Evaluation of Minimum Bridge Span Openings Applying Ship Domain Theory

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The background for this study is the Great Belt Fixed Link Project, Denmark, which includes the construction of a large span suspension bridge crossing an international shipping route. As part of a comprehensive vessel collision study for the proposed bridge, analyses of vessel collisions to bridge piers at several U.S. and Canadian bridges have been carried out. By use of empirical rules for navigation span opening requirements derived from ship domain theory, it has been possible to use vessel collision experience from bridges with different span openings, vessel traffic flow, navigational conditions, and environmental conditions. The results, achieved through the analyses of existing bridges, support the use of the empirical rules in the derived form to estimate the minimum span opening for the East Bridge. The results confirmed the need for a large span as found by computer-based maneuvering simulations. The empirical rules are considered to be useful tools, which could be applied to a first-step estimation of the minimum navigation span opening of bridges and also as part of the analysis of navigational safety at existing bridges. The study included development of another method to evaluate the relationship between bridge design and ship traffic by estimation of the number of close encounters in the vicinity of the bridge on the basis of the assumption of Poisson-distributed vessel arrival.

The background for the reported work is the ongoing Great Belt Fixed Link Project, which will connect Zealand and Funen in Denmark with a combined bridge and tunnel link via the small island of Sprogoe. The Great Belt Strait is approximately 17–km wide at the point of crossing and Sprogoe is located approximately in the middle. An international shipping route passes through the eastern part of the strait and is the only deep-water route connecting the Baltic Sea with the North Sea. The traffic flow is approximately 20,000 vessels per year. At the moment there is intensive ferry traffic across the strait (a total of approximately 50,000 movements per year), most of which will disappear after the fixed link is installed.

The fixed link consists of three parts. The western part of the link will be a combined rail and road bridge. The Eastern Channel crossing will consist of a bored tunnel for train traffic and a suspension bridge (the East Bridge) for motor vehicles. The East Bridge will have a number of piers located in navigable water and thus be exposed to the risk of vessel collisions.

Preliminary investigations for a fixed link was carried out during 1977 to 1979 and included a study of the risk of vessel collision (*1*). In 1989, the Great Belt Link Ltd. asked COWIconsult to undertake a new comprehensive investigation of the interaction between vessel traffic and the planned bridge structures across the Eastern Channel. The vessel collision study was carried out in cooperation with Ben C. Gerwick, Inc., San Francisco.

The work included collecting data on the existing conditions for the vessel traffic in the Great Belt, forecasting expected traffic development, collecting vessel accident statistics and data on environmental conditions, evaluating the effect of the planned bridge structures on the navigation conditions, and evaluating risks of collisions as well as predicting potential consequences of the possible collisions. The results of the investigations have formed the basis for a new, improved vessel–bridge collision model. Methods to reduce the risk of vessel collision have been investigated. A conceptual design of a vessel traffic service system has been developed in cooperation with representatives from the Danish Navy and the Danish Maritime Authorities.

The navigation span opening has proved to be one of the most important design parameters for the design of the bridge. Different methods have been applied to evaluate the effect of the span opening on the navigational conditions. The resulting span opening requirements have led to rejection of bridge design alternatives with span openings of less than 1,600*m*.

Computer-based maneuvering simulations were carried out in cooperation with experienced Great Belt pilots at the Danish Maritime Institute, the Copenhagen School of Navigation, and the Naval Tactical Trainer at Frederikshavn Naval Base. These analyses were significant in the clarification and verification of the effect of different navigation span openings and different changes of the navigation route under normal as well as adverse weather conditions. Because the resulting span opening requirement surpassed earlier estimates, it was found advisable to try to verify this result by an alternative method.

The second method used worldwide experience of vessel behavior and knowledge of the local vessel traffic and other main navigational conditions, and the method offers an estimate of the minimum span opening. Empirical rules for minimum span opening as a function of traffic volume, vessel sizes, and so on were formulated from ship domain theory. Vessel collision records from large bridges worldwide were collected and the empirical rules were verified by testing on a number of U.S. and Canadian bridges.

Earlier studies on vessel collisions have investigated severe accidents at large span bridges (*2*). Collisions with severe

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damage to a bridge are rare and difficult to treat statistically. In this study records of all vessel collisions to a number of bridges have been obtained and used in the analyses. Furthermore, a concept for estimation of the number of close encounters has been developed on the basis of traffic data and an assumption of Poisson-distributed vessel arrival. For instance, the method can be used to evaluate whether the shipping route should be considered a one-way or a two-way traffic route. The study has proved the advantage of using several different approaches to estimate the minimum span opening. The empirical rules developed on the basis of ship domain theory can be of interest to other bridge designers as a first step in the sometimes lengthy and complex process of determining a span opening, which will provide safe vessel passage of a bridge. Methods of transfer of vessel collision experience from other bridges and the empirical methods for evaluation of minimum span opening are described in this paper.

PURPOSE OF STUDY

The purpose of the study has been to develop methods to use vessel collision experience from other bridges to evaluate the risk of collision to the piers of the proposed Great Belt East Bridge. One of the main tasks in this connection has been to develop methods to evaluate whether a bridge is designed to provide safe navigation according to the actual vessel traffic, navigational conditions, and environmental conditions at the bridge location. This has led to formulation of empirical rules for estimation of minimum navigation span opening and a calculation method for estimation of the number of close encounters in the vicinity of a bridge.

EMPIRICAL RULES

Empirical methods to estimate the minimum navigation span opening of bridges have been considered in the following. The general idea is, through statistical analyses, to estimate the navigation span opening needed for the vessels to pass the bridge with a given high level of safety under normal conditions. The span opening is sufficient when vessel collision to a bridge occurs only under extreme conditions, such as navigational errors and technical errors, possibly in combination with adverse visibility and weather conditions. Analysis of the space requirements for vessels under different navigational circumstances is treated in the well-known ship domain theory.

Ship Domain Theory

To navigate safely, the captain of a vessel tries to keep a fairly large distance from other vessels, fixed objects, shallow water, and so on. The distance varies considerably for the specific vessel speed, visibility, type of encounter, and a number of navigational aspects. This safety area around the vessel is denoted as the "ship domain." The ship domain can also be approached through the "bumper area," defined as the area a vessel actually occupies in the waterway and includes a zone around the vessel in which other vessels' bumper areas should not overlap. The safety distance is smaller in the side direction than in the course direction. Figure 1 shows a sketch of a waterway with two vessels of the same size in a head-on encounter in a narrow waterway, and the approximate ship domains and bumper areas. The vessels pass at the shortest acceptable distance, as the bumper areas touch and each vessel is on the border of the other vessel's ship domain.

Bumper Areas for Vessels at Service Speed

Yamaguchi (*3*) carried out analyses of minimum navigation channel opening for the Honshu-Shikoku Bridge Authority in 1968. His conclusions were derived from maneuverability of vessels and observed distribution of separation from drilling platforms at sea. Yamaguchi concluded that the minimum navigation channel opening for a one-way shipping lane with vessels traveling at service speed is approximately $3L$, where L is the overall length of the vessel. For a two-way shipping lane the minimum opening was found to be approximately $4.5L$.

Fujii and Tanaka (*4*) analyzed the vessel movements in several Japanese straits with vessels traveling at service speed (10 to 15 knots). Their analyses are of a large amount of data obtained through radar observations. The observed vessels were mainly smaller vessels in the range up to 10,000 gross registered tonnage (GRT). They found that the bumper area can be estimated with an ellipse with axes depending on the vessel length. They found the following lengths of the axes:

Course direction: $7L \pm L$ (1)

Side direction: $3L \pm 0.5L$ (2)

Later observations by Fujii et al. (*5*) led to the following average values:

Course direction: $8.0L$ (3)

Side direction: $3.2L$ (4)

Observations by Toyoda et al. (*6*) led to almost the same values as Fujii, and observations by Tanaka and Yamada (*7*) led to average values of $7L$ and $3L$, respectively. Other ref-

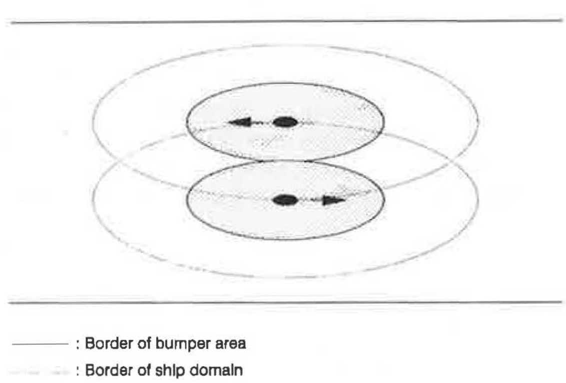

FIGURE 1 Vessels and respective bumper areas and ship domains in a narrow waterway.

erences on the subject are Hayafuji (*8*) and Okuyama et al. (*9*).

It should be noted that these values are average values for different conditions of visibility and other weather conditions. An important condition for use of these values is that the waterway has sufficient width to provide free navigation at service speed and with no obstructions in the channel (islands, shallow water, etc.). It should also be noted that these results have been derived from waters with a higher traffic density than most European and U.S. waters and with a large fraction of small vessels.

Goodwin (*10*) studied the size of bumper areas by observing vessel traffic in the Dover Strait. Her studies resulted in much larger bumper areas, indicating a minimum channel opening of 0.5 nautical miles (approximately 900 m) for one-way lane. This work was done on the basis of much fewer observations than were the Japanese observations. The relatively small traffic density in the Dover Strait compared with the Japanese straits probably makes these observations less representative for the minimum bumper area.

Equations 3 and 4 were developed on the basis of the largest and most representative set of data. Therefore, these bumper areas are used in the derivation of an empirical rule for estimating the minimum navigation span opening of a bridge crossing a waterway with free navigation.

Bumper Area for Harbor Speed (Hard Core Model)

As mentioned previously, the results derived from Equations 3 and 4 are valid only for waters in which vessels can navigate at service speed. In cases in which the traffic in the waterway is restricted in any way, a different bumper area must be applied. The theory for very restricted waters has been treated in the "Hard Core Model."

Fujii et al. (*5*) and Fujii and Yamanouchi (*11*) studied the Hard Core Model for narrow channels and harbor traffic in which the vessels are traveling at reduced speed. Fujii studied the phenomenon, for instance, in the ports of Tokyo and Yokohama. The following bumper area axes were a result of these studies:

$$\text{Course direction: } 6.0L \tag{5}$$

$$\text{Side direction: } 1.6L \tag{6}$$

The average speed of the observed vessels was 6 to 8 knots. These results are for somewhat fewer radar observations than in the case of the bumper area for vessels at service speed, again with the main part being smaller vessels.

The Hard Core Model should be used only

- If very limited areas such as ports or narrow rivers are being considered, or
- If the following conditions are fulfilled
  —Waterways with restrictions on vessel speed; no head-on, overtaking, or crossing encounters; and a suitable traffic management system to ensure the restrictions are observed;
  —Vessels traveling at harbor speed (however, the vessels should still be controllable with the rudder);
  —The distance to the nearest bend in the route should be long enough to ensure that the navigation is not affected by the bend.

Vessels are expected to maintain service speed and thus the full bumper area as long as the channel width is wider than the minimum channel width.

For a one-way lane, the minimum channel width is equal to the width of the bumper area of a vessel at service speed. To maintain service speed in case of two-way traffic, a channel width corresponding to the total bumper area width of two meeting vessels plus a separation zone between the bumper areas is necessary.

The Japanese investigations give no clear picture of the width of the minimum separation zone between the lanes. The matter is discussed in Fujii et al. (*12*), which summarized the work of Toyoda, Sakaki, Tanaka, Fujii, and others. A rough average of the results shows that vessels at anti-directional encounter do not pass with less than $3.5L$ to $5.0L$ distance between the vessels. Using the domain theory, this corresponds to a separation zone of $0.3L$ to $1.8L$.

In many straits and rivers, the official navigation channel is rather narrow, but outside the channel the water is deep enough for middle-size vessels in loaded condition and large vessels in ballast condition. This should be taken into consideration when estimating the actual width of a navigation channel.

Formulation of Empirical Rules

For one-way traffic, the domain theory suggests a minimum navigation span opening equal to the width of the bumper area of a typical large vessel passing the bridge. The typical large vessel should be a representative for the largest group of vessels passing the bridge, however, not the largest vessel. In the following the typical large vessel is found by estimating the 95 percent fractile vessel size from traffic statistics on the basis of dead weight tonnage (DWT) or draft. This fractile indicates that 95 percent of the total number of vessels passing are less than or equal to the size of the typical large vessel. By using an empirical conversion equation from tonnage or draft to vessel length, it is possible to estimate the typical vessel length.

For two-way traffic the following equations for the minimum navigation span opening of a bridge can be derived from the ship domain theory. For waterways with vessels traveling of service speed

$$W = (2 \cdot 3.2 + a)L \tag{7}$$

where W = navigation span opening m and a = coefficient for width between lanes (separation zone) and separation between bumper areas and piers.

For waterways with vessel traveling at reduced speed

$$W = (2 \cdot 1.6 + b)L \tag{8}$$

where b = coefficient for width between lanes (separation zone) and separation between bumpers areas and piers.

As mentioned previously, investigations in Japan suggest a separation zone of approximately $0.3L$ to $1.8L$ in case of vessels traveling at service speed. In the following, a minimum separation zone and separation between bumpers areas and bridge piers of $1.0L$ in both cases is assumed, that is, $a = b = 1.0$. The situation in a waterway crossed by a bridge and with two typical large vessels passing is illustrated in Figure 2. An encounter of two vessels of same size is shown. It should be noted that these empirical rules are valid only if effects of bends and other obstructions in the navigation route can be neglected.

Shoji (*13*) has estimated that the minimum distance from a bridge line to the position of the nearest turn in the navigation route should be at least $8L$ and preferably $20L$. If the distance is smaller, the turn will result in more complicated navigation conditions. These results are based on analysis of collisions at bridges worldwide, and the vessel lengths used are the size of the colliding vessel. Similar results have been obtained from the maneuvering simulations carried out in connection with this study.

Calculation for the Great Belt, Eastern Channel

The typical large vessel for the Great Belt Eastern Channel is found as the 95 percent fractile vessel to be 40,000 DWT. The corresponding vessel length is found to be approximately 200*m*.

According to local pilots, the traffic in the Eastern Channel passes at service speed and Equation 7 is applied to estimate the minimum required navigation span opening as follows:

$$W_{\mathrm{Min}} = 7.4 \cdot 200 = 1{,}480m$$

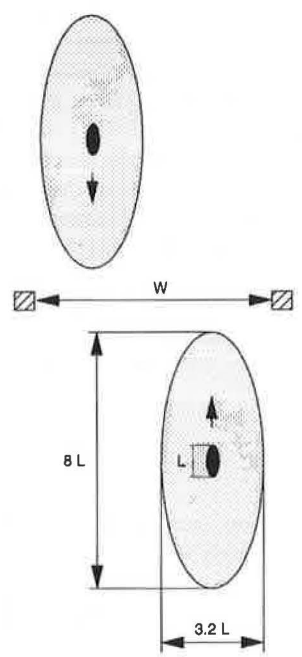

FIGURE 2 Parameters in the empirical rules for determining the minimum span opening requirement for a bridge.

In the computer-based maneuvering simulation analyses of this ship collision study (COWIconsult, for the Great Belt Link Ltd., 1989, unpublished data) it is found that navigation span openings of less than 1,400*m* are insufficient, even if the navigation route is straightened. This means that almost the same value is found for the minimum navigation span opening with the two different estimation approaches. Consideration of local navigational conditions led to a resulting span opening requirement of 1,600 *m*.

Evaluation of Traffic Density

In connection with the evaluation of minimum main span openings of bridges crossing a waterway, it is necessary to evaluate the density of the vessel traffic. If the traffic is sparse the vessel traffic can possibly be considered as one-way traffic, because vessel encounters in the vicinity of the bridge are unlikely.

Two different models for evaluation of the traffic density have been utilized:

- Traffic density based on area, and
- Traffic density evaluated using a "Bumper Chain Model."

The traffic density based on area is defined as the average number of vessels per unit area of the waterway per unit time. The density can be compensated for by the differences in bumper areas by use of weighting factors (L^2-converted traffic density). With a reference vessel of 1,000 GRT, approximately 70*m* long, the Great Belt Eastern Channel has a density of 0.05 vessels/km^2 and a L^2-converted density of 0.17. For comparison the densities for Uraga Strait in Japan is 0.7 and 1.10, respectively, and for Dover Strait 0.015 and 0.065. Thus the L^2-converted density in the Great Belt is about ⅙ of that of Uraga Strait and 3 times that in Dover Strait.

The Bumper Chain Model is based on the assumption that vessels in a narrow waterway do not overtake each other. Thus, the most dense situation occurs when vessels in a lane pass in a long line, bumper area to bumper area. The density is thus defined as the percentage of the number of vessels in the most dense situation. Again, the bumper areas should be estimated on basis of the actual vessel size distribution. At the Great Belt Eastern Channel the bumper chain density is 3 percent, whereas in Uraga Strait the density is 24 percent.

The methods can be used to estimate the actual traffic density in a strait relative to a theoretical maximum value and relative to the density in other straits. No statistical analyses have been found in the literature concluding what the practical maximum density for a strait is. Likewise, no references have been found stating a limit for when the traffic density in a two-way channel is so low that the traffic can be considered one-way traffic.

The traffic separation in the Great Belt Eastern Channel was introduced in 1976, as it was considered necessary to secure the traffic safety in the area. According to the authorities and the pilots operating in the area, it is essential to maintain the traffic separation after the bridge has been built. This indicates that traffic in the Great Belt Eastern Channel has to be considered two-way traffic.

In the analyses of span openings of existing bridges, the traffic density is therefore evaluated in the following way. If the traffic density calculated with the two methods described previously is greater than or equal to the density in the Great Belt Eastern Channel, the traffic is considered two-way traffic. If the traffic density is considerably smaller than the density in the Great Belt Eastern Channel, the traffic is considered as one-way traffic. In the latter case, a closer analysis of the traffic in the specific strait or river has been carried out by application of, for instance, the close-encounter method described later in this paper. If there is a traffic separation in the navigation channel, the traffic will in any case be considered two-way traffic because the vessels are expected to keep the intended lane under all circumstances.

Codes and Guidelines

Only few codes and guidelines exist for evaluation of minimum bridge navigation span opening. During this study only two codes or guidelines were found of interest.

On the basis of ship domain theory, the Japanese Government in 1973 passed a Maritime Safety Law (*14*), requiring that the minimum width of a fairway for international vessel traffic is 700*m* for one-way passage and 1,400*m* for two-way traffic (the length of a typical large vessel is generally set to 200*m* for the major Japanese waterways). Accordingly, the Maritime Safety Law has been applied to the major Japanese bridges developed in recent years, namely, the Bisan Seto Bridge providing two separate navigation routes of each 700*m* width and the Akashi Kaikyo Bridge with a span of 1,990*m* across the 1,500*m* route for two-way passage.

Greiner, Inc., is preparing a guide specification for the Federal Highway Administration, U.S. Department of Transportation (*15*) on the subject of vessel collision with bridges crossing navigable waterways. This specification will include recommendations for navigation span openings.

Application to Existing Bridges

To check the empirical rules for minimum navigation span opening, the rules have been tested on existing bridges. In connection with this vessel collision study, a worldwide review of major bridges with navigational conditions somewhat similar to the Great Belt East Bridge has been carried out. Bridge authorities, marine safety authorities, and engineering companies in the different countries have been addressed. The authorities in the United States and Canada have provided useful information on vessel collisions and vessel traffic at selected bridges. Therefore, the analyses in this report concentrate on bridges in these countries.

Collision statistics have been obtained from a number of different sources. The main sources of information have been the Vessel Casualty Data Base and other material from the U.S. Coast Guard and the Marine Casualty Data Base of Transport Canada. All vessel collisions reported within the last 10 years at the selected bridges have been included in the analyses. Additional information has been collected from published articles and reports on the accidents. It should be noted that the analyses were performed with limited knowledge of the bridge design, navigational conditions, and so on at the selected bridges. The information has been mainly in the form of plan and elevation diagrams for the bridges, nautical charts of the waterways, and trip/draft tables from nearby harbors.

The information varies in quality and amount of data provided. In some cases, the size of a vessel in question is only known by the draft, GRT, or DWT. For this reason, a number of empirical conversion equations have been applied to estimate some information, for example, the length of the vessel from the GRT or DWT. Rules have been taken from Fujii et al. (*5*) and from Knud E. Hansen ApS (*16*). In some cases accurate information about the actual span opening has not been available. In these cases, the navigation span width (measured from centerline to centerline of main piers) has been applied.

The calculation of the minimum navigation span opening of a specific bridge is carried out by means of the theory and rules described previously. The characteristic vessel length is taken as the 95 percent fractile of draft or tonnage. The traffic data is found mainly from trip/draft tables from nearby harbors. In each case it is evaluated if one- or two-way traffic can be assumed. As an example of estimation of minimum navigation span opening, the calculation for the Newport Road Bridge, Rhode Island, is now summarized. From 1987 trip/draft tables (*17*), it was determined that the 95 percent fractile for the draft is 8.7*m*. This corresponds to a vessel length of approximately 105*m*, assuming loaded condition. The trip/draft tables show a total annual number of bridge passages of approximately 6,300, of which only a few were large vessels. Analysis of the traffic density and calculation of the number of close encounters at the bridge indicate that the traffic can be assumed to be one-way traffic.

The analysis of the navigational aspects of the waterway shows that free navigation with vessel traveling at service speed can be expected. Under these circumstances the minimum span opening can be estimated from Equation 4 to be $3.2 \cdot 105 = 336m \approx 340m$ (rounded to the nearest 10*m*). This indicates that the actual span opening of 488*m* is sufficient.

Such estimates have been carried out for 26 bridges in Canada and the United States. These bridges have been selected by the following criteria:

- Main span openings of the bridges were greater than 200*m* (with a few exceptions),
- Data on vessel traffic and on a typical large vessel have been available, and
- One or more bridge piers are placed in navigable water.

All the bridges that were examined are shown in Table 1. There are two main groups of bridges. The first group contains the bridges for which the empirical rules for the minimum span opening are fulfilled and the second group contains the bridges for which the empirical rules were not fulfilled.

The first group contains 12 bridges, of which two collisions (at the Greater New Orleans Bridge and the Newport Road bridge) have been reported within the last 10 years. The second group contains 14 bridges. During the same time, 46 collisions have been reported for the second group of bridges. The Greater New Orleans Bridge was hit by a barge in 1985. The span opening of approximately 480*m* is wide enough for

TABLE 1 COMPARISON OF ACTUAL SPAN OPENING, MINIMUM SPAN OPENING REQUIREMENT, AND THE OBSERVED NUMBER OF COLLISIONS WITHIN THE LAST 10 YEARS FOR 26 U.S. AND CANADIAN BRIDGES

Bridges Following the Empirical Rules:

Bridge Name	State	Open Year	Navigation Span Opening As Built (m)	Min. (m)	CAT[a]	TRAF[b]	COLL[c]
Delaware River Mem.	Delaware	1951	655^S	190	F	2	0
Golden Gate	California	1937	1280^S	410	F	2	0
Greater New Orleans	Louisiana	-	480^S	350	V	2	1
Lions Gate	Br. Columbia	-	396^C	290	H	1	0
Longview	Oregon	1930	366^S	350	F	2	0
Luling	Louisiana	1972	370^S	250	V	2	0
Mackinac Straits	Michigan	1957	914^C	320	F	1	0
Mc Cullough Mem.	Oregon	1936	242^S	180	V	1	0
Newport Road	Rhode Island	1969	488^S	340	F	1	1
S.F.-Oakland Bay	California	1936	$2x702^S$	400	F	2	0
Tappan Zee	New York	1955	369^S	300	V	1	0
Verrazano Narrows	New York	1964	1298^S	1180	F	2	0

Bridges Not Following the Empirical Rules

Bridge Name	State	Open Year	Navigation Span Opening As Built (m)	Min. (m)	CAT	TRAF	COLL
Carquinez Strait	California	1927/1958	$2x305^C$	420	F	1	1
Francis Scott Key	Maryland	1978	335^C	420	V	2	2
Houston Ship Chan.	Texas	1982	229^S	420	V	2	0
Huey P. Long	Louisiana	1935	229^C	250	V	2	6
Laviolette	Quebec	1967	305^C	350	V	1	0
New Westminster Rail	Br. Columbia	1904	$2x49^C$	530	V	1	12
Ogdenburg-Prescott	N.Y./Ontario	1960	335^S	350	V	1	1
Québec	Quebec	1917	232^C	350	V	1	2
Richmond-San Raphael	California	1956	300^C	450	F	1	1
Second Narrows Rail.	Br. Columbia	1969	137^C	290	H	1	1
South. Pacific Rail.	Louisiana	1907/1971	98^S	220	F	2	3
Sunshine Skyway	Florida	1954	263^S	530	F	1	3
		1987	366^S				0
Vicksburg	Louisiana	-	265^S	320	V	2	11
Wm. Preston Lane	Maryland	1952/1973	457^C	1250	F	2	1

Dash (-) means that the opening year has not been obtained

S - Span width, i.e. distance between centers of piers
C - Span opening (horizontal clearance), i.e. width of navigable channel

[a]CAT - Waterway category:
F: Free navigation. V: Very limited waterway. H: Harbor navigation
[b]TRAF - Traffic category:
1: One-way traffic assumed. 2: Two-way traffic assumed
[c]COLL - Number of collisions within the last 10 years

the present traffic according to the empirical rule. However, the navigation channel does not apply to all the conditions of the empirical rule, as there are strong bends in the route close to the bridge. Furthermore, the maneuverability of a tug-towed barge is lower than that of a self-propelled vessel. The Newport Road Bridge was hit by a large tanker in 1981, which was attributed to navigation failure in dense fog.

The Laviolette Bridge is in the group of bridges not following the rule but, in fact, the bridge has a span opening almost wide enough according to the empirical rule (305*m* compared with 350*m*). Considering the accuracy of the calculation method, the bridge is, in practice, following the rule. The Houston Ship Channel Bridge has the main piers located on only 3*m* of water, that is, not in navigable water for larger vessels. It is therefore not surprising that no collisions to the piers have been reported.

Altogether, the analyses indicate that for the cases in which the empirical rules are followed, very few collisions have taken place within the last 10 years. In the cases where the rules are not followed one or more collisions have taken place within the last 10 years. The results achieved through these analyses support the use of the empirical rules in the derived form to estimate the minimum span opening for the East Bridge. The overall span opening requirements were found to be surprisingly independent of local environmental conditions such as currents, wind, and visibility.

CLOSE ENCOUNTER METHOD

An obvious extension of the empirical rule is to estimate how often a situation arises where two antidirectional vessels meet in the vicinity of the bridge and their total bumper area widths and separation zone width exceeds the actual span opening. For instance, the method can be used as a tool in the evaluation of whether the shipping route should be considered a one-way or a two-way traffic route, which is important for the evaluation of the minimum span opening. The method has been developed by Ostenfeld-Rosenthal (COWIconsult for the Great Belt Link Ltd., 1990, unpublished data).

Calculation Method

By application of Equation 7 to the vessel lengths L_1 and L_2, the total space requirement for navigation at service speed is

$$3.2L_1 + 3.2L_2 + 0.5L_1 + 0.5L_2 = 3.7\,(L_1 + L_2) \qquad (9)$$

If this total width exceeds the navigation span opening, the situation is referred to as a close encounter. The total zone length in the traffic direction has been estimated to be 16 times the length of the largest of the meeting vessels.

The occurrence of vessels in a zone around the bridge requires a statistical description of the vessel traffic. The Poisson process is generally accepted as a good description of such events—and it has in this study also been found to fit the vessel traffic in Great Belt very well. Because several of the involved parameters depend on the vessel type, it has been found necessary to use a simulation approach to calculate the yearly expected number of close vessel encounters as a function of the bridge span opening. A simulation program has been developed and a calculation for the proposed Great Belt East Bridge and a number of existing bridges has been carried out.

Figure 3 shows that with the present assumptions the Great Belt Bridge should have a navigation span of 1,800*m* in order to completely avoid close encounters. A span of 1,600*m* would mean approximately 17 close encounters per year, and a span of 1,200*m* would mean approximately one close encounter per day.

Applications to Existing Bridges

The number of close encounters has been calculated for some of the bridges in Table 1. Only bridges with one navigation span for both directions have been analyzed. The results of the calculations are shown in Table 2 together with the approximate annual traffic volume at the specific bridge.

The results for the Greater New Orleans Bridge and the Longview Bridge show that a close encounter occurs approximately once a day, which is relatively high considering that the span openings apply to the empirical rules. This is because of the span opening and the heavy traffic in the waterways, causing many multi-encounter situations. At the William Preston Lane, Jr. Memorial Bridge there are approximately two close encounters per day—a rather high number, which supports the conclusion that the span opening of this bridge is too narrow. The results for the Golden Gate Bridge, the Sunshine Skyway Bridge, the Newport Road Bridge, the Tappan Zee Bridge, and the Richmond-San Rafael Bridge show low numbers of close encounters, which result mainly from the low traffic density and low proportion of large vessels. The analysis indicates that the main risk for these bridges is not the multi-encounter situations, but rather one-vessel situations with loss of control.

The analyses show that the number of encounters at a bridge is highly dependent on the vessel traffic and the distribution of vessel-size classes. There is a tendency for bridges that do not follow the empirical rules on minimum span opening to also have a large number of close encounters. It is, however, not possible at this stage to draw general conclusions concerning the relationship between number of close encounters and number of vessel-to-bridge collisions.

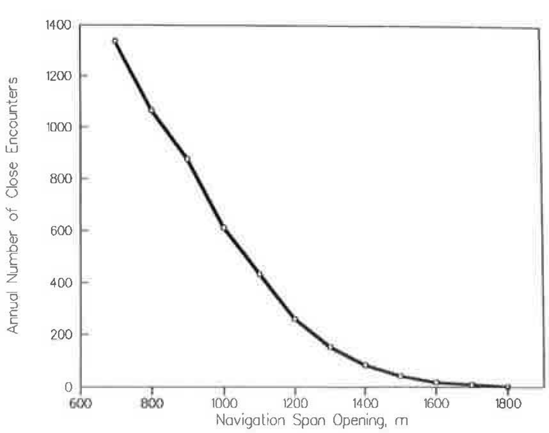

FIGURE 3 Number of close encounters as a function of span opening of the proposed Great Belt East Bridge.

TABLE 2 TRAFFIC VOLUME AND CALCULATED NUMBERS OF CLOSE ENCOUNTERS FOR U.S. AND CANADIAN BRIDGES

Bridge Name	Approximate Annual Traffic Volume	Annual Number of Close Encounters
Golden Gate	37,000	0
Greater New Orleans	148,000	300
Longview	113,000	460
Newport Road	6,300	7
Ogdenburg-Prescott	3,000	160
Richmond-San Raphael	8,000	40
Sunshine Skyway	4,000	88
Tappan Zee	4,400	2
Wm. Preston Lane	11,000	640

CONCLUSIONS

In this study different methods to estimate the minimum navigation span opening of a bridge by the use of empirical methods have been analyzed. Empirical rules have been derived on basis of the ship domain theory. The determination of the average bumper areas is based on a number of independent statistical analyses of the subject from waterways in Japan and Europe. The different rules are applied depending on the traffic density in the vicinity of the bridge, the average speed of the vessels, the size of a typical large vessel passing the bridge, and different navigational aspects at the bridge location.

Application of the empirical rules to a number of existing large span bridges shows practically no collisions within the last 10 years at bridges following the rules, but shows, in general, one or more collisions at bridges with span openings significantly smaller than the required minimum according to the empirical rules.

The use of empirical rules has proved to be a practical tool as a first step in the estimation of the minimum navigation span opening of bridges and the analysis of navigation safety at existing bridges. The rules provide an approximation of minimum span opening using knowledge of main local navigational and climatological conditions.

The empirical rules have been an important factor in the decision of navigation span opening for the Great Belt East Bridge. The results confirmed the need for a large span as found by computer-based maneuvering simulations taking into account detailed information of local conditions (traffic, currents, wind, visibility, alignment, bends in the route, etc.).

The close encounter method offers an interesting supplement to the empirical rules described in the preceding. Further work should be carried out to refine the method and to make sensitivity analyses.

The experience from the Great Belt Fixed Link Project indicates that minimum span opening should be determined on the basis of several different estimation methods. The use of the empirical rules provides a convenient first-step estimation of the minimum span opening for the bridge designer. The knowledge of local navigational and climatological conditions can in a later phase be used as basis for more advanced and time-consuming methods (e.g., computer simulations).

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