Ship Impact Risk Analysis of the Tappan Zee and Castleton-on-Hudson Bridges, Hudson River

PAIK-KEE LOW AND RICHARD WILSON

The exposure to risk of ship-bridge collisions at the Tappan Zee and Castleton-on-Hudson bridges on the Hudson River in New York State is evaluated in this paper. Provided are a description of the major factors affecting the potential for ship-bridge collisions and an estimate of the observed and potential frequency of ship-bridge accidents at the two bridges. A statistical analysis is used in this paper to predict the probability of a ship-bridge collision based on accident rates obtained for each class of bridges, defined here as the set of bridges over navigable waters in the United States of similar characteristics to the bridge of interest. The probability of an accident occurring at each of the two study bridges represents the average number of accidents that could occur each year. This can also be represented by the number of years between two consecutive accidents (or the return period). This is calculated by taking the direct inverse of the probability of occurrence of a ship-bridge accident. The return period found for the Tappan Zee Bridge was 55 years, and for the Castleton-on-Hudson Bridge the return period was 268 years. These results serve as indicators for precautionary measures to reduce the risk and severity of a ship-bridge collision.

Recent years have seen an increase in serious accidents involving ship collisions with major bridges. These accidents have claimed many lives and resulted in millions of dollars in damages, lost transportation services, repair and replacement costs, and spills and releases from the ships. Various factors have contributed to this increase, including the rapid growth in size and tonnage of the world fleet of merchant vessels during the last 25 years. In addition, bridges are not always designed with attention to the waterborne traffic that passes beneath them. As a result, they may be poorly located for ship maneuvering, lack sufficient navigational clearance, or have piers that may be placed so that vessels that stray from the main navigational channel would collide with them before running aground. Moreover, most bridges are not designed to withstand the horizontal impacts of these vessels. Hence, protection systems for them may need to be provided.

Evaluated in this paper is the potential of ship-bridge collisions at the Tappan Zee and the Castleton-on-Hudson bridges on the Hudson River in New York State. Provided is a description of the major factors affecting the potential for ship-bridge collisions, analysis of the considerations regarding the natural setting and general river conditions at the two bridges, and an estimate of the predicted frequency of ship-bridge accidents.

The first section of the paper contains a description of the study approach and identifies the data used. In the second section, the ship-bridge collisions on the Hudson River are described, and a brief survey of international bridge accidents is presented that identifies their nature and the factors that contributed to their occurrence. The third section provides a description of the Tappan Zee and the Castleton-on-Hudson Bridges, the characteristics of the river within their vicinity, weather conditions, and types of vessels that pass beneath each bridge. In the fourth section, the results of the study are presented and the risks to the two bridges assessed.

APPROACH AND DATA SOURCES

Although no national standards defining acceptable levels of risk for ship-bridge collisions exist, a risk analysis identifies the risk of ship-bridge collisions for the Tappan Zee and Castleton-on-Hudson Bridges. This information can be used to evaluate methods to reduce such risks.

The model adopted in this risk assessment conforms to the simple, general equation:

$$TR = 1/(N \times PC)$$

where

TR = the number of years between two accidents (return period),
N = the number of annual vessel transits beneath a bridge, and
PC = the ship-bridge collision rate at a bridge.

When a vessel strays from the main navigational channel, it could hit a bridge pier or superstructure. The probability that a collision would occur is dependent on such variables as the geometry and depth of the waterway, the location of the bridge piers, the density of the waterborne traffic on the waterway, human error, mechanical failure, or unfavorable or adverse environmental conditions such as fog or storm.

In this paper, the probabilities of a ship-bridge collision occurring at either the Tappan Zee or Castleton-on-Hudson Bridges are estimated by analyzing national maritime traffic and accident statistics for the period 1981 to 1986 for the appropriate classes of bridges, and the traffic profiles of the vessels and ships that pass beneath the two bridges.

A class of bridges is defined here as the set of bridges of similar horizontal clearance to the study bridge. The Tappan

---

Parsons Brinckerhoff Quade and Douglas, Inc., 1 Penn Plaza, New York, N.Y. 10119.

Zee Bridge has a horizontal clearance in the main navigational channel of 1,098 ft, whereas the Castleton-on-Hudson Bridge has a horizontal clearance of 552 ft. The classes were established for horizontal clearance ranging from 900 to 1,300 ft for the Tappan Zee class, and 500 to 600 ft for the Castleton-on-Hudson class. Each class of bridges is analyzed for the total number of ship-bridge collisions that occurred from 1981 to 1986, and the total vessel traffic that passed beneath each bridge within that class for the same period. Therefore, the average annual rate of ship collisions, *PC*, is obtained for that class of bridges by dividing the total number of accidents by the total number of vessel transits.

After obtaining the number of ships and barges (*N*) that transit beneath each bridge, the probability or chance of a ship-bridge collision occurring at that bridge ($N \times PC$) can then be established. Hence, the smaller the return period, the greater the risk that a ship-bridge collision could take place.

The data on national maritime accidents were primarily obtained from the marine accident files maintained by the United States Coast Guard (USCG); the United States Army Corps of Engineers (USACE) provided data on vessel movements (*1*). Only data on movements by self-propelled vessels were considered relevant, as barges are accompanied by tugboats. The two classes of bridges were determined through a search of data included in the USCG *Bridges Over the Navigable Waters of the United States*, all volumes, 1984 (*2*). The traffic profile (*N*) of the Hudson River was obtained from the USACE Waterborne Commerce Statistics Center, the Maritime Association of the Port of New York and New Jersey, and the Hudson River Pilots Association (HRPA). Relevant bridges and accidents obtained through the data search are listed in Tables 1 through 4.

TASKS UNDERTAKEN

A vessel listing for the Hudson River [see Appendix *B* in the Parsons Brinckerhoff study (*4*)] was created by combining information from the Maritime Association on ship movement with data from Lloyd's Register of Ships (*3*) and then resorted according to vessel types and classes. A data base for bridges of the United States over navigable waters was also created according to size of horizontal span. This was done to obtain bridges of similar sizes and characteristics (i.e., class) for comparison with the proposed bridges. Accident statistics were then compiled by sorting the accident data base according to the horizontal clearances of two classes of bridges. The results can be found in Appendix *C* in the Parsons Brinckerhoff study (*4*).

National accident statistics were obtained from the USCG Office of Marine Safety in Washington, D.C. (records pertaining to ship/bridge collisions for the years 1980 to 1988). These records provided a listing of all accident cases that involved ship-bridge collisions. From this list, an accident data base was compiled that included the name of the waterway and the bridge where each accident took place. By making correlations with information contained in *Bridges Over the Navigable Waters of the United States* (*2*), the type and horizontal clearance of these bridges were also included. The data base is presented in Appendix *D* in the Parsons Brinckerhoff study (*4*).

Telephone interviews were also conducted with various organizations to obtain information on vessel traffic and navigation on the Hudson. The organizations contacted included the

- U.S. Coast Guard
- Maritime Association of the Port of New York and New Jersey
- Towboat and Carriers Association of New York and New Jersey
- U.S. Army Corps of Engineers
- Hudson River Pilots Association
- Albany Port District Commission
- Barge/Tug Transportation Companies
  - –New York Trap Rock Corporation
  - –Reinauer Transportation Company
  - –Red Star Marine Services, Inc.
  - –Berman Enterprises, Inc.
  - –Bouchard Transportation Company
  - –Buchanan Marine Corporation
  - –Eklof Marine Corporation
  - –Gallagher Brothers Sand & Gravel Corporation

HISTORICAL ACCIDENT EXPERIENCE

Discussed in this section are the nature and causes of accidents on the Hudson River and around the world that involved ship-bridge collisions.

Ship-Bridge Collisions on the Hudson River

A review of the files maintained by the First Coast Guard District at Governor's Island, New York, for all bridges crossing the Hudson River north of Yonkers to Albany, New York, indicated that there was only one reported maritime accident involving a bridge on the Hudson River. This was confirmed by a search of the records of national maritime accidents (according to regional water-body designations) maintained by the USCG at its Office of Marine Safety. The accident at the Tappan Zee Bridge occurred on December 31, 1975. A tugboat pushing a tank barge northbound at reduced speed with visibility impaired by fog made contact with the west pier of the west pass after difficulties with its radar equipment. Although there was a lookout stationed at the bow of the barge, communications were insufficient to give timely warning of the impending collision to the tugboat's pilothouse.

The bridge sustained minor damage to its fendering system. The barge was punctured, resulting in the discharge of oil into the river. A copy of the accident report is given in *Ship Impact Risk Analysis* (*4*).

Ship-Bridge Collisions Around the World

Although none of the bridges across the Hudson River has been involved in major ship-bridge collisions, such accidents have occurred nationally and internationally. A *Ship Collision Risk Assessment* by COWIconsult for the Sunshine Skyway Bridge in Tampa, Florida, in 1981 (*5*), gives a list of examples

TABLE 1 TAPPAN ZEE CLASS BRIDGES (900–1,300 ft)

SEQ	WATERWAY	CITY	ST NAME AND LOCATION OWNER	MILEPOST	TYPE	LENGTH	LW	HW	USE
1	EAST RIVER	NEW YORK CITY	NY QUEENSBORO BR W CHANNEL NY CITY-NYC	5.5	F	900	138	131	HWY
2	MISSISSIPPI-LOWER	CARUTHERSVILLE	MO CARUTHERSVILLE I 55-MO AND TN	838.9	F	900	96	52	HWY
3	ST. JOHNS RIVER	JACKSONVILLE	FL DAME PT JACKSONVILLE FL-JACKSONVILLE	9.8	F	906		160	HWY
4	WILLAMETTTE RIVER	PORTLAND	OR FREEMONT BR	10.9	F	928	163	147	HWY
5	MISSISSIPPI-UPPER	ST LOUIS	MO VETERANS MEMORIAL BRIDGE	180.2	F	940	102	65	HWY
6	WHITE RIVER	NEWPORT	AR LOUISIANA GAS COMPANY	243.5	SUS	944	67	42	PL
7	HUDSON RIVER	NEWBURGH	NY NEWBURGH & BEACON NY I 84-NY	62.0	F	960		139	HWY
8	HUDSON RIVER	NEWBURGH	NY NEWBURGH-BEACON NY-NY	62.0	F	960	185	181	HWY
9	NIAGARA RIVER	NIAGARA	NY UPPER STEEL ARCH-NIAGARA FALLS	13.0	F	960	189		HWY
10	ST. JOHNS RIVER	JACKSONVILLE	FL JACKSONVILLE EXP COMMODORE PT	22.1	F	960	143	141	HWY
11	NIAGARA RIVER	LEWISTON	NY LEWISTON NY-NIAGARA FALLS	7.1	F	980	200	195	HWY
12	CARQUINEZ STRAIT	VALLEJO-UPSTRM	CA VALLEJO BR SOUTH(LEFT) SPAN NORTH PIER	0.2	F	998	151	145	HWY
13	CARQUINEZ STRAIT	VALLEJO-UPSTRM	CA VALLEJO BR SOUTH(LEFT) SPAN SOUTH PIER	0.2	F	998	141	135	HWY
14	CARQUINEZ STRAIT	VALLEJO-UPSTRM	CA VALLEJO BR NORTH(RIGHT) SPAN NORTH PIER	0.2	F	1000	157	151	HWY
15	CARQUINEZ STRAIT	VALLEJO-UPSTRM	CA VALLEJO BR NORTH(RIGHT) SPAN SOUTH PIER	0.2	F	1000	152	146	HWY
16	COOPER RIVER	CHARLESTON	SC CHARLESTON SC US 17-SC	3.0	F	1000	155	150	HWY
17	OHIO RIVER	MAYSVILLE	KY MAYSVILLE-ABERDEEN US 60	408.4	SUS	1000	80	38	HWY
18	SAN FRANCISCO BAY	SAN RAFAEL	CA RICHMOND SR 17 (MAIN CHANNEL-CTR SPAN)	13.0	F	1000	190	185	HWY
19	OHIO RIVER	COVINGTON	KY COVINGTON-CINCINNATI	470.5	SUS	1004	74	27	HWY
20	COLORADO RIVER	BLYTHE	CA BLYTHE	121.1	F	1020		48	PL
21	CARQUINEZ STRAIT	VALLEJO-DNSTRM	CA VALLEJO BR NORTH(RIGHT) SPAN NORTH PIER	0.2	F	1030	162	156	HWY
22	CARQUINEZ STRAIT	VALLEJO-DNSTRM	CA VALLEJO BR NORTH(RIGHT) SPAN SOUTH PIER	0.2	F	1030	153	147	HWY
23	CARQUINEZ STRAIT	VALLEJO-DNSTRM	CA VALLEJO BR SOUTH(LEFT) SPAN NORTH PIER	0.2	F	1030	150	144	HWY
24	CARQUINEZ STRAIT	VALLEJO-DNSTRM	CA VALLEJO BR SOUTH(LEFT) SPAN SOUTH PIER	0.2	F	1030	140	134	HWY
25	CLEARWATER RIVER	OROFINO	ID OROFINO DENT BR - CLEARWATER CO	17.0	F	1035	30		HWY
26	WILLAMETTE RIVER	ST JOHNS	OR ST JOHNS-MULTNOMAH	5.9	SUS	1068	189	174	HWY
27	COLUMBIA RIVER	ASTORIA	OR ASTORIA TO PT ELLICE (MAIN CHANNEL)	13.5	F	1070	193	186	HWY
28	EAST RIVER	NEW YORK CITY	NY TRIBOROUGH BR	7.8	F	1070	143	138	HWY
29	SAN FRANCISCO BAY	SAN FRANCISCO	CA SF/OB W SPAN B-C PIER B	8.9	SUS	1072	224	218	HWY
30	SAN FRANCISCO BAY	SAN FRANCISCO	CA SF/OB W SPAN B-C PIER C	8.9	SUS	1072	227	221	HWY
31	SAN FRANCISCO BAY	SAN FRANCISCO	CA SF/OB W SPAN C-D PIER C	8.9	SUS	1079	226	220	HWY
32	SAN FRANCISCO BAY	SAN FRANCISCO	CA SF/OB W SPAN C-D PIER D	8.9	SUS	1079	224	218	HWY
33	COLORADO RIVER	TOPOCK	AZ TOPOCK	233.7	F	1080	72	53	HWY
34	COLUMBIA RIVER	LONGVIEW	WA LONGVIEW (RAINIER)	66.0	F	1085	187	176	HWY
35	HUDSON RIVER	NYACK	NY TAPPAN ZEE BR	27.0	F	1098	144	139	HWY
36	PATAPSCO RIVER	BALTIMORE	MD SOLLERS PT-HAWKINS PT I 395	6.0	F	1100		185	HWY
37	MISSISSIPPI-LOWER	BATON ROUGE	LA BATON ROUGE-PORT ALLEN	229.3	F	1120	165	125	HWY
38	LONG BEACH HARBOR	LOS ANGELES	CA VINCENT THOMAS BR	3.0	SUS	1150	189	185	HWY
39	EAST RIVER	NEW YORK CITY	NY MANHATTAN BR	1.1	F	1200	144	134	HWY-RR
40	MISSISSIPPI-LOWER	LULING	LA LULING AND DESTREHAN	121.7	F	1200	154	133	HWY
41	RED RIVER	RED RVR PARISH	LA TENNESSEE GAS TRANSLINE	205.5	SUS	1250	76	51	PL

SOURCE: PARSONS BRINCKERHOFF

of ship-bridge collisions that took place between 1960 and 1980 in the United States and around the world.

The causes of such collisions are often a complex combination of various factors that fall into three main categories:

1. Human error (e.g., lack of experience; misjudgment; negligence; misunderstanding between captain, pilot, and helmsman; incorrect interpretation of chart or notice to mariners; violations of rules of the road; incorrect evaluation of current and wind conditions; and so on);
2. Mechanical failure (e.g., engine, steering, radar equipment); and
3. Environmental conditions (e.g., strong winds and storm, fog, rough current conditions, heavy traffic, narrow river channel width and shape, poor navigational aids).

The nature and impact characteristics of these collisions have also been categorized:

1. The hull of the ship hits a bridge pier and moves, overturns, or breaks it;

TABLE 2 CASTLETON-ON-HUDSON CLASS BRIDGES (500–600 ft)

SEQ	WATERWAY	CITY	ST NAME AND LOCATION OWNER	MILEPOST	TYPE	LENGTH	LW	HW	USE
1	ALLEGHENY RIVER	CHESWICK	PA CHESWICK PA I 80-PA	14.2	F	500	64	53	HWY
2	ALLEGHENY RIVER	CHESWICK	PA CHESWICK PA-BLE	14.2	F	500	89	78	RR
3	ARKANSAS RIVER	LITTLE ROCK	AR LITTLE ROCK AR 440-AR	112.9	F	500	57	52	HWY
4	ARTHUR KILL	STATEN ISLAND	NY STATEN ISLAND NY-ELIZABETH NJ-BO	11.6	VL	500	35	31	RR
5	CAPE COD CANAL	BOURNE	MA BOURNE MA-BUZZARDS BAY	0.7	VL	500	11	7	RR
6	CAPE COD CANAL	BOURNE	MA BOURNE MA SR 28-US ARMY COE	2.0	F	500	139	135	HWY
7	CAPE COD CANAL	SAGAMORE	MA SAGAMORE MA US 6-US ARMY COE	5.2	F	500	142	135	HWY
8	CHSPKE & DLWR CANAL	CANAL	DE CANAL DE-CR	7.7	VL	500	50	45	RR
9	COLUMBIA RIVER	KENNEWICK	WA KENNEWICK WA-WA	330.0	F	500	61		HWY
10	COLUMBIA RIVER	PORTLAND	OR PORTLAND I 205 (MAIN CHANNEL)	112.7	F	500	136	119	HWY
11	DELAWARE RIVER	BRISTOL	PA BRISTON PA-BURLINGTON NJ-BURLINGTON CO	117.8	VL	500	68	62	HWY
12	DELAWARE RIVER	DELAIR	NJ DELAIR NJ-CR	104.6	VL	500	55	49	RR
13	GASTINEAU CHANNEL	JUNEAU	AK JUNEAU AK-AK		F	500	66	50	HWY
14	HOUSTON SHIP CANAL	HOUSTON	TX TEXAS TURNPIKE AUTHORITY	40.0	F	500		175	HWY
15	HOUSTON SHIP CHANNEL	HOUSTON	TX HOUSTON TX-TEXAS-TURNPIKE AUTH	40.0	F	500		175	HWY
16	ILLINOIS RIVER	CREVE COUER	IL CREVE COEUR IL I 474(TWIN)-IL	158.0	F	500		54	HWY
17	KANAWHA RIVER	POINT PLEASANT	WV POINT PLEASANT WV US 35-WV	0.1	F	500	69	30	HWY
18	KOOTENAI RIVER	BONNERS FERRY	ID BONNERS FERRY ID-BONNERS FERRY	152.1	SUS	500	36	32	PL
19	LOS ANGELES RIVER	LONG BEACH	CA QUEENS WAY	2.7	F	500	50	45	HWY
20	MISSISSIPPI-LOWER	NEW ORLEANS	LA PARIS ROAD SR 47-US GOVT	13.0	F	500	140	137	HWY
21	MISSISSIPPI-UPPER	MUSCATINE	IA MUSCATINE SR 92-IA	455.9	F	500	64	52	HWY
22	MISSISSIPPI-UPPER	ROCK ISLAND	IL ROCK ISLAND I 280-IL	478.3	F	500	62	52	HWY
23	MISSISSIPPI-UPPER	ST LOUIS	IL MCKINLEY BR	182.5	F	500	95	58	HWY-RR
24	OHIO RIVER	BROOKVILLE	IL IRVIN COBB BR US 45	937.3	F	500	91	46	HWY
25	OHIO RIVER	CAIRO	IL CAIRO IL-ICG	977.7	F	500	104	44	RR
26	OHIO RIVER	CINCINNATI	OH CINCINNATI OH-SOU	472.3	F	500	78	25	RR
27	OHIO RIVER	KENOVA	WV KENOVA WV-NW	315.7	F	500	74	30	RR
28	OHIO RIVER	MARTINS FERRY	OH MARTINS FERRY	89.0	F	500	80	32	RR
29	ROGUE RIVER	AGNESS	OR NEAR AGNESS OR - LARRY LUCAS	26.0	SUS	500	80	6	PL
30	SAN DIEGO BAY	SAN DIEGO	CA CORONADO BAY BRIDGE SPAN 20/21	7.8	F	500	179	175	HWY
31	ST LOUIS RIVER	DULUTH	MN I 535 RICES POINT	5.4	F	500	123	120	HWY
32	SUSQUEHANNA RIVER	HAVRE DE GRACE	MD HAVRE DE GRACE MD-BO	2.0	F	500	88	86	RR
33	TENNESSEE RIVER	CALVERT CITY	KY CALVERT CITY I 24-KY	21.1	F	500	87	45	HWY
34	MISSISSIPPI-UPPER	HASTINGS	MN HASTINGS MN US 61 10	813.9	F	502	63	47	HWY
35	MONONGAHELA RIVER	DONORA	PA DONORA PA-PA	36.3	F	502	54	25	HWY
36	OHIO RIVER	CINCINNATI	OH CINCINNATI OH-KY	469.9	F	502	78	23	HWY
37	MISSISSIPPI-UPPER	ST LOUIS	IL MERCHANTS BR	183.2	F	503	92	55	RR
38	ATCHAFALAYA RIVER	SIMMESPORT	LA SIMMESPORT LA S I-LA	132.7	F	504	102	50	HWY
39	MONONGAHELA RIVER	RANKIN	PA RANKIN SR 837-ALLEGHENY CO	9.6	F	505	75	40	HWY
40	MONONGAHELA RIVER	BROWNSVILLE	PA BROWNSVILLE US 40-PA	56.2	F	506	46	18	HWY
41	MISSISSIPPI-UPPER	SAVANNA	IL SAVANNA-SABULA US 52	537.8	F	508	64	57	HWY
42	OHIO RIVER	AMBRIDGE	PA AMBRIDGE-ALIQUIPPA SR 18 65	16.8	F	510	78	58	HWY
43	SNAKE RIVER	CENTRAL FERRY	WA CENTRAL FERRY WA SR 127-WA	83.2	F	510	60	58	HWY
44	MISSOURI RIVER	SOUTH OMAHA	NE SOUTH OMAHA NE US 275	612.2	F	514	62	52	HWY
45	COOS BAY	NORTH BEND	OR US 101-OR	9.8	F	515	126	120	HWY
46	MISSISSIPPI-UPPER	ROCK ISLAND	IL CENTENNIAL BR US 67	482.1	F	515	65	45	HWY
47	MONONGAHELA RIVER	HOMESTEAD	PA HOMESTEAD SR 837-ALLEGHENY CO	7.3	F	516	51	18	HWY
48	MISSISSIPPI-UPPER	ST LOUIS	IL EADS BR	180.0	F	517	79	42	HWY-RR
49	KENTUCKY RIVER	TYRONE	KY TYRONE KY-SOU	84.0	F	518	196	156	RR

TABLE 2 *(continued)*

SEQ	WATERWAY	CITY	ST NAME AND LOCATION OWNER	MILEPOST	TYPE	LENGTH	LW	HW	USE
50	PASSAIC RIVER	NEWARK	NJ NEWARK NJ PULASKI SKYWAY-NJ	2.0	F	520	140	135	HWY
51	SNAKE RIVER	RAPARIA	WA RAPARIA WA US 12 LYONS FERRY BR-WA	59.2	F	520		52	HWY
52	ALLEGHENY RIVER	EMLENTON	PA EMLENTON PA I 80-PA	90.6	F	521	162	140	HWY
53	CHSPKE & DLWR CANAL	CHESAPEAKE CITY	MD CHESAPEAKE CITY MD US 213-US GOVT	13.9	F	523	137	135	HWY
54	CHSPKE & DLWR CANAL	ST GEORGES	DE ST GEORGES DE US 13-US GOVT	4.5	F	523	139	135	HWY
55	ICWW ALT. ROUTE	MORGAN CITY	LA BERWICK BAY US 90-LA	0.7	F	525		73	HWY
56	LK WSHG SHP CANAL	SEATTLE	WA US 99 GEO. WASHINGTON MEMORIAL BRIDGE	2.7	F	525	74	73	HWY
57	DELAWARE RIVER	EASTON	PA EASTON PA-DEL RIVER JT TOLL BR COMM	183.7	F	526		28	HWY
58	ILLINOIS RIVER	BEARDSTOWN	IL BEARDSTOWN IL US 67 SR 100-IL	87.9	F	526	69	49	HWY
59	OHIO RIVER	METROPOLIS	IL METROPOLIS IL-PI	944.1	F	530	98	44	RR
60	MERRIMACK RIVER	TYNGSBORO	MA TYNGSBORO BRIDGE SR 3A 113	47.4	F	533		18	HWY
61	MISSOURI RIVER	ROCHEPORT	MO ROCHEPORT I 70	185.0	F	533	67	55	HWY
62	OHIO RIVER	LOUISVILLE	KY LOUISVILLE KY-JEFFERSON IN-CR	602.9	F	537	77	36	HWY
63	MISSISSIPPI-UPPER	HANNIBAL	MO MARK TWAIN BR US 36 61-MO&IL	309.2	F	546	66	57	HWY
64	OHIO RIVER	STEUBENVILLE	OH STEUBENVILLE	66.7	F	546	72	38	RR
65	DELAWARE RIVER	FLORENCE	NJ FLORENCE NJ-PA & NJ TURNPIKE COMM	121.2	F	550	141	135	HWY
66	OHIO RIVER	HUNTINGTON	WV WEST END SR 94-WV	310.7	F	550	74	29	HWY
67	HUDSON RIVER	CASTLETON	NY CASTLETON NY-NY	135.7	F	552	139	135	HWY
68	ILLINOIS RIVER	MEREDOSIA	IL MEREDOSIA SR 104-IL	71.3	F	554	72	47	HWY
69	OHIO RIVER	WHEELING	WV 9TH ST I 70-WV	90.2	F	554	76	29	HWY
70	MONONGAHELA RIVER	PITTSBURGH	PA GLENWOOD SR 885-PA	5.9	F	557	50	17	HWY
71	MISSISSIPPI-UPPER	CLINTON	IA CLINTON US 30	518.1	SUS	568	63	53	HWY
72	BERWICK BAY	MORGAN CITY	LA MORGAN CITY LA US 90-LA	17.7	F	571	73		HWY
73	MISSOURI RIVER	KANSAS CITY	MO PASEO BR US 69 71	364.8	SUS	573	69	55	HWY
74	MUSKINGUM RIVER	BEVERLY	OH BEVERLY OH-OHIO POWER CO	29.0	SUS	575	68	30	CB
75	MYSTIC RIVER	CHELSEA	MA TOBIN MEMORIAL BR	0.1	F	575	144	135	HWY
76	MISSISSIPPI-UPPER	ST LOUIS	IL POPLAR ST BR	179.2	F	580	97	55	HWY4
77	OHIO RIVER	EVANSVILLE	IN EVANSVILLE IN-HENDERSON KY US 41	786.8	F	580	84	42	HWY
78	BERWICK BAY	MORGAN CITY	LA MORGAN CITY LA US 90-LA	17.7	F	583	50		HWY
79	GIWW MGN CITY	MORGAN CITY	LA SR 75-LA LWR GRAMD RVR BAYOU SORREL	38.4	F	583		50	HWY
80	ICWW ALT. ROUTE	BAYOU SORREL	LA LOWER GRAND RIVER SR 75-LA	38.4	F	583		50	HWY
81	CHSPKE & DLWR CANAL	REEDY POINT	DE REEDY POINT DE SR 19-US GOVT	1.0	F	584		135	HWY
82	MOUNT HOPE BAY	BRISTOL	RI BRISTOL-PORTSMOUTH RI-MT HOPE BR COMM	0.0F	(SUS	585	139	135	HWY
83	NEWARK BAY	NEWARK	NJ NEWARK & BAYONNE NJ-NJ	4.0	F	585	139	135	HWY
84	CHSPKE & DLWR CANAL	CANAL	DE SUMMIT BRIDGE DE US 301-US GOVT	9.7	F	586	138	135	HWY
85	MONONGAHELA RIVER	MONESSEN	PA MONESSEN PA-PA	38.0	F	594	47	19	HWY
86	AMERICAN RIVER	SACRAMENTO	CA SACRAMENTO CA	7.1	SUS	600	39	10	FB
87	HOOD CANAL	PORT GAMBLE	WA HOOD CANAL FLTG BR CENTER SPAN	5.0	P	600			HWY
88	KOOTENAI RIVER	PORTHILL	ID PORTHILL - US GOVT	105.9	SUS	600		16	HWY
89	MISSOURI RIVER	ST CHARLES	MO ST CHARLES MO-NW	27.1	F	600	72	56	RR
90	NARRAGANSETT BAY W.	NORTH KINGSTON	RI RI-JAMESTOWN BR COMM	5.7	F	600	138	134	HWY
91	NECHES RIVER	PORT ARTHUR	TX PORT ARTHUR SR 87-TX	1.5	F	600	176	172	HWY
92	OHIO RIVER	METROPOLIS	IL METROPOLIS IL-PADUCAH KY I 24	940.8	F	600	70	15	HWY
93	OHIO RIVER	NEW ALBANY	IN NEW ALBANY I 64-KIT	607.4	F	600	98	21	HWY-RR
94	SACRAMENTO RIVER	SACRAMENTO	CA SACRAMENTO CA WATT AVE-SACRAMENTO CO	7.1	SUS	600	39	10	FB
95	SAN DIEGO BAY	SAN DIEGO	CA CORONADO BAY BRIDGE SPAN 19/20	7.8	F	600	199	195	HWY
96	ST CLAIR RIVER	PORT HURON	MI BLUEWATER BRIDGE	39.1	F	600	135		HWY
97	TOWN CREEK	CHARLESTON	SC CHARLESTON SC US 17-SC	3.0	F	600	140	135	HWY
98	TOWN CREEK	CHARLESTON	SC CHARLESTON SC US 17-SC	3.0	F	600	140	135	HWY

SOURCE: PARSONS BRINCKERHOFF

TABLE 3 ACCIDENTS IN CASTLETON-ON-HUDSON CLASS BRIDGE, 1981–1986

RECORD#	CASE	TYPE	CY	HORZ	PERIODAY WATER	MILEPOST	CAUSE	VSLNAME	USE	LENGTH	BRIDGE NAME
1	0029PAD82	F	82	500 N	02XIRO	977.7	PERRJDG	ACBL 1791	BSLD	200	CAIRO IL-ICG
2	0035PAD84	F	84	500 N	02XIRO	977.7	PFALACW	BARGE M 76	UNK	135	CAIRO IL-ICG
3	0044PAD82	F	82	500 N	02XIRO	937.3	PERRJDG	DK 107	BSLD	195	IRVIN COBB FR IL US45-KY
4	2883PHI81	VL	81	500 D	03AIRD	104.6	PCRLSNS	CERRO BOLI	BSLD	753	DELAIR NJ-CR
5	MC86001974	F	86	500 T	02XIRO	472.4	POPERER	SHE 8046	BSLD	195	CINCINNATI OH-SOU
6	0150SLM83	F	83	503 D	02XIRU	183.0	PERRJDG	LAWRENCE C	TOW	69	MERCHANTS BR - ST LOUIS
7	0283SLM83	F	83	503 N	02XIRU	183.2	PERRJDG	CAPT CARL	TOW	68	MERCHANTS BR - ST LOUIS
8	MC86004099	F	86	503 N	02XIRU	183.2	POPERER	SG 578 B	BSLD		MERCHANTS BR - ST LOUIS
9	MC86005938	F	86	515 D	13PIXN	9.8	PIMPSFP	ELGAREN	RORO	709	US 101 NORTH BEND-OR
10	0729NEW82	F	81	525 D	08GIXI	0.7	VINHRSP	NMS 1403	OIL	195	BERWICK/MORGAN US 90-LA
11	1623NEW83	F	83	525 D	08GIRQ	0.7	PERRJDG	PBR 358	OSV	178	BERWICK/MORGAN US 90-LA
12	MC85007133	F	85	530 N	02XIRO	944.0	PERRJDG	R 6317	BSLD	195	METROPOLIS IL-PI
13	0004LOU84	F	84	537 D	02XIRO	603.0	PIMPSCR	PORT OF MO	TOW	93	BIG 4 RAILROAD BRIDGE
14	0009LOU83	F	83	537 N	02XIRO	603.0	POPERER	CC 57	BSLD	195	BIG 4 RAILROAD BRIDGE
15	2659LOU81	F	81	537 D	02XIRO	603.0	POPERER	RL 1401	BSLD	195	BIG 4 RAILROAD BRIDGE
16	0144SLM82	F	82	546 D	02XIRU	309.2	POPERER	RUTH BRENT	TOW	103	MARK TWAIN MO US36/61
17	MC85007702	F	85	554 N	02XIRI	71.0	POPERER	USL 475	OIL	118	MEREDOSIA IL SR104-IL
18	MC86005626	F	86	554 N	02XIRI	71.0	POPERER	MSS 678	OIL	195	MEREDOSIA IL SR104-IL
19	0012SLM84	F	84	580 D	02XIRU	179.2	VFLDMOT	B 242	BSLD	195	POPLAR ST ST LOUIS
20	0020SLM83	F	83	580 N	02XIRU	179.0	PFALATR	MPC 70	UNK	195	POPLAR ST - MO ST LOUIS
21	0072SLM84	F	84	580 N	02XIRU	179.2	PERRJDG	BRENDA J	TOW	113	POPLAR ST ST LOUIS
22	0120SLM84	F	84	580 N	02XIRU	179.2		CC 7705B	BSLD	200	POPLAR ST ST LOUIS
23	0171SLM82	F	82	580 D	02XIRU	179.0	PFALACW	ARTHUR J D	TOW	117	POPLAR ST - MO ST LOUIS
24	0171SLM84	F	84	580 N	02XIRU	179.2	PERRJDG	CIA 170	BSLD	195	POPLAR ST ST LOUIS
25	MC84000220	F	84	580 D	02XIRU	179.0	PERRJDG	MEM 407 B	BSLD	200	POPLAR ST - MO ST LOUIS
26	0059NEW84	F	84	583 D	08GIRZ	37.5	PFALACW	AS 105	OIL	246	BAYOU SORREL SR 75-LA
27	MC87002079	F	86	585 D	09XIRMU	4.0	PLCKKNO	CYSTAL KIN	BSLD	521	NEWARK & BAYONNE NJ
28	0032PAD84	F	84	600 N	02XIRO	940.9	POPERER	ACBL 712	BSLD	200	I24-KY METROPOLIS IL
29	0120PAD83	F	83	600 N	02XIRO	941.0	PERRJDG	OR 4134	BSLD	195	METROPOLIS IL/KY I24

TABLE 4 ACCIDENTS IN TAPPAN ZEE CLASS BRIDGES, 1981–1986

Record#	CASE	TYPE	CY	HORZ	PERIODAY WATER	MILEPOST	CAUSE	VSLNAME	USE	LENGTH	BRIDGE NAME
1	MC85002672	F	85	900 D	02XIRL	838.9	PERRJDG	M 6621	BSLD	195	CARUTHERSVILLE I55-M0&TN
2	MC86006063	F	86	900 N	02XIRL	838.9	POPERER	BUNGE 56	BSLD	195	CARUTHERSVILLE I55-M0&TN
3	0013SLM84	F	84	940 T	02XIRU	180.2	PERRJDG	BILL HENRY	TOW	110	VERERANS MEM BR ST LOUIS
4	0014SLM84	F	84	940 D	02XIRU	180.2	PFALACW	USL 477	UNK	236	VERERANS MEM BR ST LOUIS
5	0047SLM82	F	82	940 D	02XIRU	180.0	PFALACW	GWG-207	OIL	264	VETERANS MEM IL US40/66
6	0071SLM84	F	84	940 D	02XIRU	180.2	PFALACW	MEM 392 L	UNK	195	VERERANS MEM BR ST LOUIS
7	0162SLM82	F	82	940 D	02XIRU	180.0	PFALACW	RUSTY FLOW	TOW	140	VETERANS MEM IL US40/66
8	0322SLM84	F	84	940 N	02XIRU	180.2	PERRJDG	ACBL 1840	BSLD	200	VERERANS MEM BR ST LOUIS
9	1696SLM81	F	81	940 N	02XIRU	180.0	PERRJDG	X-913	BSLD	195	VETERANS MEM IL US40/66
10	4513SLM81	F	81	940 N	02XIRU	180.0	POPERER	AT 191	BSLD	195	VETERANS MEM IL US40/66
11	0271SFC82	F	82	1000 D	12PIBS	0.2	POPERER	ORIENTAL H	BBLK	556	CARQUINEZ BRIDGE
12	3549NEW81	B	81	1000 D	08GIXI	3.1	PUNKNOW	JOSEPHINE	WORK	165	DANZIGER BR US 90-LA
13	0085SFC83	SUS	83	1079 D	12PIBS	8.9	PFALACW	SILETZ	UNK	198	BAY BRIDGE (D BAY)
14	2753NEW81	P	81	1250 D	08GIXN	478.5	PFALRUL	DUNCAN L H	TOW	132	PORT ALLEN CANAL SR77-LA
15	3520NEW81	B	81	1250 N	08GIXI	59.0	PERRJDG	USL 604	CHEM	236	BAYOU DULARGE BRIDGE
16	3522NEW81	SW	81	1260 N	08GIXI	134.0	PINATT	ARAPAHO	TOW	55	CYPREMORT(LOUISA)SR319LA
17	0769NEW83	SW	83	1290 D	08GIRQ	95.0	PIMPMOT	ING 581	BSLD	195	KROTZ SPRINGS LA-MP

2. The stem of the ship or the deck house hits a bridge column or other supporting structure above the pier top;
3. The stem of the ship, deck house, or cargo hits the superstructure of the bridge.

A list of 19 accidents that were cited in the study previously mentioned as being significant examples of major accident scenarios is presented in Table 5.

In addition, a major ship-bridge collision occurred in 1981 when the main tower of the 1,600–ft Newport suspension bridge in Rhode Island was struck head-on by a fully laden 45,000–ton tanker. The ship was shortened 12 ft through bow crushing, but the bridge pier suffered only superficial damage. The majority of these accidents were caused by a combination of environmental factors such as adverse weather conditions (resulting in reduced visibility or loss of control), followed by

TABLE 5 SHIP COLLISIONS AGAINST BRIDGES, 1960–1980

		Category of main cause/Impact
1960	OLD SEVERN RAILWAY, ENGLAND Ship: Two oil barges hooked up together Accident: Broadside collision with a pier Damage : Two spans fell down Cause: Tugskipper's negligence in rough weather	C/I
1963	SORSUND, NORWAY Ship: 5,000 DWT cargo boat Accident: Stem of ship hit the bridge columns above the foundations Damage: Bridge column broke Cause: Helmsman's faulty maneuver	A/II
1964	MARACAIBO, VENEZUELA Ship: 36,000 DWT tanker Accident: Broadside collision with two piers more than 2000 feet from the navigational spans Damage: Three spans fell down Cause: Failure of electrical system affecting steering gear	B/II
1964	PONTCHARTRAIN, LOUISIANA Ship: Tug towing two barges Accident: Three trestles were hit by the tug and barges Damage: Two spans fell down Cause: Helmsman's lack of attention	A/I
1967	CHESAPEAKE, VIRGINIA Ship: Coal barge Accident: Battering against the bridge deck Damage: Six spans damaged Cause: Barge torn loose in storm	C/III
1970	CHESAPEAKE, VIRGINIA Ship: 14,000 t.disp. US-navy ship Accident: 1-1/2 hours battering against the bridge Damage: Five spans knocked down and 11 others damaged Cause: Ship torn loose in the storm	C/III
1972	CHESAPEAKE, VIRGINIA Ship: Empty barge Accident: Gouging the deck and knocking down several piles Damage: Five spans damaged Cause: Towline from tug snapped in rough weather	C/III
1972	SIDNEY LANIER, GEORGIA Ship: 13,000 DWT freighter Accident: The superstructure was hit by the bow of the ship Damage: Three spans fell down Cause: The helmsman misunderstood the pilot's instructions	A/III

(continued on next page)

TABLE 5 (*continued*)

1974	PONTCHARTRAIN, LOUISIANA Ship: Tug pulling four empty barges Accident: Two supports destroyed (high piling) Damage: Three spans fell down Cause: The tug pilot fell asleep	A/I
1975	NEW WESTMINSTER, CANADA Ship: Empty barge Accident: Hit the superstructure Damage: One span fell down Cause: Barge torn loose in the storm	C/III
1975	TASMAN, AUSTRALIA Ship: 7,200 DWT bulk carrier Accident: Head-on and broadside collision with two piers Damage: Three spans fell down Cause: Loss of steering ability due to engine stop (Captain's careless navigation)	A/I
1976	PASS MANHAC, LOUISIANA Ship: Barge loaded with oyster shells Accident: An intermediate support destroyed (high piling) Damage: Three spans fell down Cause: Strong current (tug skipper's responsibility)	A/I
1977	PASSAIC, NEW JERSEY Ship: Empty oil/barge Accident: Collision with a pier Damage: Two spans fell down Cause: Broken towline to tug	C/I
1977	HOPEWELL, VIRGINIA Ship: 25,000 DWT tanker Accident: The stem of the ship destroyed a pier bent about 400 feet from the navigational span centreline Damage: Two spans fell down Cause: Fault in steering gear	B/II
1977	SAN FRANCISCO-OAKLAND, CALIFORNIA Ship: Barge-mounted marine crane towed by tug Accident: The crane hit the superstructure in side span Damage: Structural damage to the superstructure Cause: Tug skipper's careless navigation	A/III
1978	BERWICK BAY, LOUISIANA Ship: Tug pushing four barges Accident: The lead barge hit the side span bridge superstructure Damage: The 232-foot steel span fell into the water and sank Cause: Tug skipper's careless navigation	A/III
1979	VANCOUVER, CANADA Ship: 22,000 DWT bulk carrier Accident: Stem of ship hit the superstructure in side span about 300 feet from navigational span center Damage: One span fell down Cause: Captain's misjudgment of landmarks due to dense fog	C/II
1980	SUNSHINE SKYWAY, FLORIDA Ship: 35,000 DWT bulk carrier Accident:Stem of Ship hit bridge column above pier top about 800 feet from navigational channel Damage: Almost three spans fell down Cause: Pilot's careless navigation in rough weather with reduced visibility	C/II

TABLE 5 (*continued*)

1980	ALMOSUND, SWEDEN Ship: 27,000 DWT Accident: Deck house of ship hit the arch construction near the foundation on shore about 300 feet from the navigation channel Damage: Total collapse of arch span Cause: Steering difficulties in rough weather due to reduced engine power in dense fog	C/II

Note:		
	A	Human Error
	B	Mechanical Failure
	C	Environmental Conditions
	I	Hull of ship hits bridge pier
	II	Stem of ship or deck house hits bridge column
	III	Stem of ship, deck house, or cargo hit superstructure

Source: COWIconsult, "Ship Collision Risk Assessment," Sept. 1981

human errors in judgment in conjunction with mechanical failures. These factors result in varying degrees of vessel aberrancy. Vessels then run aground or are involved in collisions or rammings. For example, in a river of high traffic density or reduced visibility caused by foul weather, a vessel may enter the domain of another vessel, increasing the probability of panic maneuvers, so that a vessel, in trying to avoid another, may collide with a bridge pier.

Other factors that contribute to the probability of occurrence of a ship-bridge accident include the geometry of the waterway, its depth, the location of bridge piers, span clearances, angle of rudder at time of failure, and the size, width, length, draft, shape, and velocity of vessels. In addition, daytime and nighttime conditions, reduced visibility, and poor navigational aids affect vessel navigation. It is, however, the draft of a ship that determines whether it runs aground or reaches the bridge if it deviates off course from the navigational channel; that is, becomes aberrant. A ship in ballast has a variable draft determined by the master of the ship according to many factors. These include weather conditions, air draft constraints, depth of the waterway, and duration of the journey. The faster a ship in ballast travels, the more stable it is. However, its impact in a collision increases when moving at greater speeds. Fully loaded ships have drafts that are dictated by the load line rules. Such information on the vessel can be found in *Lloyd's Register of Ships* (*3*). The rate of aberrancy has been reported to be two to three times greater for barges than that measured for ships on the same waterway.

ENVIRONMENTAL RISK FACTORS: Castleton-on-Hudson and Tappan Zee Bridges

The environmental risk parameters affecting the Tappan Zee and Castleton-on-Hudson Bridges are examined in the following section.

Geometrical Conditions

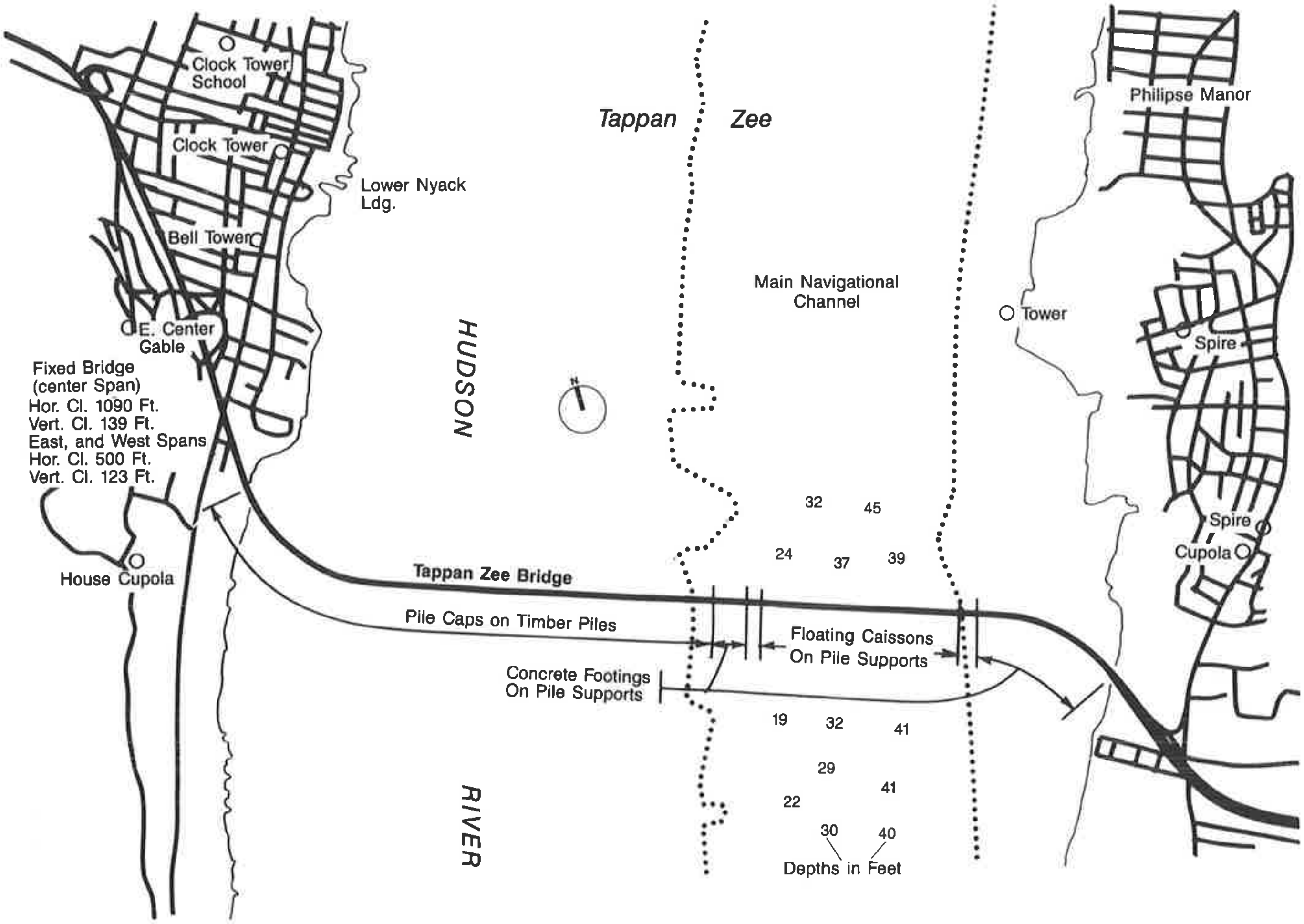
The Tappan Zee Bridge is located at milepost 23.5 on the Hudson River and crosses from South Nyack to Tarrytown. Its fixed main span has a horizontal clearance of 1,098 ft and a vertical clearance of 139 ft at mean high water. There are three navigational channels designated for passing beneath the bridge. The controlling depth is approximately 32 ft. Ships generally use only the center channel, whereas barges may also travel the east and west passes.

The Tappan Zee Bridge is about 3 mi long, with 188 bents located in the river. There are three types of foundations used to support the bents. The locations along the bridge of the different kinds of foundations are shown in Figure 1. The western portion of the bridge is made up of rigid-frame reinforced concrete bents on timber piles. The bents are spaced 50 ft apart. The pile caps are typically 91 ft long and 4 ft deep, ranging in width from 11 to 19 ft. At the north end of each pile cap there is an ice breaker structure, and on the south is a pile cluster. Along the eastern portion and a section about midriver west of the navigational channels, the bridge is supported on 12 bents that have two pier shafts, each supported on a solid circular concrete footing with steel H-piles.

Across the three navigational channels and at four bents to the west, the bridge is supported by eight floating caissons on piles. Cylinder piles are used under the caissons supporting the 1,200-ft main span. H-piles were used for the two 500-ft flanking spans and the four caissons to the west spaced 250 ft apart. At the upriver side there are ice breakers. A fendering system encompasses the rest of the structure.

The Castleton-on-Hudson Bridge is located at milepost 135.7 on the Hudson River. It has a fixed main span with a horizontal clearance of 552 ft and a vertical clearance of 135 ft at mean high water. There is one navigational channel designated for passing beneath the bridge. Controlling depth of the channel is also about 32 ft. A location plan is shown in Figure 2.

At Castleton-on-Hudson only two of the 42 bridge piers are located in the Hudson River. One of the piers is in shallow water near the east side and the other is near the middle of the river. The midriver pier, along with another pier located at the west shoreline 600 ft away, supports the main span across the 360–ft channel. The foundations for these bridge piers are massive concrete placed down to rock. About 350 ft downriver there is a railroad bridge. The bridge piers of



Source: NOAA, NOS Nautical Chart 12343

Scale: 1:20,000

FIGURE 1 Tappan Zee Bridge location plan.

the railroad bridge are similar in size and position within the river.

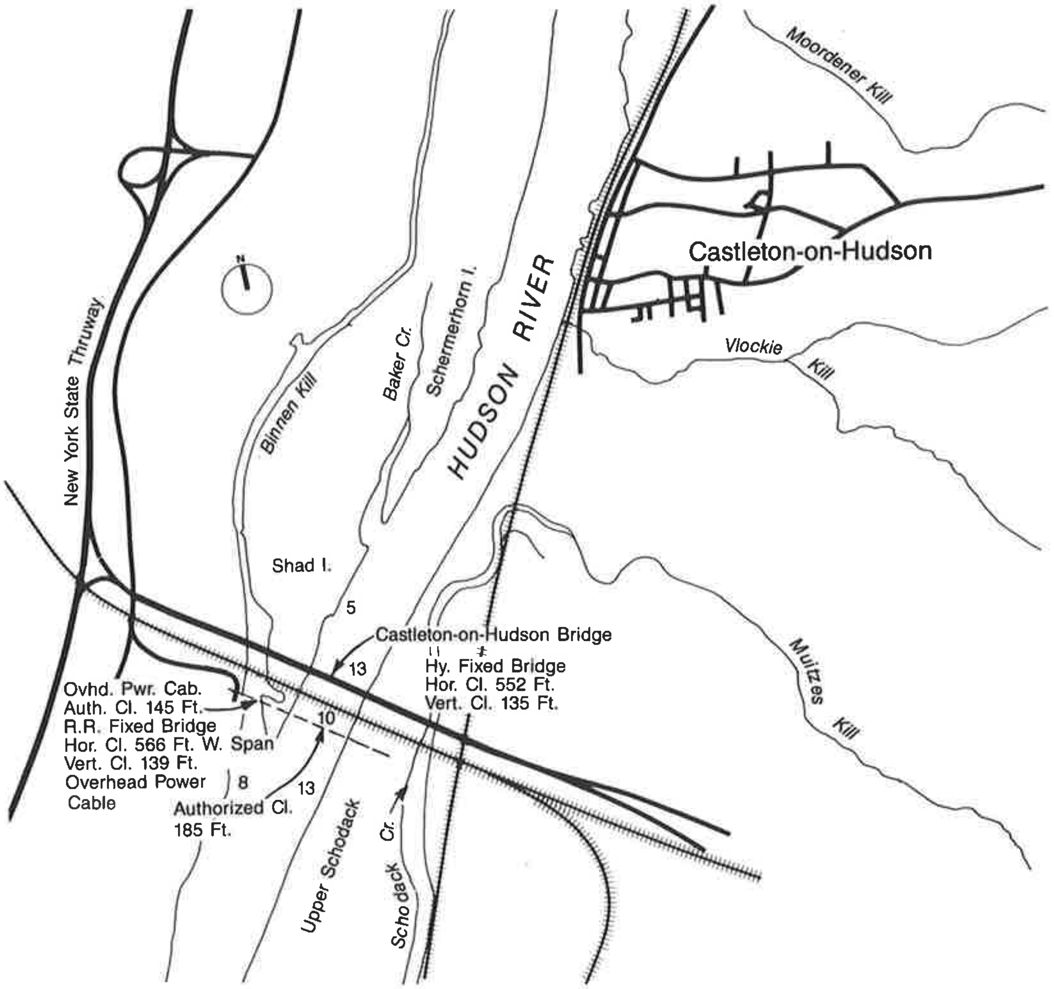
Thus the foundations of the two bridges are significantly different. The Castleton-on-Hudson Bridge has a stronger type of foundation, whereas the Tappan Zee Bridge's foundation is more vulnerable.

Navigational Conditions

The following information on navigational conditions comes from the *U.S. Coast Pilot*, Vol. 1 (*6*):

> Navigation along the Hudson as far north as Kingston is easy; above Kingston numerous steep-to shoals and middle grounds make navigation trickier. Tides in the Hudson River are affected by freshets, winds, and droughts. The mean range of tide is 4.5 ft at The Battery, 3.7 ft at Yonkers, 2.8 ft at Newburgh, 3.1 ft at Poughkeepsie, 3.7 ft at Kingston, 4.6 ft at Albany, and 4.7 ft at Troy. The velocities of currents are 1.4 knots flood and 1.4 knots ebb northwest of The Battery, 1.6 and 2.2 knots at the George Washington Bridge, 0.9 and 1.1 knots at Newburgh, 1.1 and 1.2 knots at Poughkeepsie, 1.3 and 1.6 knots at Kingston, and 0.3 knot flood and 0.8 knot ebb at Albany. In even extremely severe winters, Coast Guard icebreakers and continuous river traffic maintain an open channel to Albany. The ice season usually starts in early January and ends in mid-March.
>
> Normally shipping is affected most seriously in the Hudson River between Tappan Zee and Albany. Modern vessels experience little difficulty maneuvering through the ice, but may be slowed by other river traffic. In addition to the problem of getting through the ice, aids to navigation are covered or dragged off station by moving ice.

According to comments by the Hudson River Pilots Association (HRPA), navigation at the Castleton is considered more difficult than it is at the Tappan Zee because ships must maneuver to begin the turn just north of the bridge. Also the channel is narrower at Castleton. HRPA noted that none of the bridges crossing the river has radar reflectors or radar markers, the use of which could be helpful during times of reduced visibility.



Source: NOAA, NOS Nautical Chart 12348
Scale: 1:20,000
Depths in Feet

FIGURE 2 Castleton-on-Hudson Bridge location plan.

Weather Conditions

The following information on weather conditions is obtained from USACE, the Port of Albany, and ports on the Hudson River, New York 1984 (*7*).

> The climate at Albany and the lower Hudson River Valley is primarily continental in character, but is subject to some modification from the maritime climate which prevails in the extreme southeastern portion of New York State. The moderating effect on temperatures is more pronounced during the warmer months than in the cold winter season when outbursts of cold air sweep down from Canada with greater vigor than at other times of the year. In the warmer portion of the year temperatures rise rapidly during the daytime to moderate levels. As a rule, temperatures fall rapidly after sunset so that the nights are relatively cool.
>
> Winters are usually cold and occasionally fairly severe. Maximum temperatures during the colder winter months often are below freezing, and nighttime low temperatures frequently drop to 10 degrees or lower. Sub-zero temperatures occur rather infrequently, about a dozen times a year. Snowfall in the area is quite variable and over some of the higher nearby areas ranges up to 75 inches or more for a season. Snow flurries are quite frequent during the cold months.
>
> Precipitation is sufficient to serve the economy of the region in most years, and only occasionally do periods of drought become a threat. A considerable portion of the rainfall in the warmer months is from showers associated with thunderstorms, but hail is not usually of any consequence.
>
> On the whole, wind velocities are moderate. The north-south Hudson River Valley has had a marked effect on the lighter winds, and the warm months usually average out as a south wind. Destructive winds occur infrequently.
>
> The area enjoys one of the highest percentages of sunshine that can be found in the State. This is true of the Hudson Valley area from Albany southward to the coast with slightly more sunshine progressively southward. Seldom does the area experience extended periods of cloudy days or extended periods of smog. Occasionally during the warm months there are short periods when high humidity associated with temperatures above 85 degrees is rather uncomfortable. Tornadoes are rather rare in the Albany area; six have been reported since 1826. The days of heavy fog average twenty-three a year.

Although climate and currents do not seem to offer any major obstacles to navigation, the occasional fog or storm resulting in reduced visibility has, at least in part, brought about an accident and an oil spill on the Hudson at the Tappan Zee. In addition, the HRPA indicated that transverse winds from the west can sometimes cause difficulty with navigation around Tappan Zee. Weather conditions are continuously reported on radio by the National Oceanic and Atmospheric Administration for the upper and lower Hudson areas.

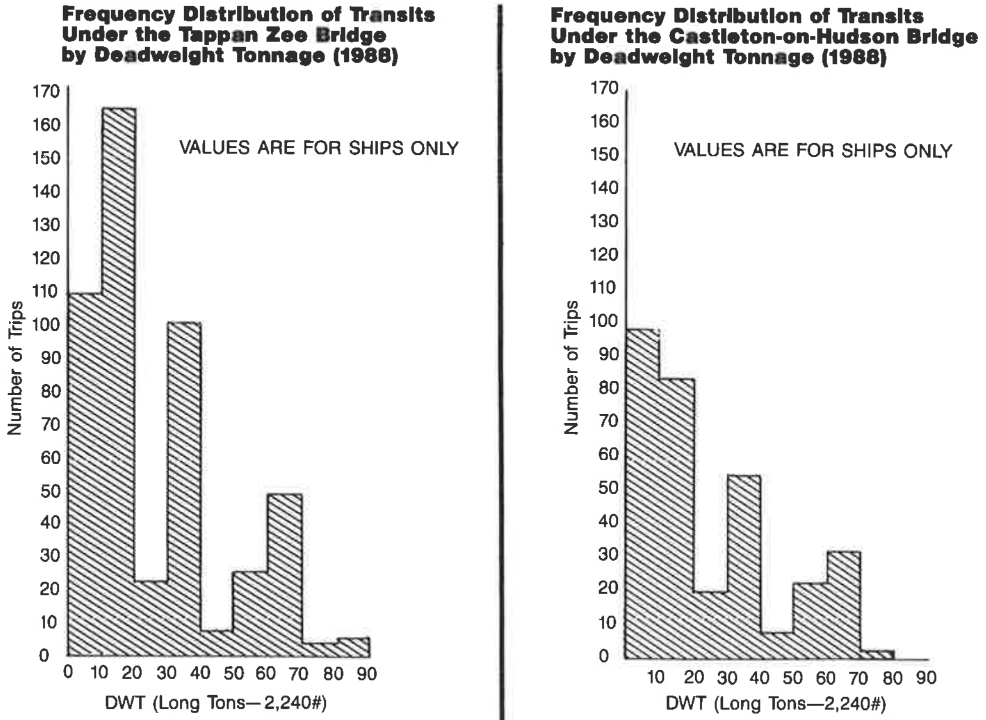
Vessel Types and Traffic Load

Piloted ships and barges propelled by tugs are the two basic types of maritime traffic navigating the Hudson River. Data on ship movements obtained from the Maritime Association of the Port of New York and New Jersey indicate that about 125 ships travel annually upriver under the Tappan Zee Bridge to call at ports along the Hudson. Approximately 100 of these ships travel to the Port of Albany, passing also beneath the Castleton-on-Hudson Bridge.

Many of the ships that are listed make more than one call at a particular port along the river during the year. In 1988, almost half of the ships returned within the calendar year on several occasions, and one bulk carrier was recorded as having made 18 trips. A review of the information on stopovers shows that the vessels travel to a single destination on the river. As ships do not exit via the canal system, each call on a river port generally represents two transits (upriver and downriver) beneath any bridge passed. The vessels travel at speeds ranging from 8 to 12 knots.

According to the Maritime Association of the Port of New York and New Jersey, about 328 and 488 total ship transits were made in 1988 by ships passing the Castleton-on-Hudson and Tappan Zee Bridges, respectively. These numbers represent the relative exposure of the bridges to potential ship collisions. The deadweight tonnage frequency distribution in Figure 3 shows that many of the ships are in the 50,000 to 70,000 tonnage range, or are less than 20,000 tons. Tankers are the heaviest vessels that transit the Hudson.

The Towboat and Harbor Carriers Association of New York and New Jersey has identified more than 30 companies that offer towing or barge services, or both, for the Hudson River.



Frequency Distribution of Transits Under the Tappan Zee Bridge by Deadweight Tonnage (1988)

Frequency Distribution of Transits Under the Castleton-on-Hudson Bridge by Deadweight Tonnage (1988)

Range	Trips
0<10	108
10<20	164
20<30	22
30<40	100
40<50	8
50<60	26
60<70	50
70<80	4
80<90	6
Total	488

Source:
Maritime Association of the Port of New York and New Jersey

Range	Trips
0<10	100
10<20	86
20<30	20
30<40	58
40<50	8
50<60	22
60<70	32
70<80	2
80<90	—
Total	328

Source:
Maritime Association of the Port of New York and New Jersey

FIGURE 3 Frequency distribution of transits.

Unlike ships, which are subject to compulsory pilotage, barge movements are not routinely monitored by a central agency. General information on barge traffic and operation on the Hudson was obtained primarily through telephone interviews. The U.S. Army Corps of Engineers' statistics on waterborne commerce in the United States are a limited source of assumptions on barge traffic information. The HRPA and the barge operators confirmed a ratio of 1 to 8 for traffic volume between ships and barges on the Hudson River, indicating total vessel transits of 3,000 annually. However, the USACE's *Waterborne Commerce of the United States* (*1*) indicates an estimated average annual total number of transits of 4,500 on the Hudson River.

For the purposes of this study, barges were categorized as either oil or traprock types. Tank (oil) barges are used to deliver oil to terminals on the Hudson River as far north as Albany. These barges vary in size from 9,000 to 25,000 DWT (approximately 25,000- to 70,000-barrel capacity). The drafts of these barges when loaded range from 10 to 30 ft. Tank barges are generally pushed one at a time at speeds of 6 to 9 knots. Barges do not require pilots under the Compulsory Pilotage Regulation, as there is an exclusion for barges below a gross weight tonnage of 10,000 GWT (about 180,000-barrel capacity). As shown in Table 6, all barge traffic on the Hudson River does not require pilots.

There are two barge operators on the river dealing in traprock. Unlike oil barges, sand and rock barges do not vary in size or capacity. They generally have a 1,200–ton capacity. Loaded barges are moved downstream in fleets of 8 to 15 barges/trip at about 5 knots. Empty barges are brought upriver in a similar fashion at approximately 8 knots. The quarries are located south of Castleton; consequently, only the Tappan Zee Bridge is subject to such traffic. These barge operations are seasonal and take place from April through December. Earlier trips in the spring are contingent on temperature and ice conditions. Each barge flotilla makes an average of five trips downstream per week.

Vessel Impact Force

Although the size of vessels navigating the Hudson is limited by the depth of the channel, it should be noted that the larger the vessel (in terms of its weight) and the faster it sails, the greater the collision impact. For example, a vessel of 5,000 DWT traveling at a design speed of 16 knots can produce an impact force of about 7,100 tons based on the method of estimation by Woisin and Gerlach (*8*). Most of the ships traveling on the Hudson have design speeds in excess of 15 knots. A vessel of 40,000 DWT traveling at a speed of 12 knots can

TABLE 6 TYPICAL BARGE SIZES ON HUDSON RIVER

OIL BARGES

Dimensions (Feet)	Capacity/Approx. DWT (Barrels/Long Tons)
240x43x14	20,000 / 3,500
330x39x15.5	30,000 / 5,700
330x56x21.5	57,000 / 10,300
300x64x21.5	60,000 / 11,700
320x64x23	68,000 / 13,400
230x52x24	41,000 / 8,200
295x45x16	25,000 / 6,000
316x60x24	65,000 / 13,000
302x90x24	85,000 / 17,000
316x60x24	70,000 / 13,000
446x74x30	140,000 / 28,000

Average DWT = 11,800 Tons

SAND & STONE BARGES

Dimensions (Feet)	Approx. DWT (Long Tons)	
120x40x12	1,100	
130x40x12	1,200	
130x36x18	1,300	(1500 Max)

Average DWT = 1,200 Tons

Source: Telephone Interviews with Local Marine Transporters result in a collision impact of 12,000 tons. Impacts can vary from a mere glancing of the piers to a full head-on collision, with their energy increasing exponentially with ship speed. Ships in light ballast are considered the most dangerous vessels under these circumstances. Having considerable impact force, they are a danger to bridge piers, and because they also float high in the water are equally a danger to the bridge superstructure. Small vessels and barges generally travel at slower speeds. Wind affects empty barges particularly, impairing their directional stability. Barges, being the most weakly constructed vessels, have significantly lower impact forces than most other vessels. The kinetic energy of a ship is a function of its effective mass and the velocity at which it travels. In a collision, this energy is absorbed through the crushing of the ship and the deformation and displacement of the pier, the pier fenders (if they exist), and then the water resistance. If a ship strikes a pier at an angle, a considerable amount of the energy is dissipated through the rotation and displacement of the ship off its original course. In a head-on collision, the ship's center of gravity is not shifted and maximum impact is encountered by either the ship or the pier. (The exact prediction of deformational consequences is extremely complex and beyond the scope of this paper.) Bridge pier strengths vary greatly among bridges and even among piers of the same bridge. The latter case is illustrated by the various types of foundations used to support the numerous spans of the Tappan Zee Bridge.

To redesign a bridge pier to increase its ability to withstand such vessel impact forces would be prohibitively expensive. Hence, reasonable protective systems should be provided while accepting a certain level of risk. (There are several categories of risk: owner's, bridge user's, and third party. Third party risk refers to the risk to ships and persons on ships caused by collision with a bridge.) The next section presents the assessment by this study of the levels of risk that each of the two bridges faces.

RISK ASSESSMENT

The results of the data search and analysis are presented in Table 7. The accuracy of these numbers is directly related to the accuracy of the available data. The estimated average annual vessel transits per class of bridges was based on traffic activity for self-propelled vessels at each reach of the related river (*1*). The estimated annual Hudson River vessel transits per bridge are given for Tappan Zee and Castleton-on-Hudson bridges as adjusted values, taking into account traffic information received from the USACE Waterborne Commerce Statistics Center, the Maritime Association of the Port of New York and New Jersey, and the Hudson River Pilots Association.

The return periods were calculated to be 55 years and 268 years, respectively, for the Tappan Zee and Castleton-on-Hudson Bridges. For example, in the Tappan Zee class, there are 41 bridges ranging from 900 to 1,300 ft in horizontal clearance in the United States. Within this class of bridges, there were 17 ship-bridge accidents from 1981 to 1986, inclusive. The total number of vessel transits beneath all 41 bridges from 1981 to 1986 was 4,222,920. Therefore, the accident rate (PC) was $17/4{,}222{,}920 = 0.000004$. This is the probability or chance that any one vessel that transits beneath a bridge in the Tappan Zee class has an accident at the bridge. Because the estimated annual number of vessel transits on the Hudson that pass beneath the Tappan Zee Bridge is $N = 4{,}500$, the annual probability or chance of an accident occurring at the Tappan Zee Bridge or ($N \times$ PC) is 0.0181. Recalling the first equation, the return period is then 55 years. It should be noted that the estimated annual transits may overstate the actual number of transits, as that reflects traffic on a reach; thus the return periods may be lower. The Tappan Zee has a higher risk of an accident, and both of the return periods are small compared with the Scandinavian risk-acceptance standard of 10,000 years. The orders of magnitude indicate

TABLE 7 RESULTS OF STUDY DATA SEARCH AND ANALYSIS

Period of study: 1981-1986	Castleton-on-Hudson	Tappan Zee
Horizontal Clearances	552 feet	1098 feet
Class of Horizontal spans	500-600 feet	900-1300 feet
Number of Bridges in Class	98	41
Number of Accidents per Class	29	17
Estimated Average Annual Vessel Transits per Class	1,947,236	703,820
Estimated Total Vessel Transits per Class	11,683,416	4,222,920
Estimated Annual Hudson River Vessel Transits per Bridge	1,500	4,500
Probability of Occurrence of Vessel Accidents	0.0037	0.0181
Return period for Vessels	268 years	55 years

Source: Parsons Brinckerhoff

the possibility of ship-bridge accidents at these two bridges and warn of the dangers that could occur in the event of such an accident on the Hudson.

Although the Tappan Zee Bridge crosses a straight part of the Hudson, its exposure to collisions by maritime vessels is enhanced by the increased length and number of piers required by the width of the river. The major or catastrophic events following impacts by a large vessel are of concern in the case of the occurrence of the following situations:

Scenario 1: A ship striking a floating caisson-type foundation, breaching the watertight buoyancy chambers.

Scenario 2: A ship striking either the superstructure or the pier shaft supports for the span.

Under the present conditions, the floating caissons on pile supports lack adequate protection from the large vessels. Hudson River traffic data indicate that a large majority of the vessels have hull designs that include bulbous bows. Although the mass concrete ice-breaker structure at the north of the caisson might deflect an aberrant vessel, the pile clusters and fendering system do not have sufficient energy-absorbing capacity or strength to prevent impact. In the event of damage to the caisson, the caisson may lose its buoyancy and overstress the pile supports, causing catastrophic failure of the bridge. The threat of such severe damage exists for large ships in ballast as well as ships fully loaded because the caissons are located in the deeper waters within the navigational channel.

Another problem with collisions by the heavier vessels with the caissons arises because the buoyant structure cannot develop sufficient frictional forces along its base at the river bottom and there are no batter piles to transfer lateral loads. Large horizontal loads might cause lateral displacements affecting the integrity of the superstructure. Hence, some of the larger oil tanker barges could disrupt the deep-water foundations.

A ship accident as described in Scenario 2 can happen almost anywhere along the length of the bridge. As shown in Figure 1, minimum water depths along the alignment at mean low water are generally better than 6 ft. Because mean high water is about 3 ft more, aberrant vessels with drafts up to 9 ft would collide with most places along the bridge. A typical vessel in the 16,000 DOT class transiting in ballast has a minimum draft of about 9 ft. However, to avoid air draft problems with the bridges, the larger vessels take on substantial ballast. According to the Hudson River Pilots Association, the ballasted vessels have bow drafts of 10 to 15 ft and stem drafts ranging 20 to 28 ft.

Unlike the Tappan Zee, the Castleton-on-Hudson Bridge does not have extensive physical exposure. Besides crossing a narrower stretch of river, the bridge piers are shielded on the downstream side by the supports of the adjacent railroad bridge.

The span over the entire crossing at the Castleton-on-Hudson Bridge remains high, providing a vertical clearance of 135 ft, and therefore an aberrant vessel primarily represents a threat only for collisions with the substructure. Considering the massiveness of the footings founded on rock, it appears that the smaller vessels might cause damage but would not cause catastrophic failures. The fendering system for the mid-river pier is suitable for dealing with smaller vessels should there be a mishap. The maximum depth of water around the piers varies from about 10 to 21 ft. Larger vessels traveling light or in ballast could stray from the channel and reach the bridge piers. It is these vessels that are a concern for risk and would require protective structures at the Castleton-on-Hudson Bridge.

It should be noted that the risk of oil spills resulting from vessel-bridge collisions is always there, whether a bridge pier or structure is damaged or not.

CONCLUSION

In conclusion, this study has found that the vessel traffic density is fairly low on the Hudson River and that navigational conditions are generally good. The climate and river currents do not pose any serious obstacles to safe navigation.

Risk of a ship-bridge collision at the Tappan Zee and Castleton Bridges on the Hudson River were analyzed in this study. The return period for the Tappan Zee Bridge was 55 years. The return period for the Castleton-on-Hudson Bridge was 268 years. The results serve merely as indicators for precautionary measures. As indicated in the section on risk assessment in this paper, the disasters that could occur at the Tappan Zee Bridge in particular would result in significant consequences. For example, damage to any of the hollow caissons of the main piers would lead to the probable collapse of the pier and, consequently, to the superstructure. The other smaller piers of the Tappan Zee Bridge are also highly vulnerable to relatively large aberrant vessels in light ballast, as the water depths allow for their passage without running aground. Given the relatively small return periods for the Tappan Zee Bridge, it is recommended in this study that further studies be undertaken to find appropriate measures to reduce the risk and severity of a ship-bridge collision. One of the piers of the Castleton-on-Hudson Bridge is particularly vulnerable, although it is relatively sturdy in comparison to the main piers of the Tappan Zee Bridge. It requires protection against large vessels. It is noted that 85 percent of all ship-bridge accidents in the United States between 1981 and 1986 resulted from pilot navigational error. It is recommended that preventive measures such as improved navigational aids be considered in addition to structural solutions.

ACKNOWLEDGMENTS

The permission of the New York State Thruway Authority to present and publish this paper is gratefully appreciated. The authors acknowledge the kind assistance provided by the Marine Safety Evaluation Branch of the U.S. Coast Guard and particularly thank T.W. Purtell and Thomas Pettin, together with William C. Heming of the First Coast Guard District Office, and Joyce McIlroy, Marine Intelligence, Maritime Association of the Port of New York. The authors wish to personally thank Waisum Alain To for his help with the data base system, and David Atkin, Jim Brown, Tom Kuesel, and Mike Abrahams for their frank and timely reviews of the text of the paper.

REFERENCES

1. *Waterborne Commerce of the United States*, Parts I–V. U.S. Army Corps of Engineers, 1981–1986.
2. *Bridges Over the Navigable Waters of the United States*. Atlantic, Pacific, Great Lakes, Gulf Coast, and Mississippi River System Volumes, U.S. Coast Guard, 1984.
3. *Lloyd's Register of Shipping*. New York, 1988.
4. *Tappan Zee and Castleton-on-Hudson Bridges, Hudson River: Ship Impact Risk Analysis*. Parsons Brinckerhoff Quade & Douglas, New York, Oct. 1989.
5. *Sunshine Skyway Bridge: Ship Collision Risk Assessment*. COWIconsult, Tampa, Fla., Sept. 1981.
6. *United States Coast Pilot*. Vol. 1, Atlantic Coast: Cape Cod to Sandy Hook. National Oceanic and Atmospheric Administration, 1988.
7. *The Port of Albany and Ports on the Hudson River*. Port Series No. 6, U.S. Army Corps of Engineers, Revised 1984.
8. G. Woisin and W. Gerlach. *On the Estimation of Forces Developed in Collisions Between Ships and Offshore Lighthouses*. IALA Conference, Stockholm, Sweden, 1970.

Publication of this paper sponsored by Committee on Ports and Waterways.