. It can be useful for bridge planning to evaluate alternatives and in design to determine impact load criteria.

The kinetic energy equation is most sensitive to the impact velocity, which is also the most uncertain variable. The complexity of the marine elements and their interaction with vessel behavior pose an analytical challenge in estimating the impact velocity and its probability for bridges in a marine environment. Mechanistic models of vessel behavior can be instrumental in arriving at accurate estimates of the velocity. Site condition statistics must be analyzed in conjunction with vessel operating data to obtain the probability distributions.

Aberrance frequencies should be based on local statistics because foreign data may not be applicable. Long bridges require an aberrance statistic related to vessel-kilometers of travel.

Each variable should be conveniently divided into a number of intervals so that manageable probability mass functions can be analyzed on a microcomputer. In complex risk analyses, breaking the problem into parts and selection of these intervals is an art as much as it is a science, and it is made on the basis of data availability and interactions between various groups of variables. For this reason, a rigid software program encoding all prescribed analytical procedures would not be suitable, but an interactive program might be.

In studies affording collection of all required data in sufficient detail to feed all equations of the present model, Monte-Carlo simulations combined with mechanistic modeling of vessel behavior would be well justified.

ACKNOWLEDGMENT

This paper is based on the author's work for Public Works Canada and for the British Columbia Ministry of Transportation and Highways.

REFERENCES

1. E. Rosenblueth. What Should We Do with Structural Reliabilities. In *Reliability and Risk Analysis in Civil Engineering: Proceedings of the Fifth International Conference on Applications of Statistics and Probability in Soil and Structural Engineering* (N. C. Lind, ed.), Vol. 1, Institute for Risk Research, University of Waterloo, Ontario, Canada, 1987.
2. P. Bein. Probabilistic Model of Barge Impact Energy on the Annacis East Bridge Piers. In *Modelling Under Uncertainty: Proceedings, First International Conference on Modelling Under Uncertainty* (S. B. Jones and D. G. S. Davies, eds.), Institute of Physics Conference Series 80, Institute of Physics, Bristol and Boston, 1986.
3. P. Bein. Risk Modelling of Vessel Impacts on a Multispan Bridge. In *Proceedings, International Conference on Structures Under Shock and Impact (SUSI)*, Wessex Institute of Technology, Southampton, United Kingdom, July 1989.
4. Canadian Coast Guard. *Vulnerability of Bridges in Canadian Waters.* TP3446. Transport Canada, Ottawa, 1982.
5. *Ship Collisions with Bridges: The Nature of the Accidents, Their Prevention and Mitigation.* Marine Board, Commission on Engineering and Technical Systems, National Research Council, Washington D.C., 1983.
6. R. Saul and H. Svensson. Means of Reducing the Consequences of Ship Collisions with Bridges and Offshore Structures. In *Proceedings, International Association for Bridge and Structural Engineering*, Vol. 41, 1982, p. 165.
7. United States Coast Guard. *Statistics of Casualties: Proceedings of the Marine Safety Council*, 1980, 1981, 1982, and 1983 (Microfiche ASI Series 7404–11).

The opinions expressed herein are those of the author.

Publication of this paper sponsored by Committee on General Structures.