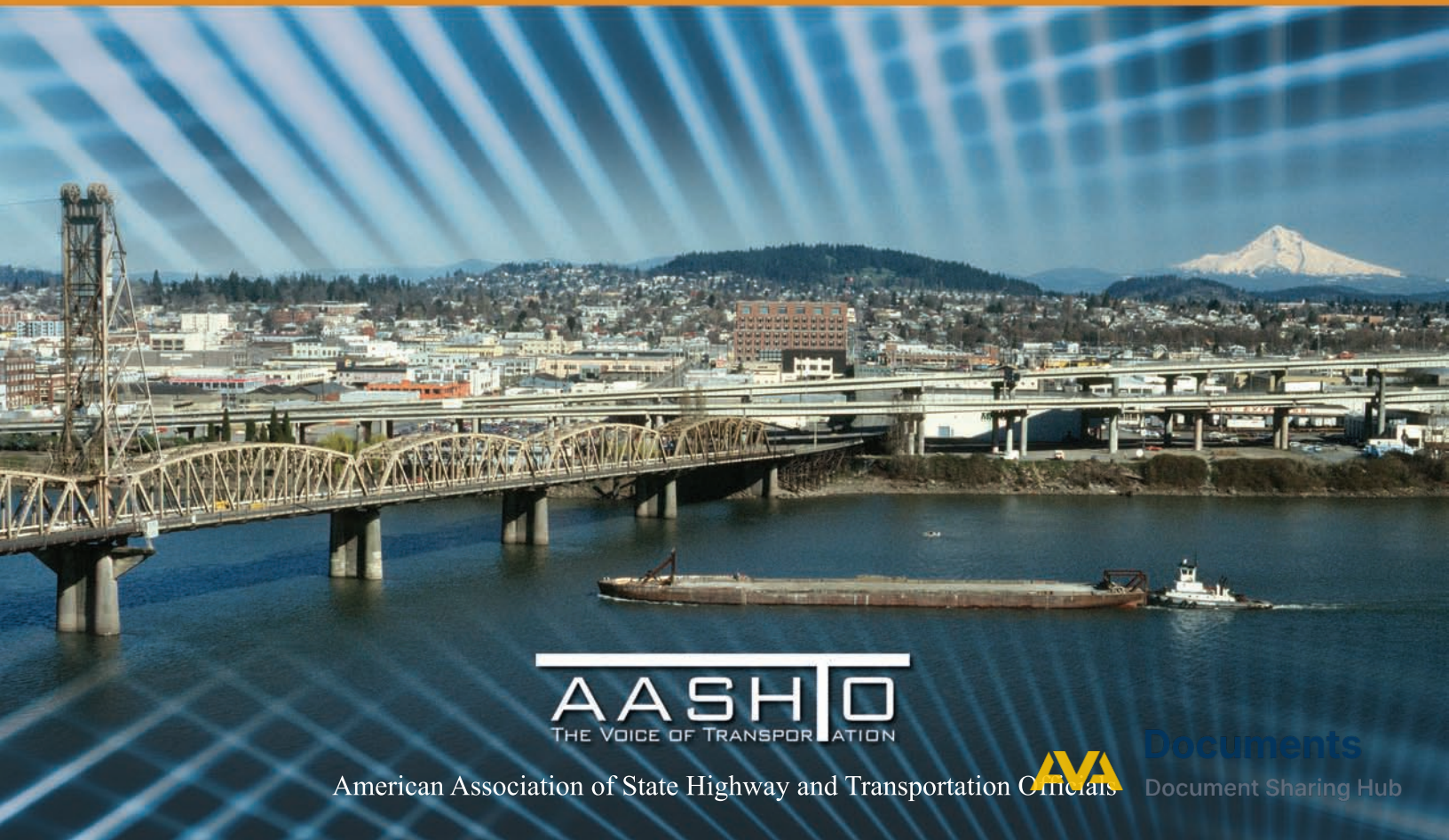




Guide Specifications and Commentary for

Vessel Collision Design of Highway Bridges

Second Edition, 2009



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American Association of State Highway and Transportation Officials



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FOREWORD

The 1980 collapse of the Sunshine Skyway Bridge was a major turning point in awareness and increased concern about vessel collision and the safety of bridges crossing navigable waterways in the United States. Studies initiated as a result of this tragedy led to the 1988 pooled-fund research project sponsored by 11 states and the Federal Highway Administration (FHWA) which developed a proposed design code for use by bridge engineers in evaluating structures for vessel collision. This effort culminated in 1991 with the adoption by the American Association of State Highway and Transportation Officials (AASHTO) of the *Guide Specification and Commentary for Vessel Collision Design of Highway Bridges* (AASHTO, 1991).

The 1991 AASHTO Guide Specification established design provisions for bridges crossing navigable waterways to minimize their susceptibility to damage from vessel collisions. The provisions applied to both new bridges and to the analysis of existing bridges to determine vulnerability and potential retrofit. The intent of the AASHTO provisions is to provide bridge components with a “reasonable” resistance capacity against ship and barge collisions. In navigable waterway areas where collision by merchant vessels may be anticipated, the Guide Specification requires that bridge structures be designed to prevent collapse of the superstructure by considering the size and type of vessel fleet navigating the channel, available water depth, vessel speed, structure response, the risk of collision, and the operational classification of the bridge.

This Second Edition of the Guide Specification was developed to incorporate lessons learned from the use of the original 1991 Vessel Collision Guide Specification; incorporate the current LRFD Bridge Design methodology; clarify some of the risk procedure elements; make minor modifications and corrections; and discuss, and incorporate where deemed necessary, results from barge and ship collision research conducted since the original vessel collision publication. The use of the Guide Specification procedures to evaluate existing bridges has been highlighted in this revised edition, and a new worked example illustrating the vessel collision risk assessment procedures has been provided.

Compared to more mature and established fields such as wind and earthquake engineering, vessel collision design is in its infancy stages. Although there are a number of important research needs within the discipline, the key areas of ship impact forces; barge impact forces; risk acceptance criteria; physical protection systems; and aids-to-navigation improvements should be highlighted as areas of future research.

This Second Edition was prepared by the consulting firm of Moffatt and Nichol. The principal author was Michael A. Knott, P.E. (who was also the principal author of the original 1991 Guide Specification). Moffatt and Nichol provided their services under contract to HDR Engineering on behalf of the Federal Highway Administration (FHWA).

INTRODUCTION

1.1 PURPOSE

In navigable waterway areas, where vessel collision by merchant ships and barges may be anticipated, bridge structures shall be designed to prevent collapse of the superstructure by considering the size and type of the vessel, available water depth, vessel speed, and structure response. The requirements apply to all bridge types which cross a navigable shallow draft inland waterway or canal with barge traffic, and deep draft waterways with large merchant ships. The provisions are for normal merchant steel-hulled vessels (ships and barges) and are not applicable for waterways whose maritime traffic consists of recreational or other special vessels constructed of wood or fiberglass.

The intent of the vessel collision requirements is to establish analysis and design provisions to minimize bridge susceptibility to catastrophic collapse. The purpose of the provisions is to provide predictable design vessel collision effects in order to proportion bridge components with a reasonable resistance to collapse. The provisions apply to bridges crossing navigable waterways which carry waterborne commerce as established by federal and state agencies. Judgment should be used when applying the criteria to waterways in which no defined navigation channel exists and no commercial maritime traffic can be reasonably anticipated.

Bridges over a navigable waterway meeting the criteria above, whether existing or under design, should be evaluated as to vulnerability to vessel collision in order to determine prudent protective measures. The recommendations listed below summarize the essential elements which should be addressed in developing a program for evaluating bridges and providing pier protection for vessel collision.

1.1.1 Interdisciplinary Team

Vessel collision evaluations of new and existing bridges should be conducted by an interdisciplinary team comprised of structural, geotechnical, and hydraulic engineers. In special cases where benefit/cost analysis of risk reduction is required, an economic specialist should also be part of the team. Representatives and coordination with the U.S. Coast Guard, the Army Corps of Engineers, and other federal and state agencies as appropriate for the bridge location should also be included in the interdisciplinary evaluation.

1.1.2 New Bridges

Vessel collision evaluations of new bridges over navigable waterways should be conducted in accordance with this Guide Specification.

The AASHTO Guide Specifications contain three alternative analysis methods for determining the design vessel for each bridge component in the structure in accordance with two-tiered risk acceptance criteria. Method I is a simple to use semi-deterministic procedure; Method II is a detailed risk analysis procedure; and Method III is a cost-effectiveness of risk reduction procedure (based on a classical benefit/cost analysis). The Guide Specifications require the use of Method II risk analysis for all bridges unless special circumstances exist as described in the code for the use of Methods I and III. Special circumstances for using Method I include shallow draft waterways where the marine traffic consists almost exclusively of barges, and for using Method III include very wide waterways with many piers exposed to collision, as well as existing bridges to be retrofitted.

1.1.3 Existing Bridges

Unless an existing bridge was designed in accordance with the previous 1991 edition of the AASHTO Vessel Collision Specifications, all remaining existing bridges over navigable waterways with commercial barge and ship traffic should be evaluated using a vulnerability assessment in accordance with the Method II risk analysis procedures contained in this current guide specifications. The vulnerability assessments would meet NTSB recommendations to AASHTO, FHWA and other federal agencies for improved bridge safety based on previous vessel collision accidents involving bridge failures.

Based on the vulnerability assessment evaluations of existing bridges within the state system, a screening process based on the estimated annual frequency of collapse can be used to identify and rank high risk bridges, and to prioritize vulnerable structures for potential rehabilitation, retrofit, pier protection countermeasures, or replacement.

AASHTO recognizes the potential that a significant portion of older bridges crossing navigable waterways in the Nation may not meet the risk acceptance criteria for new bridges contained in the AASHTO Specifications adopted since 1991. The intent of performing vessel collision vulnerability assessments on the existing bridge system is to identify those structures that are particularly vulnerable to catastrophic collapse. The vessel collision vulnerability information would provide a framework for States to be aware of high-risk safety needs requiring immediate or short-term action, as well as information to prioritize and budget for the long-term needs for bridge rehabilitation or replacement. The risk assessment of the existing bridges will be used as a part of the prioritization process and allocation of federal funds.

AASHTO recognizes that the cost of retrofitting the potentially large number of existing bridges over navigable waterways to meet the risk acceptance criteria for new bridges may not be realistic based on current

budget constraints of most State DOTs. However, the vulnerability assessments will allow States to identify those structures that are particularly high risk and vulnerable to catastrophic collapse due to vessel collision. Federal funding may require that such high-risk bridges receive priority treatment by State DOTs with options for retrofitting, rehabilitation, installation of pier protection system countermeasures, or replacement.

1.2 BACKGROUND

Ship and barge collisions with bridges that are located in coastal areas and along inland waterways represent a growing and serious threat to public safety, port operations, motorist traffic patterns, and environmental protection in many cities throughout the world. In the 42-year period from 1960 to 2002, there have been 31 major bridge collapses worldwide due to ship or barge collision, with a total loss of life of 342 people.

Seventeen of the bridge catastrophes discussed above occurred in the United States, including the 1980 collapse of the Sunshine Skyway Bridge crossing in Tampa Bay, Florida, in which 1,300 feet of the main span collapsed and 35 lives were lost as a result of the collision by an empty 35,000-DWT (deadweight tonnage) bulk carrier.

Recent bridge collapses in the United States include the Queen Isabella Bridge connecting San Padre Island to the Texas mainland, which was hit by a barge in September 2001 (8 fatalities); and the collapse of the I-40 Bridge over the Arkansas River near Webber Falls, Oklahoma, which was hit by a barge in May 2002 (13 fatalities).

It should be noted that there are numerous vessel collision accidents with bridges which cause damage that varies from very minor to significant damage, but do not necessarily result in collapse of the structure or loss of life. A recent U.S. Coast Guard study (May 2003) of towing vessels and barge collisions with bridges located on the U.S. inland waterway system during the 10-year period from 1992 to 2001 revealed that there were 2,692 accidents with bridges. Only 61 of these caused bridge damage in excess of \$500,000 (1,702 caused very minor damage with no repair costs to the bridge), and there were no fatalities within the study period. The study concluded that 90 percent of the barge accidents were related to human performance (78 percent to pilot error and 12 percent to other operational factors). Only 5 percent were related to mechanical problems, and for the remaining 5 percent there was insufficient information to assign a cause.

C1.2

Many factors account for the present ship/bridge accident problem confronting many countries around the world. One factor is that a larger number of merchant ships are making more frequent transits past more bridges. Since 1960, the number of bridges across major waterways leading to U.S. coastal ports has increased by one-third. During that same period, the number of vessels in the world fleet has increased three-fold and worldwide seaborne tonnage has increased by more than 255 percent (McDonald, 1983; U.S. Department of Commerce, 1978).

Other factors include poorly sited bridges. Inadequate attention is often given to the bridge's relationship with waterborne traffic with the result that bridges are placed too near tricky bends or turns in the navigation channel, or too near waterfront docks where berthing maneuvers could threaten the bridge. Many bridges today have inadequate spans over the navigation channel for the safe transit of modern ships which regularly exceed 800 feet in length and 100 feet in width. These narrow spans leave little room for error on behalf of the merchant vessel—particularly under adverse wind and hydraulic current conditions. These small spans often result from economic pressure on behalf of the bridge owner and designer to minimize the in-place cost of the substructure and superstructure of the bridge without regard to the potential for ship impact against the structure.

Economic pressures have long been recognized as conflicting with safety. This is true of both the bridge industry and the maritime industry. In the latter, safety concerns are often placed second to the maintenance of ship schedule—with predictably disastrous consequences. Since masters and pilots are often rated on their ability to make schedules, they are sometimes very reluctant to abort transits into harbors even during adverse environmental conditions. This may have been one of the factors involved in the Skyway Bridge accident, where the pilot on-board the empty inbound merchant ship attempted to transit under the bridge during very low visibility, dense rainfall, and high wind conditions. The vessel struck an anchor pier of the bridge located approximately 800 feet from the centerline of the channel.

A comprehensive literature review of the current domestic and foreign practice, experience, and research

1.2.1 AASHTO Guide Specification (1991)

The 1980 collapse of the Sunshine Skyway Bridge was a major turning point in awareness and increased concern for the safety of bridges crossing navigable waterways in the United States. Studies initiated as a result of this tragedy led to the 1988 pooled-fund research project sponsored by 11 states and the Federal Highway Administration (FHWA) which developed a proposed design code for use by bridge engineers in evaluating structures for vessel collision. This effort culminated in 1991 with the adoption by the American Association of State Highway and Transportation Officials (AASHTO) of the *Guide Specification and Commentary for Vessel Collision Design of Highway Bridges* (AASHTO, 1991).

The AASHTO Guide Specification established design provisions for bridges crossing navigable waterways to minimize their susceptibility to damage from vessel collisions. The provisions applied to both new bridges and to the analysis of existing bridges to determine vulnerability and potential retrofit. The intent of the AASHTO provisions was to provide bridge components with a “reasonable” resistance capacity against ship and barge collisions. In navigable waterway areas where collision by merchant vessels may be anticipated, the Guide Specifications require that bridge structures be designed to prevent collapse of the superstructure by considering the size and type of vessel fleet navigating the channel, available water depth, vessel speed, structure response, the risk of collision, and the operational classification of the bridge.

It should be noted that damage to the bridge (even failure of secondary structural members) is permitted by the code as long as the bridge deck carrying motorist traffic doesn’t collapse (i.e., sufficient redundancy and alternate load paths exist in the remaining structure to prevent collapse of the superstructure).

When the original 1991 Guide Specification was developed in the late 1980s, most analysis was done by hand calculation; therefore, the specification provisions included some simplifying requirements to minimize the hand analysis effort. With modern personal computers and software programs, the vessel collision risk analysis procedures can be easily programmed. Therefore, some of those earlier simplifications have been removed in this 2008 Edition of the Guide Specifications.

findings available on the subject of vessel collision with bridges was performed during the development of the Guide Specifications. Particular attention was given to new research conducted since the initial adoption of the 1991 Guide Specifications, as well as lessons learned from users of the 1991 specifications.

C1.2.1

Since its adoption by AASHTO in 1991, the Guide Specification has been used to design numerous new bridges and to evaluate existing structures for their susceptibility to vessel collision. Because the code was published as a “guide specification,” its use by the State Departments of Transportation (DOTs) was optional, not mandatory.

In general, the use of the code was well received in the engineering community. The major drawbacks in the early implementation of the specifications involved lack of experience in collecting the large amount of vessel fleet data needed to perform the risk analysis for each bridge, as well as a general unfamiliarity of most bridge designers (and bridge owners) in directly using risk concepts in structural design.

Historically in the United States, the risk of structural collapse and potential loss of life have been (and to a great extent still are) buried in various “safety factors,” “reliability indexes,” etc., used in structural design equations within the design codes. Similar to most countries, the United States has a great amount of difficulty in dealing directly with engineering risks in a public environment (and this is reflected in our design codes). Defining an acceptable level of risk is a value-oriented process and is by nature subjective. This subjectiveness and the wide range of public opinion concerning risk acceptance levels results in an engineering issue that most bridge designers would rather not address.

The vessel collision code is somewhat unique in the United States in that the acceptable risk of collapse is clearly stated by the Guide Specifications, and risk analysis procedures are directly used to design the structure.

Experience to date has shown that the use of the vessel impact and bridge protection requirements of the AASHTO Guide Specifications for planning and design of new bridges has resulted in a significant change in proposed structure types over navigable waterways. Incorporation of the risk of vessel collision and cost of protection in the total bridge cost has almost always resulted in longer span bridges being more economical than traditional shorter span structures. This is a consequence of bridge designs involving longer spans requiring fewer piers, and therefore fewer pier protection systems, thus producing lower total (bridge plus protection system) costs.

Experience has also shown that it is less expensive to include the cost of protection in the planning stages of

a proposed bridge than to add it after the basic span configuration has been established without considering vessel collision concerns. Typical costs for adding protection, or for retrofitting an existing bridge for vessel collision, have ranged from 25 percent to over 100 percent of the existing bridge costs.

C1.2.1.1 Extreme Event Combinations (Scour)

The 1991 AASHTO Guide Specification recommended a load combination of vessel impact plus dead load for bridge design under ultimate (survivability) conditions. It was not anticipated that scour (or other extreme events) would occur simultaneously with vessel collisions.

It should be noted that the magnitudes and consequences of individual extreme events such as ship and barge collisions; scour due to flooding; earthquakes; ice flows; hurricane-driven storm surge and waves; terrorist attacks, etc., usually govern the design process for new highway bridges. If the simultaneous occurrence of two or more of these events is considered (for example, a ship collision or earthquake occurring on a bridge pier whose foundation had been subjected to scour during a flood event), the combination of these separate extreme events will generally result in a dominating load combination with significant cost consequences.

Design based on superposition of extreme loads (as currently advocated by some engineers and government agencies) can lead to a significant design increase costing millions of dollars on each project. Since a simultaneous occurrence of two or more extreme events with maximum magnitudes is unlikely, a rational design approach must be formulated for use by bridge engineers. Toward this end, the FHWA sponsored a conference in Atlanta, Georgia, on December 1996, entitled the "Design of Bridges for Extreme Events." The conference proceedings contain a collection of papers dealing with vessel collision, scour, and earthquake design for highway bridges (FHWA, 1996). Concerning the possible combination of vessel collision and scour, Nowak and Knott recommended an evaluation of the following two load cases (Nowak and Knott, 1996):

1. Minimum impact loads associated with a drifting empty barge breaking loose from its moorings and hitting a bridge (potentially during storm and high-water conditions). The drifting barge impact loads should be combined with one half of the predicted long-term plus one half of the predicted short-term scour. For this load case, long-term scour should be taken as the sum of the contraction scour portion of live bed scour and scour due to long-term channel degradation. Short-term scour should be taken as the short-term portion of the live bed scour associated with the 100-year storm/flood event.

2. Maximum impact loads associated with a ship or barge tow striking the bridge while transiting the navigation channel under typical waterway conditions (i.e., not during extreme storm events and high-water conditions). The vessel impact loads should be combined with one half of the predicted long-term scour.

Short-term scour includes contraction, local and live bed scour in which river or bay bottom material (sand, clay, gravel, etc.) is removed as a result of increased water velocities caused by flooding conditions in conjunction with the overall bridge geometry and substructure shape on the hydraulic conductivity of the site.

In the United States, historical data indicates that merchant ships and barge tows will not transit river and harbor areas during periods of high water and flood events which cause abnormal and dangerous water currents in the navigation channel. During such flood events, vessels will normally leave the harbor, tie-up at docks, or anchor in designated areas of the waterway. Following the passage of the flood stages of the waterway, and once currents return to normal levels, merchant shipping will recommence in the waterway. It is anticipated that the short-term (live bed) scour areas near the bridge piers will have been significantly refilled by sediment transport mechanisms in the waterway by that time. Note that no records of scour concerns are reported on any of the 31 major bridge collapses mentioned at the beginning of this report.

At limited locations in the United States, live bed scour conditions do not exist and instead, clearwater scour conditions may exist. In clearwater scour situations, up-river site conditions are such that there is virtually no particulate matter (soil, gravel, etc.) to transport; therefore, river bed material removed by local contraction scour is not replaced after flood-level water velocities subside. Under this special condition, the full depth of scour should be used in the vessel collision analysis.

Long-term scour includes aggradation and degradation scour and refers to scour across the entire waterway width. This is a permanent site condition with a magnitude (depth) that increases with time, and is independent of the presence of a bridge or the structure's geometry—this scour will occur regardless of the bridge. Long-term scour (if it is present at all) is usually a gradual deterioration of base support across the waterway.

1.2.2 AASHTO LRFD Bridge Design Specifications

The *AASHTO LRFD Bridge Design Specifications*, 4th Edition (2007), incorporates the major analysis and design requirements of the 1991 AASHTO Guide Specification for Vessel Collision. Unlike the Guide Specification, for which usage is optional, the vessel

C1.2.2

In the LRFD Code, design values of factored load combinations were determined using rigorous statistical analysis procedures and were based on a target beta reliability index of $\beta = 3.5$. However, the statistical analysis was performed only for the basic load

collision requirements are now mandatory for users of the LRFD Bridge Design Code.

The vessel collision force in the LRFD Code (designated as CV) is considered an “Extreme Event II” load combination, in which a load factor of 1.0 is used for the vessel collision force in combination with the dead load, 50 percent of the live load, water loads and stream pressure, earth pressure, and friction (no other extreme events are combined with the vessel collision force).

1.3 BASIC CONCEPTS

Development of the Guide Specifications has been predicated on the following basic concepts:

- hazard to life be minimized,
- risk of bridge service interruption to be minimized,
- importance of bridge to be reflected in required safety level,
- specifications to accept damage of secondary structural members provided bridge service can be maintained,
- specifications to be simple and unambiguous,
- ingenuity of design not to be restricted, and
- provision to be applicable to all of the United States.

1.4 DESIGN ANALYSIS

When the specifications provide for an empirical formula as a design convenience, a rational analysis based on a theory accepted by the Subcommittee on Bridges and Structures of the American Association of State Highway and Transportation Officials, with stresses in accordance with the specifications, or by model testing supported by analysis, will be considered

combinations with dead load and live load. Extreme loads and their combinations were not considered in the LRFD calibration because of the lack of statistical data concerning the correlation of such extreme events (vessel collision, scour, earthquake, etc.). Therefore, the development of rational design criteria for extreme load events will require future research and the collection of extensive statistical data. Because of the rare nature and large variability of magnitudes associated with extreme events, some researchers believe that the current bridge design methods, statistical analysis models, and calibration procedures used in the development of LRFD load combinations are inappropriate for application to extreme event design.

The vessel collision force in the LRFD Code (designated as CV) is considered an “Extreme Event II” load combination, in which a load factor of 1.0 is used for the vessel collision force in combination with the dead load, 50 percent of the live load, water loads and stream pressure, earth pressure, and friction (no other extreme events are combined with the vessel collision force).

C1.3

The basic design philosophy embodied in the Specifications is that it is possible to design a bridge in a cost-effective manner which minimizes the risk of catastrophic superstructure collapse due to vessel collision. Bridges may be designed to resist vessel impact loads in either the elastic or plastic range, or protected by a bridge protection system. In the plastic range, significant damage to the bridge substructure is acceptable providing that superstructure collapse does not occur and that the damage is easily repairable. Structural ductility and redundancy are important in preventing superstructure collapse.

One of the basic concepts in developing the Specifications was that it would be applicable to all parts of the United States with navigable waterways, including the inland waterway system as well as the coastal areas. In order to provide flexibility in specifying design provisions, three alternative methods of selecting the design vessel (ranging from simple to complex) were developed. Two operational classifications were defined to classify bridges according to Social/Survival and Security/Defense requirements.

C1.4

The designer is cautioned that many of the equations in the Specifications for vessel collision analysis were derived from physical model studies and analysis methods in which critical assumptions have been made. Therefore, the implied accuracy of the equations in the Specifications is limited, and the use of the equation results to many significant figures is not warranted.

Engineering judgment should be used to round the equation results to establish design values to be used in applying the Specification provisions.

1.5 FLOW CHARTS

Flow charts outlining the basic steps in the vessel collision design procedures are given in Figure 1 for evaluating bridges. Method II shall be used for all bridge analysis unless the special situations presented in Article 4.1 exist, in which case Method I or III, as appropriate, may be used.

C1.5

Method II of the AASHTO Guide Specifications is a probability-based risk analysis procedure for determining the appropriate vessel impact design loads for a bridge structure. Using Method II procedures, a mathematical risk model is used to estimate the annual frequency of bridge collapse based on the bridge pier/span geometry, ultimate resistance of the pier (or span), waterway characteristics, and the characteristics of the vessel fleet transiting the channel. The estimated risk of collapse is compared to standard acceptance criteria, and the bridge characteristics (span layout, pier strength, etc.) are adjusted until the acceptance criteria are satisfied. The Method II procedure is iterative in nature and is normally performed by specialized computer programs and spreadsheets.

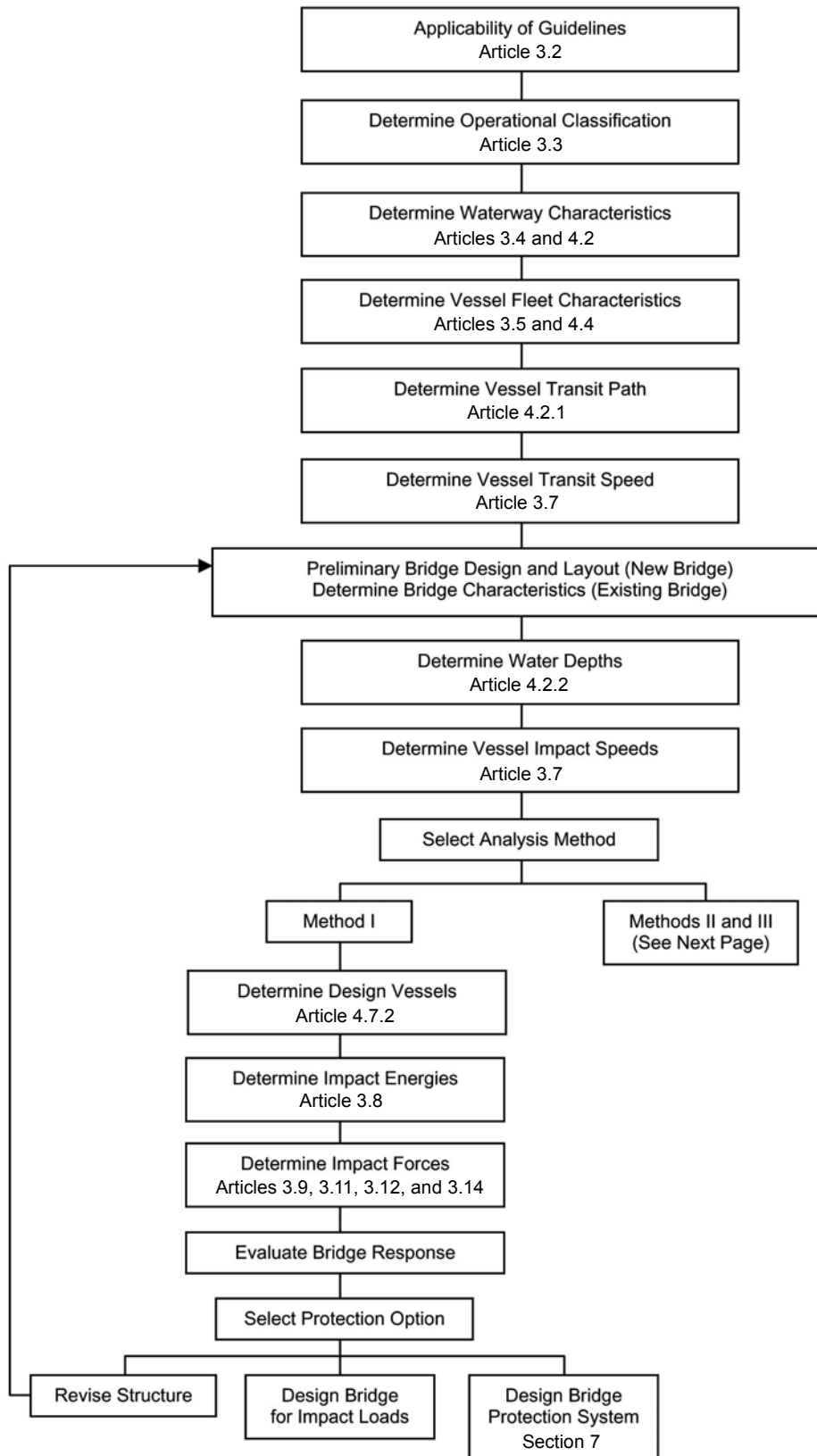


Figure 1.5-1—Design Procedure Flow Chart

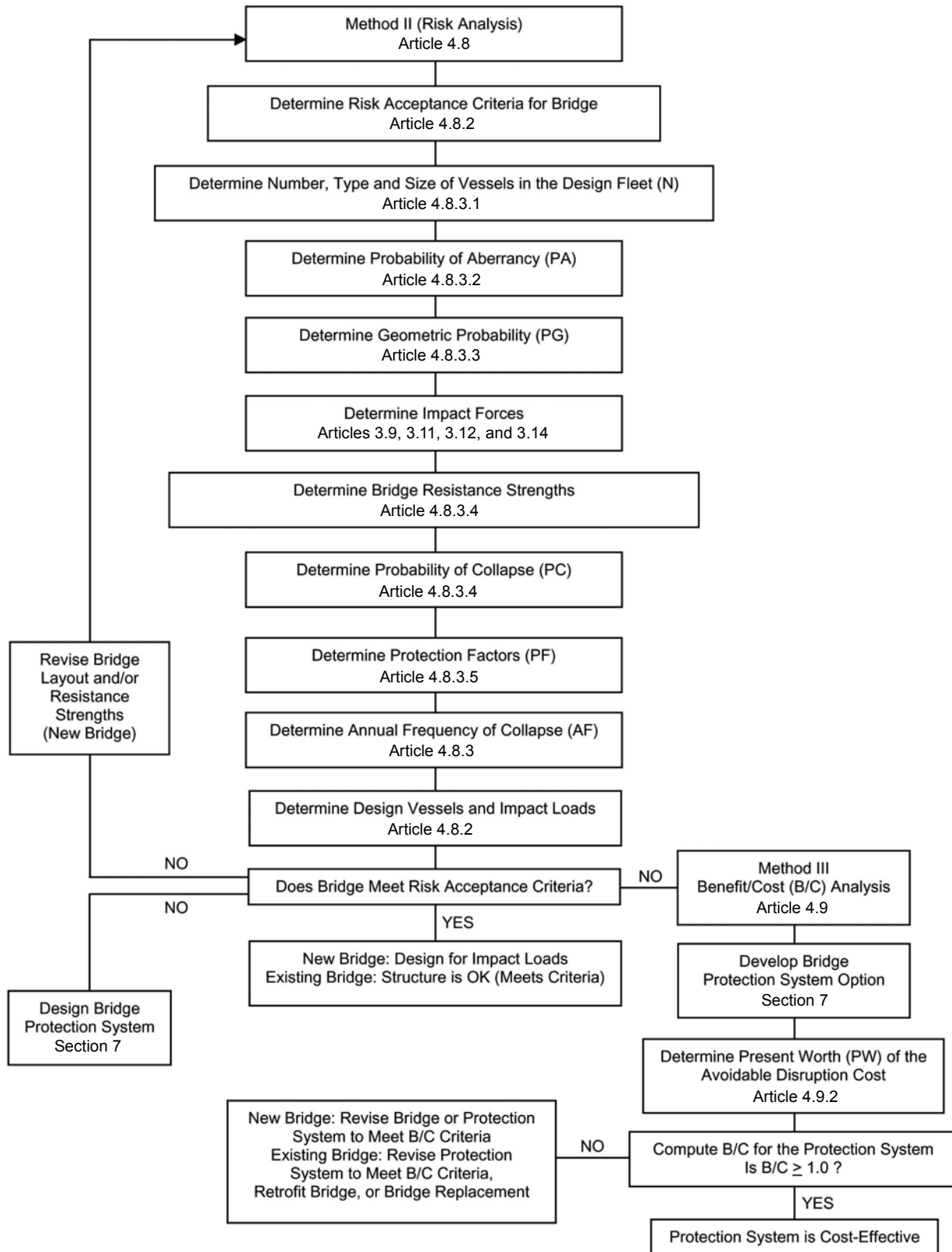


Figure 1.5-1—Design Procedure Flow Chart—Continued

REFERENCES

- AASHTO. 1991. *Guide Specification and Commentary for Vessel Collision Design of Highway Bridges*. American Association of State Highway and Transportation Officials, Washington, DC.
- AASHTO. 2007. *LRFD Bridge Design Specifications and Commentary*. American Association of State Highway and Transportation Officials, Washington, DC.
- Derucher, K., ed. 1981. "Bridge and Pier Protective Systems and Devices," *Conference Proceedings*, Stevens Institute of Technology, Hoboken, NJ.
- FHWA. 1996. *Conference Proceedings, The Design of Bridges for Extreme Events*. Federal Highway Administration, Atlanta, GA.
- IABSE. 1993. "Ship Collision with Bridges: The Interaction between Vessel Traffic and Bridge Structures." Structural Engineering Document No. 4. International Association for Bridge and Structural Engineering, Copenhagen, Denmark.
- IABSE. 1983. *IABSE Colloquium on Ship Collision with Bridges and Offshore Structures*, 3 Vols. (Introductory, Preliminary, and Final Reports). International Association of Bridge and Structural Engineers, Copenhagen, Denmark.
- Marine Board of the Commission on Engineering and Technical Systems, National Research Council. 1983. "Ship Collisions with Bridges: The Nature of the Accidents, Their Prevention and Mitigation." Prepared by the Committee on Ship-Bridge Collisions, National Academy Press, Washington, DC.
- McDonald, J. April/May 1983. "Bulk Shipping." World Wide Shipping/World Ports, Odessa, FL.
- Nowak, A. and M. Knott. 1996. "Extreme Load Events and their Combinations," *Conference Proceedings, The Design of Bridges for Extreme Events*, Federal Highway Administration, Atlanta, GA.
- Pedersen, P. T. 1993. "Ship Impacts: Bow Collisions," *Conference Proceedings* from the Third International Symposium on Structural Crashworthiness and Failure, University of Liverpool, UK.
- U.S. Coast Guard. May 2003. *American Waterways Operators Bridge Allision Work Group*. Report of the U.S. Coast Guard–American Waterways Operators, Inc. Safety Partnership, Washington, DC.
- U.S. Department of Commerce. May 1976. *Analysis of Bridge Collision Incident*. Vols. 1 and 2. Prepared by Operations Research, Inc., Washington, DC.
- U.S. Department of Commerce, Maritime Administration. May 1978. *Merchant Fleet Forecast of Vessels in U.S. Foreign Trade*. Prepared by Temple, Barker and Sloane, Inc., Wellesley Hills, MA.

SECTION 2

SYMBOLS AND DEFINITIONS

The following symbols and definitions apply to these Guide Specifications.

a	=	bow or vessel damage depth used in Article C3.9 and Figure C3.9-3; acceleration as used in Article C7.3.2 (in./s ²)
$\bar{a}$	=	average bow damage depth as used in Equation C3.10-1
a_B	=	bow damage depth of standard hopper barge as determined by Equation 3.13-1 (ft)
AF	=	annual frequency of bridge element collapse defined in Article 4.8.3 (number of collapses/year)
a_S	=	bow damage depth of ship as determined by Equation 3.10-1 (ft)
B	=	loads resulting from buoyancy forces and used in the group load combination of Equation 3.14-1; beam (width) of vessel as shown in Figure C4.8.3.5-1 (ft)
B_B	=	barge width as defined in Article 3.13 (ft)
B_M	=	beam (width) of barge, barge tows, and ship vessels used in Articles 3.5 and 4.8.3.3; as shown in Figures 3.5.1-1, 3.5.1-2, and 4.8.3.3-1; and as used in Tables 3.5.2-1 through 3.5.2-3 (ft)
B_P	=	width of bridge pier used in Figures 4.8.3.3-1 and 8.5.1-1 (ft)
BR	=	base rate of vessel aberrancy defined in Article 4.8.3.2 (dimensionless)
C	=	channel width as shown on Figures 4.2.1-1, 4.2.1-2, and 8.5.1-1 (ft); vessel coefficient as used in Equation C7.3.2-1
C_B	=	vessel block coefficient (dimensionless) as defined in Equation C3.5.2-1
C_C	=	size of barge based on cargo capacity as defined in Article 3.5 and used in Figure 3.5.1-1 (tonne, ton)
C_H	=	hydrodynamic mass coefficient defined in Equation 3.8-1 (dimensionless)
CV	=	vessel collision force used in the group load combination of Equation 3.14-1
D	=	loads resulting from dead load and used in the group load combination of Equation 3.14-1; diameter of dolphin as shown in Figure C4.8.3.5-1 (ft)
DA	=	avoidable disruption cost as shown in Figure C4.8.3.5-1 (\$)
D_B	=	bow depth of a ship or barge vessel as shown in Figures 3.5.1-1, 3.5.2-3, 3.5.2-4, 3.15.1-2, and 3.15.1-3, and in Tables 3.5.2-1 through 3.5.2-3 (ft)
DC	=	bridge collapse disruption cost as defined in Article 4.9.3 and as shown in Figure C4.8.3.5-1 (\$)
D_E	=	mean draft of an empty vessel (light draft) as shown in Figure 3.5.1-1 (ft); mean draft of a ballasted vessel as shown in Figure 3.5.2-4 (ft); effective dolphin diameter as shown in Figure C4.8.3.5-1 (ft)
D_{EB}	=	draft of ballasted ship bow as shown in Figure 3.5.2-4 and Tables 3.5.2-1 through 3.5.2-3 (ft)
D_{ES}	=	draft of ballasted ship stern as shown in Figure 3.5.2-4 (ft)
DF	=	distribution factor as used in Equation C7.3.2-4
d_f	=	depth to fixity in Equation C7.3.3-3 (in.)

D_L	=	mean draft of a fully loaded vessel as shown in Figures 3.5.1-1 and 3.5.2-4 and in Tables 3.5.2-1 through 3.5.2-3 (ft)
D_M	=	mean vessel draft as defined in Equation C3.5.2-1 (ft)
D_V	=	depth of vessel as shown in Figure 3.5.1-1 (ft)
DWT	=	size of vessel based on deadweight tonnage as defined in Articles 3.5 and 3.9 (tonne, ton)
D_x	=	horizontal stiffness as used in Equation C7.3.2-5 (kip-in.)
D_y	=	vertical stiffness as used in Equation C7.3.2-6 (kip-in.)
E	=	modulus of elasticity as defined in Equation C7.3.2-4 (ksi); modulus of elasticity of pile section as defined in Equation C7.3.3-4 (psi); absorbed collision energy as defined in Equation C3.8-3 and as shown in Figure C3.9-3 (kip-ft)
E_B	=	deformation energy as used in Figure C3.12-2 (kip-ft)
EH, EV	=	loads resulting from earth pressure and used in the group load combination of Equation 3.14-1
F	=	vessel crushing force as defined in Equation C7.3.1.1-1 (kips)
FR	=	friction in load combination as used in Equation 3.14-1
$F(x)$	=	protective structure force, as a function of deflection, as used in Equation 7.3.1 (kips)
g	=	acceleration due to gravity as used in Equation C3.8-1 (ft/s ²); real annual rate of growth of disruption costs as used in Equation 4.9.2-1 (rate/year)
GRT	=	gross registered tonnage as defined in Article C3.5 (ft ³)
H	=	ultimate bridge element strength as defined in Article 4.8.3.4 (kips); height of dophin to location of the plastic hinge as used in Equation C7.3.3-6 and Figure C7.3.3-8 (ft)
h	=	distance from the top of the cell to the plane of maximum interlock stress as defined in Article C7.3.3, used in Equation C7.3.3-2, and shown in Figure C7.3.3-8 (ft)
H_L	=	depth of barge head-log on its bow as shown in Figure 3.5.1-1 (ft)
H_P	=	ultimate bridge pier resistance strength as defined in Article 4.8.3.4 (kips)
H_S	=	ultimate bridge superstructure resistance strength as defined in Article 4.8.3.4 (kips)
I	=	moment of inertia of pile section as used in Equation C7.3.3-4 (in. ⁴)
i	=	discount rate used in Equation 4.9.2-1 (rate/year)
I_p	=	moment of inertia of pile as used in Equation C7.3.2-4 (in. ⁴)
I_w	=	waler moment of inertia as defined in Article 7.3.2 (in. ⁴)
K	=	equivalent spring constant of pile and fender as used in Equations C7.3.2-1 and C7.3.2-2 (kip/in.)
K_a	=	active earth pressure coefficient as used in Equation C7.3.3-2
KE	=	design impact energy of vessel collision as defined in Equations 3.8-1, C3.8-2, 7.3-1, and C7.3.1.1-1 (kip-ft); kinetic energy as defined in Equation C3.8-1 (kip-ft); ship collision energy as defined in Equations 3.10-1, C3.10-1, and C3.10-2 (kip-ft); kinetic energy to be absorbed as used in Equations C3.8-3 and C7.3.1-2 (kip-ft); barge collision energy as defined in Equations 3.13-1 and C3.13-1b (kip-ft)

K_f	=	spring constant of fender as used in Equation C7.3.2-2 (kip/in.)
K_p	=	spring constant of pile as used in Equation C7.3.2-2 (kip/in.)
L	=	distance of dolphin from pier as shown in Figure C4.8.3.5-1 (ft); length of pile above fixity as used in Equations C7.3.2-4 and C7.3.2-5 (in.)
L_B	=	length of individual barge as shown in Figure 3.5.1-1 (ft)
L_{CB}	=	length from bow to collision bulkhead for ships as defined in Figure 3.5.2-3 (ft)
LL	=	live load as used in load combination Equation 3.14-1
LOA	=	length overall of ship or barge tow as shown in Figures 3.5.1-2, 3.5.2-3, and 3.5.2-4 and in Tables 3.5.2-1 through 3.5.2-3 (ft)
LP	=	length of bridge pier as defined in Figure 8.5.1-1 (ft)
L_W	=	length of vessel at waterline as defined in Equation C3.5.2-1 (ft)
M	=	mass of vessel as used in Article C7.3.2 (kip-s ² /in.)
MHW	=	mean high-water level of waterway as shown in Figures 3.15.1-1 through 3.15.1-3, 3.16-1, C7.3.1.1-1, and C7.3.1.2-1 (ft)
MIC	=	motorist inconvenience cost due to bridge collapse as defined in Article 4.9.3 (\$)
MLW	=	mean low water level as shown in Figures C7.3.1.1-1, C7.3.1.2-1, and C7.3.3-4 (ft)
MSL	=	mean sea level as shown in Figures C7.3.1.3-1, C7.3.3-6, C7.3.3-7, C7.3.4-6, and C7.3.5-1 (ft)
N	=	number of one-way passages of vessels transiting under the bridge as defined in Article 4.8.3 (number/year)
n_h	=	modulus of horizontal subgrade reaction as used in Equation C7.3.3-4 (lb/in. ³)
NHW	=	normal high water level as defined in Article 1.2.3 of the Risk Assessment Example
NRT	=	net registered tonnage as defined in Article C3.5 (ft ³)
P	=	loads resulting from vessel impact and used in the group load combination of Equation 3.14-1 and shown in Figures C3.9-2 and C3.9-3; applied force to structure as used in Equation C7.3.2-1 (kips)
p	=	collision or impact force as defined in Article C4.8.3.4; lateral fill pressure used in Equation C7.3.3-2 (lb/ft ²)
P_B	=	barge collision impact force for head-on collision between barge bow and a rigid object as defined in Article 3.12 (kips)
P_{BH}	=	ship collision impact force between ship bow and a rigid superstructure as defined in Equation 3.11.1-1 (kips)
P_{DH}	=	ship collision impact force between ship deckhouse and a rigid superstructure as defined in Equation 3.11.2-1 (kips)
P_{MT}	=	ship collision impact force between ship mast and a rigid superstructure as defined in Equation 3.11.3-1 (kips)
P_S	=	ship collision impact force for head-on collision between ship bow and a rigid object as defined in Equations 3.9-1 and 3.10-1 (kips)

PA	=	probability of vessel aberrancy as defined in Article 4.8.3 (dimensionless)
PC	=	probability of bridge collapse as determined in Article 4.8.3 (dimensionless)
PF	=	protection factor as determined in Article 4.8.3
PG	=	geometric probability of vessel collision with bridge pier/span as determined in Article 4.8.3 (dimensionless)
PIC	=	port interruption cost as defined in Article 4.9.3 (\$)
PRC	=	pier replacement cost as defined in Article 4.9.3 (\$)
$P(t)$	=	compression phase of impact over time as used in Article C3.9
$\bar{P}(a)$	=	mean impact force averaged over damage depth as used in Equations C3.9-1 and C3.10-1 and as shown in Figure C.3.9-3 (kips)
$\bar{P}(t)$	=	impact force averaged over damage depth as used in Equations C3.9-1 through C3.9-3b and as shown in Figures C3.9-2, C3.9-4, and C3.9-5
PW	=	present worth of disruption cost as determined in Equation 4.9.2-1 (\$)
R	=	area of the density function between $\pm\theta$ as shown in Figure C4.8.3.5-1
r	=	dolphin radius as used in Equation C7.3.3-1 (ft)
R_B	=	ratio of barge width as defined in Equation 3.13-1; PA correction factor for bridge location as defined in Equations 4.8.3.2-1 and 4.8.3.2-2a through 4.8.3.2-2c (dimensionless)
R_{BH}	=	ratio of exposed superstructure depth to the total ship bow depth as defined in Equation 3.11.1-1 (dimensionless)
R_C	=	PA correction factor for currents parallel to vessel transit path as defined in Equations 4.8.3.2-1 and 4.8.3.2-3 (dimensionless)
R_D	=	PA correction factor for vessel traffic density as defined in Article 4.8.3.2 (dimensionless)
R_{DH}	=	reduction factor for ship deckhouse collision force as defined in Article 3.11.2 (dimensionless)
R_L	=	rake length of vessel bows as shown in Figures 3.5.1-1 and 3.5.2-3 (ft)
R_{XC}	=	PA correction factor for crosscurrents acting perpendicular to vessel transit path as defined in Equations 4.8.3.2-1 and 4.8.3.2-4 (dimensionless)
S	=	bridge main span length over navigable channel as shown in Figure 8.5.1-1 (ft)
SF	=	loads resulting from stream flow forces and used in the group load combination of Equation 3.14-1
s_i	=	shear on interlocks as used in Equation C7.3.3-6 (lb)
S_p	=	vertical pile spacing as used in Article 7.3.2 (in.)
SRC	=	span replacement cost as defined in Article 4.9.3 (\$)
S_w	=	horizontal waler spacing as used in Article 7.3.2 (in.)
T	=	relative stiffness factor for normally loaded clay, granular soils, silt, and peat as used in Equations C7.3.3-3 through C7.3.3-5 (in.)

t	=	stopping time as used in Article C7.3.2 (sec); interlock tension as used in Equation C7.3.3-1 (lb/in.)
V	=	design impact speed of vessel as determined in Articles 3.7, 3.8, and 3.9 (ft/s); impact velocity as used in Article C7.3.2 (in./s)
V_C	=	waterway current component acting parallel to the vessel transit path as determined in Equation 4.8.3.2-3 (knots)
V_s	=	shear on centerline as used in Equation C7.3.3-7 (lb)
V_T	=	vessel transit speed in the navigable channel as defined in Article 3.7 (ft/sec)
V_{XC}	=	waterway current component acting perpendicular to the vessel transit path as determined in Equation 4.8.3.2-4 (knots)
W	=	displacement weight of vessel as defined in Equations C3.5.2-1, 3.8-1, and C3.8-1, (tonne, ton)
WA	=	water load and stream pressure used in group load combination Equation 3.14-1
W_E	=	ballasted displacement weight of vessel as shown in Figure 3.5.1-1 and Tables 3.5.2-1 through 3.5.2-3 (tonnes)
WL	=	waterline as shown in Figures 3.5.2-3, 3.5.2-4, and C7.3.4-10
W_L	=	fully loaded displacement weight of vessel as shown in Figure 3.5.1-1 and Tables 3.5.2-1 through 3.5.2-3 (tonnes)
W_o	=	deadweight tonnage of largest ship as defined in Article C4.7.2
W_W	=	volume of water (34.4 cubic ft per tonne of saltwater; 35.4 cubic ft per tonne of freshwater) as defined in Equation C3.5.2-1
x	=	distance to bridge element from the centerline of vessel transit path as shown in Figure 3.7-1 (ft) and Figure 4.8.3.3-1 (ft); distance to bridge element from the centerline of vessel transit path as shown in Figure 3.7-1; deflection of protection structure due to vessel impact as defined in Equation 7.3-1 (ft)
x_C	=	distance to edge of channel from centerline of vessel transit path as shown in Figure 3.7-1 (ft)
x_L	=	distance equal to $3 \times LOA$ from centerline of vessel transit path as shown in Figure 3.7-1 (ft)
Y	=	design life of the bridge (in years) as shown in Equation 4.9.2-1 (typically 75 years for a new bridge); maximum system deflection as used in Article C7.3.2 (in.)
Y_N	=	distance from pier centerline to edge of outbound channel as shown in Figure 8.5.1-1 (ft)
Y_P	=	offset distance from edge of foundation to pier column as shown in Figures 3.15.1-2 and 3.15.1-3 (ft)
Y_W	=	distance from pier centerline to edge of inbound channel as shown in Figure 8.5.1-1 (ft)
α	=	impact angle as shown in Figure C3.8-1 (degrees)
γ_f	=	average unit of weight of fill as used in Equation C7.3.3-2 and shown in Figure C7.3.3-8 (lb/ft ³)
γ_p	=	load factor, 1.25 maximum, 0.9 minimum, used in the group load combination of Equation 3.14-1
Δ_p	=	pile deflection due to unit load as used in Equations C7.3.2-3 and C7.3.2-4 (in./kip)
η	=	portion of absorbed collision energy to initial collision energy as defined in Equation C3.8-3 and shown in Figure C3.8-1

- θ = angle of channel turn or bend as defined in Article 4.8.3.2 and as shown in Figure 4.8.3.2-1 (degrees); protection angle provided by dolphin as shown in Figure C4.8.3.5-1 (degrees)
- ϕ = angle between channel and bridge centerlines as shown in Figures 4.8.3.3-1 and 8.5.1-1 (degrees); angle of internal friction for granular soils as shown in Figure C7.3.3-7 and Equation C7.3.3-8 (degrees)
- λ = frequency as used in Article C7.3.2 (sec^{-1})
- μ = coefficient of friction as used in Equation C7.3.3-6, Article C3.8, and Figure C3.8-1
- σ = standard deviation of normal distribution as defined in Article 4.8.3.3

GENERAL PROVISIONS

3.1 GENERAL

In navigable waterway areas where vessel collision by merchant ships and barges may be anticipated, bridge structures shall be designed to prevent collapse of the superstructure by considering the size and type of the vessel, available water depth, vessel speed, and structure response in accordance with the Guide Specification criteria.

3.2 APPLICABILITY OF SPECIFICATION

These specifications are for the design of new bridges and for the evaluation of existing bridges to resist the effect of collision impacts from merchant vessels.

The specifications apply to all bridge types which cross a navigable shallow draft inland waterway with barge traffic, and deep draft waterways with large merchant ships. The provisions are applicable to normal merchant vessels, either steel hulled ship or barge vessels.

The specifications are not applicable to special purpose vessels, wood, or fiberglass constructed vessels, ships smaller than 1,000 DWT, naval vessels, nor to recreational vessels. Vessel impact requirements for bridges located in waterways characterized by significant usage of these special vessels shall be established by the Bridge Owner.

The specifications apply to bridges crossing waterways which have defined navigation channels as established by federal or state agencies. Judgment must be used when applying the Guide Specification criterion to waterways in which no defined navigation channel exists.

The provisions specified in the Specification are minimum requirements.

C3.2

The Guide Specifications present vessel collision design requirements applicable to the majority of highway bridges crossing navigable waterways to be constructed in the United States. The Specifications were developed for steel-hulled merchant vessels and barges and is not applicable to vessels constructed of other materials, recreational vessels, or ships smaller than 1,000 DWT.

The Specifications specify minimum requirements. More sophisticated design and/or analysis techniques may be utilized if deemed appropriate by the design engineer and approved by the Owner.

It must be emphasized at the outset that the specification of vessel impact loads and bridge protection requirements cannot be achieved solely by following a set of scientific principles. First, the causes of vessel collision are not well understood, and experts do not fully agree on how available knowledge should be interpreted to specify the impact loads for use in design. Second, in order to achieve workable bridge design provisions, it is necessary to simplify the enormously complex matter of vessel impact occurrence, vessel impact forces and motions, and bridge response. Finally, any specification of vessel impact loadings and pier protection requirements involves balancing the risk of that impact occurring against the cost to society of requiring that structures be designed to withstand that loading. Therefore, judgment, engineering experience, and political wisdom are as necessary as scientific knowledge.

The recommended vessel impact methodologies are the work of the project consultants and are based upon the best scientific knowledge available in 2007, adjusted and tempered by experience. Throughout the following sections, explanations for the various recommendations are provided as a guide to both the user of the Specifications and to those who will improve the Specifications in the future.

A great deal of future research is required to understand the complicated processes involved in a vessel collision with bridge structures. It is expected that the methodology and key assumptions used in the Specifications will change with time as the profession

gains more knowledge about vessel collision loads, probability of collision, and bridge response, and as society gains greater insight into the process of establishing acceptable risk criterion.

3.3 OPERATIONAL CLASSIFICATION

An Operational Classification (OC) shall be assigned for all bridges crossing a navigable waterway for purposes of determining the risk acceptance and subsequent design vessels in Articles 4.7.2 and 4.8.2 as follows:

1. Critical/Essential Bridges
2. Typical Bridges

Bridges shall be classified on the basis of Social/Survival and Strategic Highway Network (STRAHNET) requirements.

Critical/essential bridges are those that must continue to function after impact from a design vessel whose probability of occurrence is smaller than for typical bridges. The Social/Survival evaluation is primarily concerned with the need for civil defense, police, fire department, or public health agencies to respond to an emergency situation which might exist on the opposite side of the waterway. Bridges which provide the only continuous transportation route for such emergency situations should be classified as critical/essential. Bridges which serve as important links in the STRAHNET should be classified as critical/essential. Additional guidelines for determining the operational classification are provided in the Commentary.

C3.3

The Operational Classification (OC) is used in conjunction with the acceptable risk criteria to establish the design vessel used to determine vessel impact loadings for bridges. Two Operational Classifications are specified: 1) Critical/Essential Bridges, and 2) Typical Bridges.

The determination of the Operational Classification is necessarily subjective. Consideration should be given to the Social/Survival and Strategic Highway Network (STRAHNET) requirements discussed below. Additional considerations should be the availability of alternate detour routes and the average annual daily traffic. The latter consideration provides an indirect means of assessing the loss of life which might occur in the event of collapse of portions of the bridge superstructure.

The Social/Survival evaluation is largely concerned with the need for roadways connecting the communities located on opposite sides of the waterway. In order for civil defense, police, fire department or public health agencies to respond to an emergency situation which might exist on the opposite side of the waterway, a continuous route must be provided. Bridges on such routes should be classified as critical/essential.

Transportation routes to essential facilities such as hospitals, police and fire stations, and communications centers must continue to function and bridges required for this purpose should be classified as critical/essential.

The well-being of the community is another major concern. Bridges which carry very high volumes of motorist traffic and those which provide routes to such facilities as schools, arenas, power installations, water treatment plants, etc., should suffer little or no damage and should be classified as critical/essential.

The operational evaluation of a bridge for Social/Survival significance in an emergency or disaster situation depends on the range of options available and the possibility of a bridge being in parallel or series with other bridges in a roadway network. Discussion may be required with highway, civil defense, and police officials.

An example of Social/Survival consequences was dramatically illustrated by the collapse of the Tasman Bridge, Hobart, Australia, in 1975 as a result of a ship collision. The Tasman Bridge was closed for 33 months while repairs were made to the structure. The nearest alternative river crossing was located 30 miles away. During the repair time, investigators found an increase in suicide rates, divorce, bankruptcy, crime, and illness in the bedroom community on the eastern shore of the Derwent River which had been severed from all hospital, medical, police, and other social services located in the City of Hobart on the western shore.

The Strategic Highway Network (STRAHNET) is a designation given to roads that provide “defense access, continuity, and emergency capabilities for movements of personnel and equipment in both peace and war.” STRAHNET includes Routes (for long-distance travel) and Connectors (to connect individual installations to the Routes). STRAHNET Routes include all of the Interstate highways as well as connecting routes to important military installations, industries and resources which include:

- military bases and supply depots and National Guard installations;
- hospitals, medical supply centers and emergency depots;
- major airports;
- defense industries and those that could easily or logically be converted to such;
- refineries, fuel storage, and distribution centers;
- major railroad terminals, railheads, docks, and truck terminals;
- major power facilities and hydroelectric centers at major dams;
- major communication centers; and
- other facilities that the state considers important from a national defense viewpoint or during emergencies resulting from natural disasters or other unforeseen circumstances.

Bridges serve as important links in the STRAHNET and such bridges should be classified as critical/essential.

3.4 DATA COLLECTION

Data shall be collected as appropriate for the analysis method utilized for the bridge design. Essential data includes description of the vessel traffic passing under the bridge, vessel transit speeds, vessel loading characteristics, waterway and navigable channel geometry, water depths, environmental conditions, and bridge geometry.

C3.4

Essential data for use of the specification methodologies includes a description of the vessel traffic passing under the bridge, vessel transit speeds, and environmental conditions. Sources for obtaining data on these items include the following:

- *Waterborne Commerce of the United States (WCUS)*, Parts 1 thru 5, Water Resources Support Center (WRSC), Fort Belvoir, VA. This document contains statistics on the commercial movement of foreign and domestic cargo on a calendar year basis. Included are detailed data by commodity and number of vessel trips for U.S. harbors and waterways. The number of vessel trips is arranged by vessel draft rather than vessel size (DWT) which is a limitation of these publications.
- *Waterborne Transportation Lines of the United States, WRSC*. This document contains information of vessel operations of American flag vessels.

operating in U.S. waterways on a calendar year basis. Included are vessel operators and their addresses; vessel description based on type, construction, net registered tonnage (NRT) length, breadth, draft, horsepower, vertical clearance, etc. Also, included is a description of operations, type of service, principal commodities carried and localities served. This document is an excellent source of data for inland waterway barge tow operations. It is of limited use for ship data since foreign flag vessels (which constitute the large majority of coastal port usage) are not included.

- *Lock Performance Monitoring (LPM) Reports, WRSC.* The report data contains valuable information on vessels using the inland waterway system. The data consists of information describing vessel traffic through locks as well as physical dimensions of locks, significant weather, and navigation conditions. Vessel data includes vessel name, flotilla dimensions, barge types, number, and tonnage.
- *U.S. Army Corps of Engineers (USACE) District Offices.* The Navigation Department for the local USACE District may have publications on past or proposed channel modifications in the waterway which might contain valuable vessel data statistics.
- *U.S. Coast Guard, Marine Safety Office (MSO).* The local MSO maintains daily arrival/departure logs for the waterways within its jurisdiction. Information in the logs includes the vessels' names and berths while in the harbor. This allows a determination as to whether the vessel called at a facility upstream or downstream of the proposed bridge site. The arrival/departure log for each vessel trip must be reviewed, which can be very time consuming.
- *Port Authorities.* Local port authorities and operators often maintain logs of vessel trip data for their waterway area. This data can be useful in developing vessel frequency data for the specific bridge location.
- *Pilot Associations.* Discussion with local harbor pilots and towboat operators is essential for determining vessel operating conditions, speed, and transit paths for the waterway. The local pilots and towboat operators are regular users of the waterway and have valuable information on the local wind and current conditions, waterway geometry, traffic density, and vessel transit speeds which are critical factors in the vessel impact methodologies.
- *National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce.* The following NOAA documents are available for most waterways: Tide Tables, Tidal Current Tables, Tidal Current Charts, United States Coast Pilots, Distance

Tables, and Nautical Charts. The Nautical Charts are particularly useful for establishing the channel geometry and water depths in the waterway.

3.5 VESSEL TYPE AND CHARACTERISTICS

The vessel types using the waterway shall be determined. Vessels shall be classified as either, 1) inland waterway barges, or 2) ships. The first category includes barge vessels using shallow draft inland waterways, including the tugs and tows which push/pull them. The second category includes ships which use deep draft waterways.

Ship size shall be determined based on the vessel's deadweight tonnage (*DWT*). *DWT* is the weight of cargo that the vessel can carry when fully loaded (1 tonne = 2,205 pounds).

The relations between *DWT* and other units of measurements of vessel size which might be encountered by the designer such as Gross Registered Tonnage (*GRT*), Net Registered Tonnage (*NRT*), and Displacement Tonnage (*W*) are explained in the Commentary.

Barge size shall be determined based on the vessel's cargo carrying capacity (*C_C*) in tons (1 ton = 2,000 pounds).

C3.5

The two basic vessel types identified for use in the Specifications are ocean-going ships and inland barges. The basic unit of measurement in defining the vessel size shall be the vessel's deadweight tonnage (*DWT*). This measurement and others that might be encountered by the bridge designer are listed below:

- Deadweight Tonnage (*DWT*) is the weight of cargo, fuel, water and stores necessary to submerge a vessel from her light draft to her loaded draft. This tonnage should not be confused with the weight of the ship. It is the "dead" weight of the cargo, etc., in distinction to the "live" weight of the ship.
- Displacement Tonnage (*W*) is the weight of the vessel. The weight of the vessel including fuel, stores, cargo, etc., when she is floating at her deepest possible draft is known as the loaded displacement (*W_L*). When the vessel is completely empty, her weight is known as light displacement (*W_E*).
- Gross Registered Tonnage (*GRT*) is calculated by measuring in cubic feet the total internal volume of a vessel (less certain exempted spaces) and dividing by 100. *GRT* is not a measurement of weight—but of volume. One "registered" ton, by law, represents 100 ft³ of a vessel's internal space.
- Net Registered Tonnage (*NRT*) is computed by deducting from *GRT* most spaces which are not used for the carriage of cargo or passengers. As in *GRT*, *NRT* is a measure of volume and not of weight.
- Deadweight tonnage (*DWT*) and displacement tonnage for ships (*W*) are expressed in tonnes (2,205 pounds). Deadweight tonnage and displacement tonnage for inland barges are expressed in tons (2,000 pounds). The designer should exercise care when researching vessel traffic and commodity data since some Federal, State, and local port agencies use the short ton (2,000 pounds) to report vessel cargo statistics.

3.5.1 Barge Vessels

Typical inland waterway barge and towboat characteristics are shown in Tables 1 and 2. Figure 1 shows detailed characteristics of three common barge types using the inland waterways. Variations from these typical dimensions exist, and the designer should verify the applicability of the data for the specific waterway and bridge location being evaluated.

C3.5.1

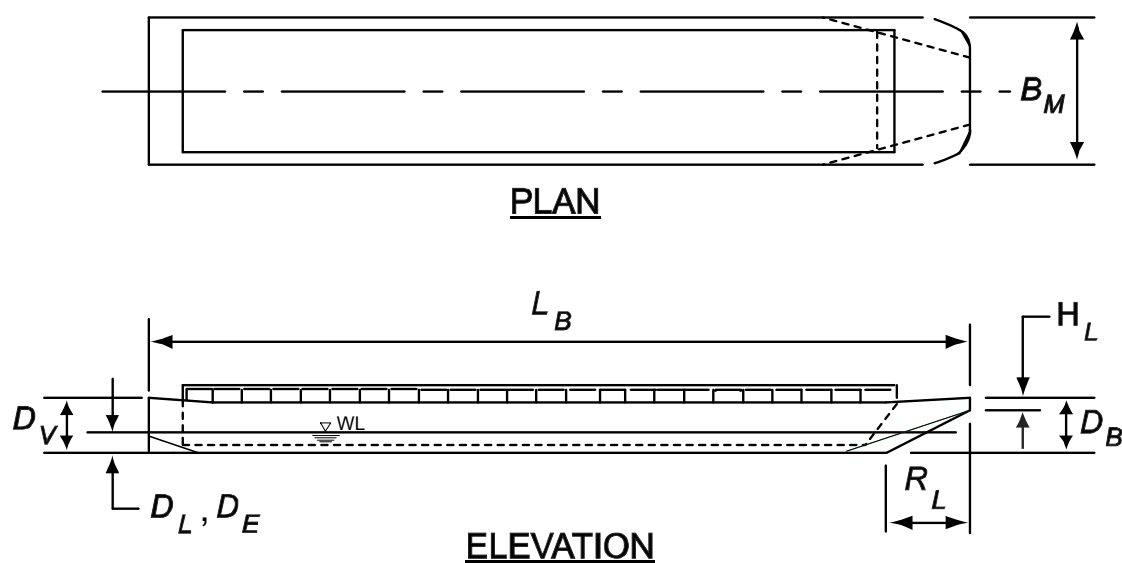
Three basic types of barges are in use on the inland waterway system: hopper (open and covered), deck, and tank barges. Barge sizes vary widely depending on the type of cargo and the waterway characteristics (including navigation locks). The barge data in Tables 1 and 2 were adapted from (Hupp, 1977). The three typical barge sizes and tow data shown in Figures 1 and 2 were based on

Barges are often towed (pushed) in groups of two or more; therefore, their dimensions and drafts tend to be standard in order to provide hydrodynamic efficiency. In addition, standardized barge dimensions facilitate the establishment of tow configurations through locks on river systems. Typical tow configurations are shown in Figure 2.

research conducted on the inland waterways of Louisiana (including the Mississippi River) by the consulting firm of Modjeski and Masters (LaDOTD and FHA, 1985). The applicability of the Figure 1 barge sizes should be verified by the bridge designer for other locations. As an example, the typical standard hopper barge on the upper tributaries of the Ohio River is 175 ft by 26 ft due to locks smaller than the modern standard of 600 ft by 110 ft.

Barges are pulled/pushed by towboats. Towboats vary in size by their function and the reach of the inland waterways system on which they operate. Towboats typically push tows of 4 to 40 barges between major terminals and port areas. The larger tows are found on the Lower Mississippi River below St. Louis where river width and depth permit their operation (LaDOTD and FHA, 1985). Tows of 15 or more barges are found on other major rivers on the inland system. The Missouri, the upper reaches of the Mississippi, and several tributaries of the Ohio have small locks and/or restrictive channels which limit tow size to less than 10 barges. Small harbor tugs are often used to move barges (usually up to four) within a port or harbor area. The designer must establish typical tow sizes for the waterway/bridge location in order to use the methodology in the Guide Specifications.

Sources for barge tow data are the U.S. Army Corps of Engineers, Water Resources Support Center, Fort Belvoir, Virginia, which keep records at all of its lock locations on barge tow activity, and the American Waterway Operators, Inc., Alexandria, Virginia, which is a trade association representing the inland waterway transportation industry. Logbooks maintained at movable bridge locations by State Departments of Transportation are often helpful in obtaining statistics on vessel activity in a waterway.

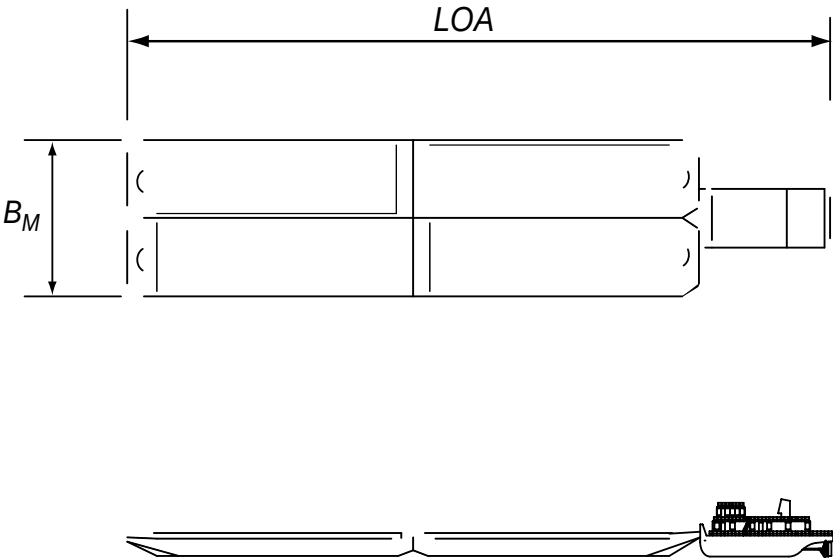


		Jumbo Hopper	Oversize Tank	Special Deck
B_M	= width (ft)	35	53	72
L_B	= length (ft)	195	290	250
H_L	= head log height (ft)	2–3	2–3	3–5
D_V	= depth of vessel (ft)	12	12	17
D_B	= depth of bow (ft)	13	13	18
R_L	= bow rake length (ft)	20	25	30
D_L	= loaded draft (ft)	8.7	8.7	12.5
D_E	= empty [light] draft (ft)	1.7	1.7	2.5
C_C	= cargo capacity (tons)	1700	3700	5000
W_E	= empty displacement (tons)	200	600	1300
W_L	= loaded displacement (tons)	1900	4300	6300
WL	= waterline			

Figure 3.5.1-1—Typical Barge Tow Characteristics

Table 3.5.1-1—Typical Characteristics of Barges on the Inland Waterways System

Barge Type	Size	Length (ft)	Width (ft)	Draft (ft)	Capacity (tons)
Open Hopper	Small	120	30	7	630
Open Hopper	Standard	175	26	9	1,060
Open Hopper	Jumbo	195	35	9	1,700
Open Hopper	Oversize	245	35	10	2,400
Covered Hopper	Jumbo	195	35	9	1,700
Deck Barge	Small	100/150	26/32	6	350/600
Deck Barge	Jumbo	195	35	9	1,700
Deck Barge	Oversize	200	50	9	2,050
Tank Barge	Small	135	40	9	1,300
Tank Barge	Jumbo	195	35	9	1,700
Tank Barge	Oversize	185/290	53	9	2,530/3,740



ELEVATION

Barge Type	Average Size of Barge in Tow	Average Number of Barges Along the Length of Tow
Jumbo Hopper	35 × 195	3
Oversize Tank	53 × 290	2
Special Deck	72 × 250	1

Figure 3.5.1-2—Typical Barge Configurations

Table 3.5.1-2—Typical Characteristics of Towboats on the Inland Waterways System

Towboat Type	Horsepower	Typical Length (ft)	Typical Width (ft)	Typical Draft (ft)
Harbor Boat	<600	50	16	4 1/2
Line Haul	600–1200	78	23	7
Line Haul	1200–2500	120	30	9
Line Haul	2500–4300	146	35	9
Line Haul	4300–8400	160	45	9
Line Haul	>8,400	185	55	9

3.5.2 Ship Vessels

Ship characteristics vary considerably depending on the size, draft, and type of cargo being carried by the vessel. Figure 1 contains three broad classes of ships typical of U.S. waterways. The ship classes include bulk carriers, product carriers/tankers, and freighter/container vessels. Figures 2 through 6 and Tables 1, 2, and 3 contain data on typical sizes, dimensions, drafts, bow shapes, and vertical clearances for these ship classes. Variations from these typical dimensions exist and the designer should verify the applicability of the data for the specific waterway and bridge location being evaluated. In particular the designer should determine if partially

C3.5.2 Ship Vessels

Ship characteristics vary considerably depending on the size, draft, and type of cargo being carried by the vessel. The three broad classes of bulk carriers, product carriers/tankers, and freighter/container vessels presented in the Guide Specifications cover the majority of vessels using U.S. Waterways. Special ships such as passenger ships, LASH vessels, LNG carriers, and naval vessels are not included in the data presented in the Guide Specifications. Data for such special ships will require additional research and judgment by the designer if they form a significant portion of the vessel traffic in a particular waterway.

loaded vessels, due to channel depth restrictions, use the waterway.

Whenever possible, the ship characteristics associated with the particular vessels using a waterway should be developed by the designer. If such data are not readily available, the typical ship data shown in Figures 2, 3, and 4, and Tables 1, 2, and 3 should be utilized (Scott, 1985; Scott, 1984; Yokohama Rubber, 1980).

One of the most difficult statistics to obtain for merchant ships is vertical clearance data. Practically all published records on ship data do not include this vital statistic which is so important to bridge designers. The information in Figures 5 and 6 for ship mast and deckhouse clearances was developed from scaled vessel drawings representing over 2,300 merchant ships provided (Scott, 1985; Scott, 1984). Figure C1 is a plot of the data for mast height clearances for freighter/container vessels illustrating the typical scatter in vessel dimensions.

Another difficult statistic to obtain, and one which significantly affects the vulnerability of a bridge to vessel collision and vertical clearance requirements, is the ballasted draft of vessels which are transiting the waterway in either an empty or partially loaded condition. All merchant ships have the capability to pump water into special compartments located in the bow and along the sides of the ship in order to minimize exposed freeboard and increase the vessel draft for proper steering and maneuverability when the vessel is traveling either empty or partially loaded. The degree to which the ship is ballasted depends solely upon the ship's master or pilot's decision given the wind and current conditions in a particular waterway. Unless otherwise determined from the actual vessels using the waterway, a ballasted ship geometry as shown in Figure 4 is recommended for design. The ballasted ship geometry of Figure 4 was based on observations and discussions with ship operators and pilots.

The ability of a ship to strike a bridge pier or superstructure element is limited primarily by the water depths in the waterway and navigable channel and the geometry of the bridge and the ship. The determination of ship draft (loaded and ballasted) and available water depth are key factors in the vessel impact analysis. In utilizing the typical ship data in this Article, the bridge designer should be aware that very large merchant ships frequently transit U.S. waterways in partially loaded conditions due to draft limitations in the navigable channel. Modifications to the typical data must be made to account for such vessels. As an example, an 80,000 DWT bulk carrier with a fully loaded draft of 45.6 ft would typically transit partially loaded with a draft of only 33.0 ft in a channel whose limiting water depth was 35.0 ft. In this condition the mast height and bow height above the waterline would be 12.6 ft higher than when fully loaded.

For vessels transiting in other than a fully loaded condition, the displacement weight can be estimated by:

$$W = \frac{(C_B)(L_W)(B_M)(D_M)}{W_W} \quad (C3.5.2-1)$$

where:

W = displacement weight of vessel tonnes,

C_B = block coefficient (dimensionless),

L_W = length of vessel waterline (ft),

D_M = mean draft (ft),

B_M = mean breadth (ft), and

W_W = 34.4 (cubic feet per tonne of saltwater); 35.4 (cubic feet per tonne of freshwater).

The block coefficient, C_B , is the ratio of the immersed section of the vessel to a block having the same length, width, and depth. C_B can be estimated by substituting W_L and other values for the fully loaded vessel into Eq. C1. Using the same value of C_B , the displacement weight of the vessel for other drafts representing different loading conditions and drafts can be estimated using Eq. C1. Setting $L_W = LOA$ is usually assumed in using Eq. C1 since data on L_W is difficult to obtain. The use of LOA results in no significant error in computing C_B and W .

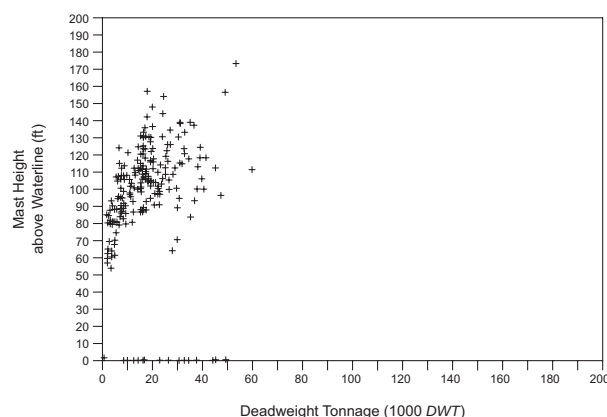
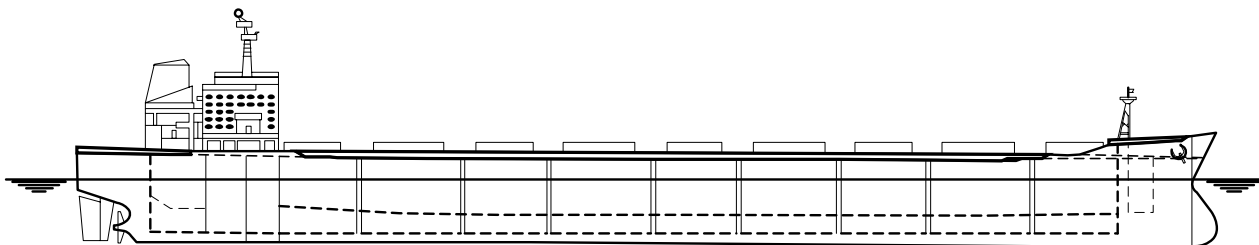
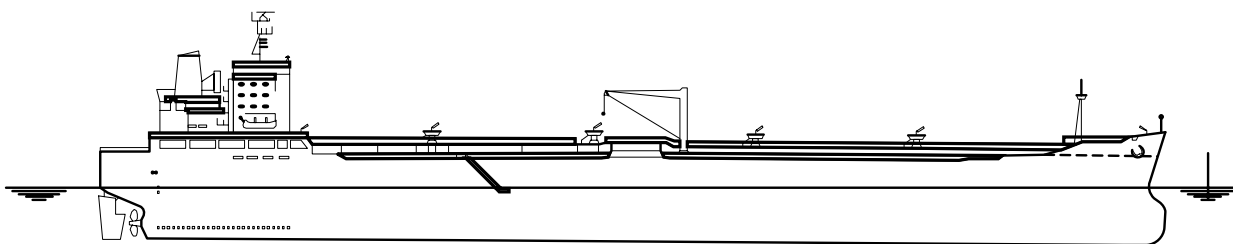


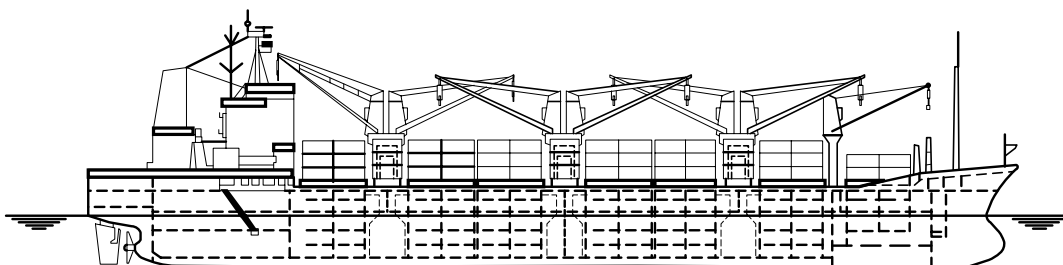
Figure C3.5.2-1—Typical Mast Height Clearance Data for Loaded Freighter/Container Ships (see Figure 3.5.2-5)



a. 81,000-DWT Bulk Carrier (length = 855 ft)



b. 67,000-DWT Product Carrier/Tanker (length = 800 ft)



c. 22,000-DWT Multipurpose Freighter/Container Ship (length = 670 ft)

Figure 3.5.2-1—Typical Ship Profiles

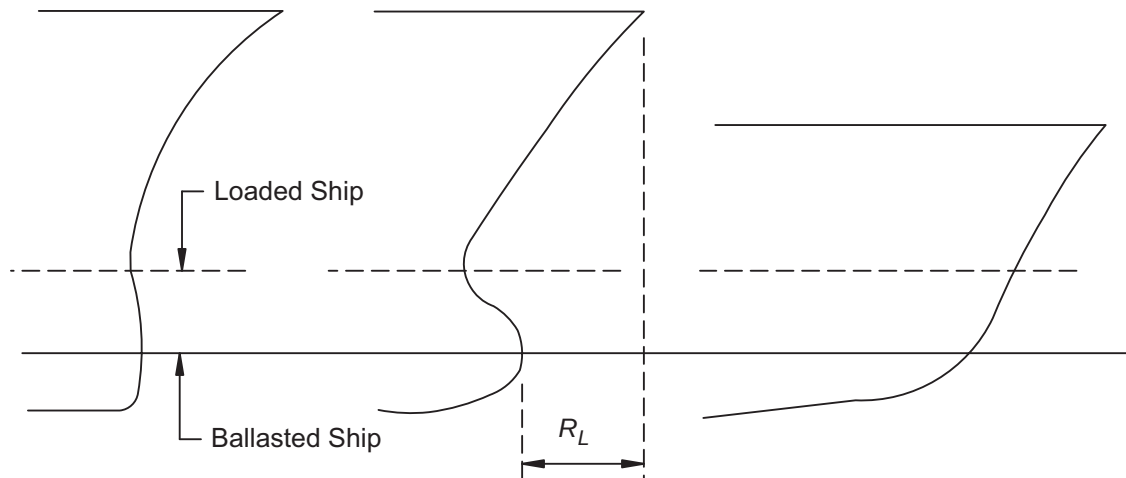
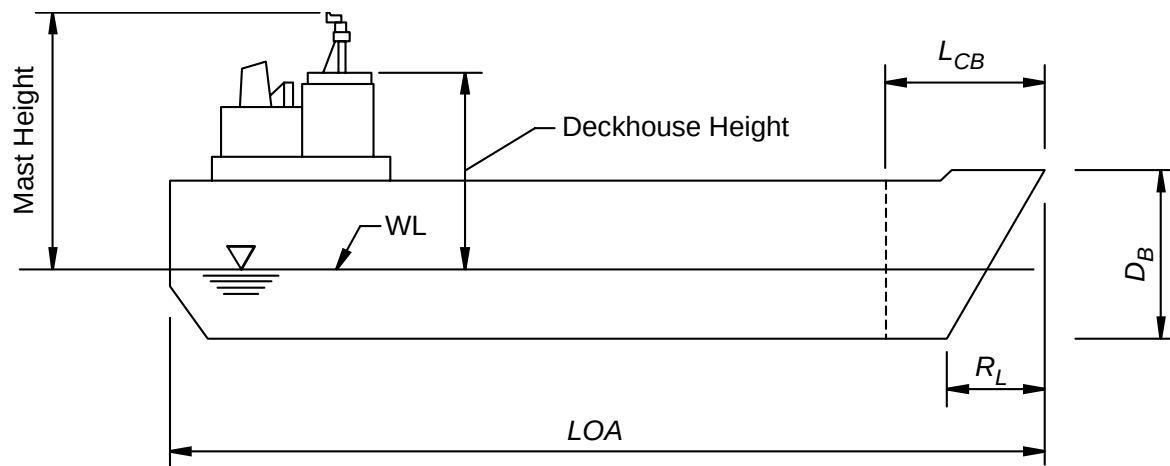
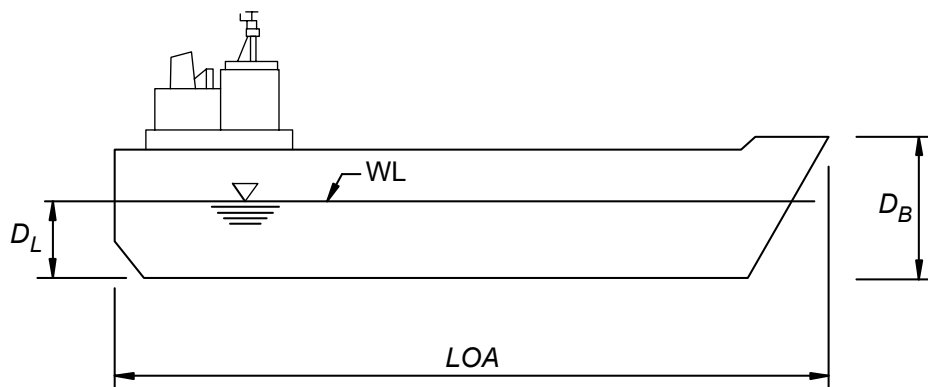


Figure 3.5.2-2—Common Ship Bow Shapes

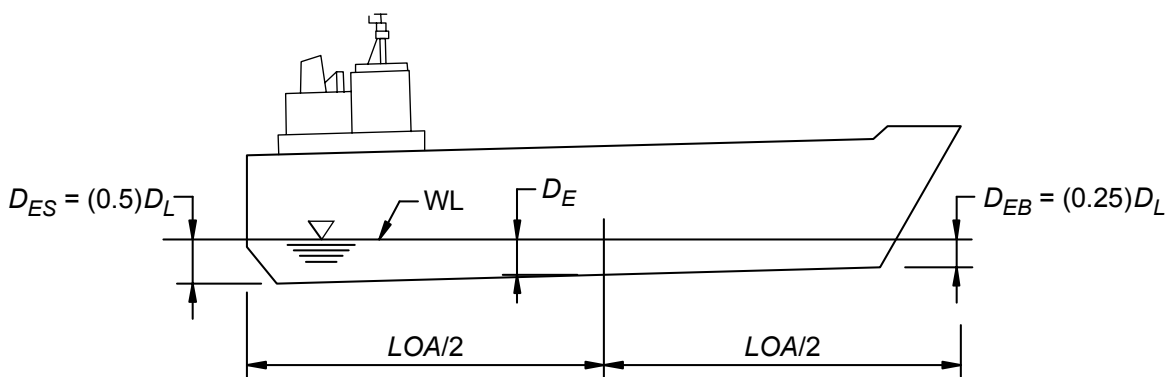


- D_B = depth of bow
 R_L = rake length of bow $\cong 0.25 D_B$
 L_{CB} = length to collision bulkhead $\cong 0.1(LOA)$
 LOA = length overall of ship
 WL = waterline

Figure 3.5.2-3—Typical Ship Bow and Vertical Clearance Dimensions



a. Loaded Ship Profile



b. Ballasted Ship Profile

Figure 3.5.2-4—Typical Ship Characteristics

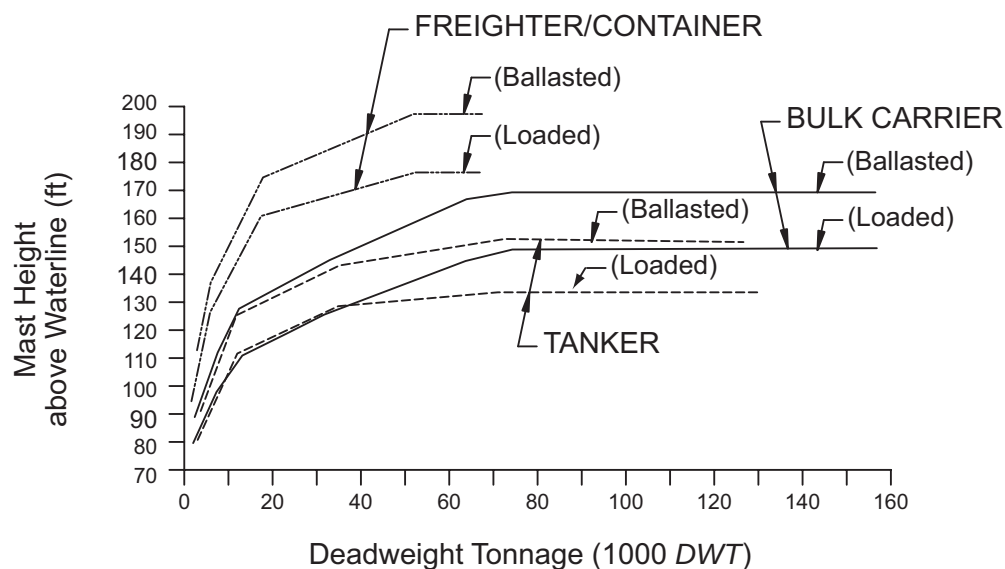


Figure 3.5.2-5—Typical Ship Mast Clearance Heights

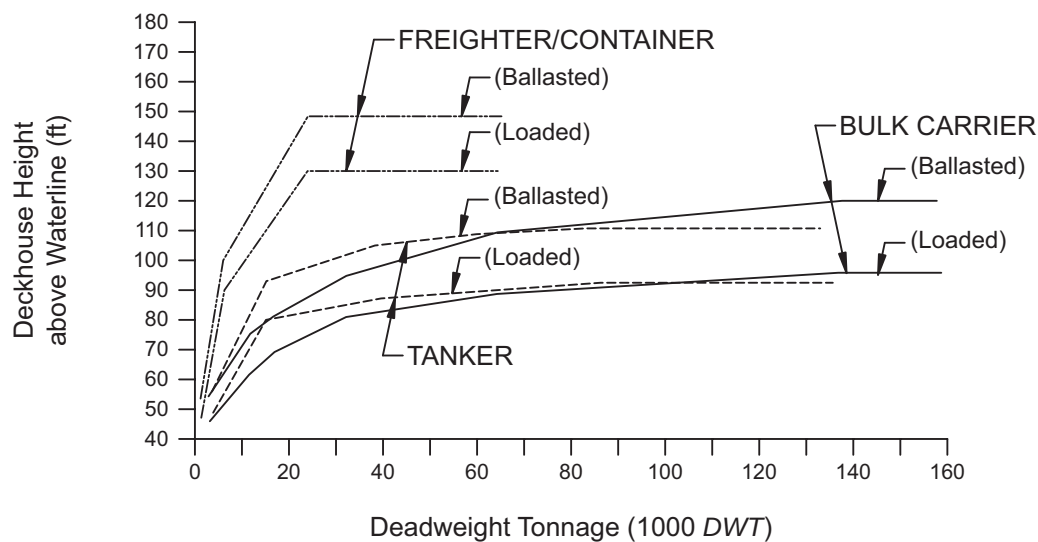


Figure 3.5.2-6—Typical Ship Deckhouse Clearance Heights

Table 3.5.2-1—Typical Bulk Carrier Ship Characteristics

Ship DWT, tonnes	Length LOA, ft	Beam, B_M , ft	Bow Depth D_B	Fully Loaded		Ballasted		
				Draft D_L , (ft)	Displacement W_L , tonnes	Draft D_{EB} , ft	Draft D_{ES} , ft	Displacement W_E , tonnes
1,000	200	29.2	27.2	14.1	1,500	3.5	7.1	600
3,000	289	41.7	38.2	22.3	4,200	5.6	11.2	1,600
5,000	341	48.9	45.2	21.3	6,800	5.3	10.7	2,600
10,000	459	61.4	57.6	26.6	13,100	6.7	13.3	4,900
15,000	515	70.5	64.2	29.5	19,300	7.4	14.8	7,200
20,000	558	77.8	68.4	31.5	25,500	7.9	15.8	9,600
25,000	577	82.4	70.8	32.2	31,500	8.1	16.1	11,800
30,000	630	89.6	74.1	34.8	37,500	8.7	17.4	14,100
40,000	682	99.1	77.8	37.4	49,400	9.4	18.7	18,500
50,000	728	107.0	80.2	39.0	61,100	9.8	19.5	22,900
60,000	771	109.3	83.7	40.4	72,800	10.1	20.2	27,300
80,000	850	120.1	86.2	43.3	95,800	10.8	21.7	35,900
100,000	902	137.8	92.8	52.8	118,600	13.2	26.4	44,500
150,000	1027	146.0	99.7	59.1	174,700	14.8	29.6	65,500

Table 3.5.2-2—Typical Product Carrier/Tanker Ship Characteristics

Ship DWT, tonnes	Length LOA, ft	Beam B_M , ft	Bow Depth, D_B	Fully Loaded		Ballasted		
				Draft D_L , ft	Displacement W_L , tonnes	Draft D_{EB} , ft	Draft D_{ES} , ft	Displacement W_E , tonnes
1,000	187	30.8	25.0	13.8	1,400	3.5	6.9	500
3,000	279	42.0	35.4	19.4	4,100	4.9	9.7	1,500
5,000	335	48.2	41.8	22.6	6,700	5.7	11.3	2,500
10,000	456	62.3	53.6	26.6	13,000	6.7	13.3	4,900
15,000	515	71.2	60.2	29.5	19,300	7.4	14.8	7,200
20,000	561	78.1	65.1	32.2	25,400	8.1	16.1	9,500
25,000	577	83.7	68.7	33.1	31,500	8.3	16.6	11,800
30,000	637	89.2	71.7	34.8	37,500	8.7	17.4	14,100
40,000	692	98.1	75.8	38.4	49,500	9.6	19.2	18,600
50,000	741	105.3	78.5	41.0	61,400	0.3	20.5	23,000
60,000	774	111.5	81.8	42.0	73,200	0.5	21.0	27,500
80,000	853	122.4	83.6	45.6	96,500	11.4	22.8	36,200
100,000	886	128.0	85.0	47.9	119,700	12.0	24.0	44,900
120,000	915	138.9	88.2	50.9	142,600	12.7	25.5	53,500
150,000	955	145.0	90.6	58.7	176,800	14.7	29.4	66,300

Table 3.5.2-3—Typical Freighter/Container Ship Characteristics

Ship DWT, tonnes	Length LOA, ft	Beam B_M , ft	Bow Depth, D_B	Fully Loaded		Ballasted		
				Draft D_L , ft	Displacement W_L , tonnes	Draft D_{EB} , ft	Draft D_{ES} , ft	Displacement W_E , tonnes
1,000	190	31.2	23.0	13.8	1,400	3.5	6.9	500
3,000	282	43.3	39.0	19.4	4,200	4.9	9.7	1,600
5,000	338	50.5	44.9	22.3	7,000	5.6	11.2	2,600
7,000	423	57.7	52.8	24.6	9,700	6.2	12.3	3,600
10,000	472	63.6	58.0	26.9	3,800	6.7	13.5	5,200
12,000	499	65.9	60.8	28.9	16,600	7.2	14.5	6,000
16,000	617	84.3	76.2	30.8	24,800	7.7	15.4	9,300
20,000	643	90.6	80.4	34.4	31,600	8.6	17.2	11,850
24,000	697	98.4	82.0	34.4	36,700	8.6	17.2	13,800
27,000	717	102.4	86.0	36.7	42,200	9.2	18.4	15,800
33,000	863	105.6	86.5	37.7	51,600	9.4	18.9	19,400
49,700	950	106.0	94.8	36.1	77,000	9.0	18.1	28,900
54,500	903	129.2	96.4	41.0	84,500	10.3	20.5	31,700

3.5.3 Special Vessels

A variety of special ship and barge vessels transit U.S. waterways. These include ocean-going barges, dredges, offshore industry transports, jack-up boring rigs, barge mounted cranes, passenger ships, Liquefied Natural Gas (LNG) vessels, and naval vessels. The applicability of the Specification is limited with respect to these vessel types and judgment must be exercised in evaluating their influence on the vessel collision problem.

3.6 DESIGN VESSEL

A design vessel shall be determined for each bridge element exposed to collision. The design vessel shall be selected in accordance with the requirements of Article 4.1 using Method II and its corresponding acceptance criteria in Article 4.8.2 unless the approval of the Owner and the special situations stated in Article 4.1.2 exist.

C3.6

Three alternative methods for selecting the design vessel for collision impact are presented in the Guide Specifications. Method II shall be used for all bridge design unless approval by the Owner and the special situations stated in Article 4.1.2 exist. Methods I, II, and III vary from relatively simple to use to relatively complex. All of the methods are suitable for manual computation. A brief overview discussion of each method is presented below. A detailed discussion of each method is presented in the Commentary in Section 4.

1. Method I is a semi-deterministic procedure for selecting the design vessel for collision impact. Method I is the simplest of the three methods to use, but is also the most conservative, resulting in higher impact forces than those developed in Method II.
2. Method II is a probability-based (risk) analysis procedure for selecting the design vessel for collision impact. Significantly more complicated than Method I, Method II requires a relatively large amount of data to conduct the analysis.

the Method II probability procedures results in a more realistic assessment of the risk of vessel collision with a bridge structure, and therefore a more accurate selection of the appropriate collision impact loads.

3. Method III is a cost-effectiveness analysis procedure for selecting the design vessel for collision impact. The determination of annual frequency of bridge collapse, AF , required in Method III shall be computed using Method II. The disruption costs associated with a potential bridge collapse are evaluated using standard benefit/cost (B/C) analysis to determine the cost-effectiveness of bridge strengthening or bridge protection measures.

3.7 DESIGN IMPACT SPEED

The design impact speed for each exposed bridge element in the waterway shall be determined based on the typical vessel transit speed within the navigable channel limits, the distance to the location of the bridge element from the centerline of vessel transit path, and the vessel length overall (LOA). The centerline of vessel transit path shall be determined according to Article 4.2.1. The typical vessel transit speed (V_T) shall represent the typical speed at which the design vessel is transiting the waterway in the vicinity of the bridge under normal environmental circumstances. A different transit speed for inbound and outbound vessels may be required depending on water current conditions in the waterway.

The design impact speed for each bridge element in the waterway shall be determined as shown in Figure 1. The design impact speed distribution shall be based on the geometry of the bridge, the navigable channel width, and the length overall (LOA) of each vessel in the design fleet.

For ship and barge tows transiting the waterway under their own power, the primary area of vessel collision concern is a central region or zone near the main navigation span of the bridge. The width or boundary of this navigation zone used in the vessel collision analysis is defined as a distance equal to $3 \times LOA$ on each side of the vessel transit path (which coincides with the channel centerline for most bridges). For barge tows, the length overall shall be equal to the total length of the tow including the barges and tug/tow boat vessel as shown in Figure 3.5.1-2.

The $3 \times LOA$ distance is also used to distribute the vessel impact speed over each of the piers located in the navigation zone as shown in Figure 1, where V = design impact speed; V_T = typical vessel transit speed in the channel; V_{MIN} = minimum impact speed (associated with the current in the waterway); x = the distance from centerline of vessel transit path; x_C = distance to the edge of channel; and $x_L = 3 \times LOA$ from the centerline of the vessel transit path.

C3.7

The selection of the design impact speed is one of the most significant design parameters associated with the vessel collision Specifications. Judgment must be exercised by the designer in determining the appropriate design speed for a vessel transiting the waterway. The chosen speed should reflect the “typical” transit speed of the design vessel under “typical” conditions of wind, current, visibility, opposing traffic, waterway geometry, etc. A different vessel speed may be required for inbound vessels than for outbound vessels given the presence of currents which may exist in the waterway.

In general, the design speed should not be based on extreme values representing extreme events such as flooding, hurricanes, and other extreme environmental conditions. Vessels transiting under these conditions are not representative of the “annual average” situations reflecting the typical transit situations.

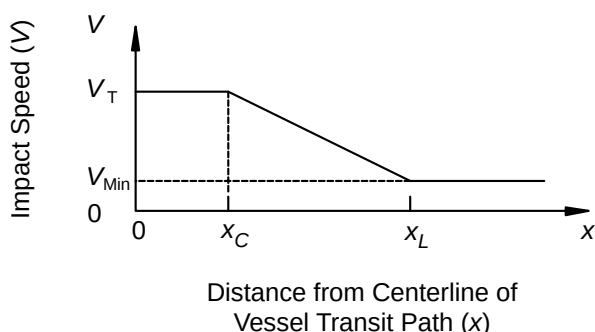
The use of a triangular distribution of vessel impact speed across the length of the bridge and centered on the centerline of the vessel transit path (Figure 1), reflects a departure from previous models of vessel collision risk assessment. The recommended use of a triangular distribution was based on the project consultants review of accident case histories during development of the Guide Specifications. While the data is certainly sparse, it seems clear that aberrant ships and barges which collide with bridge piers further away from the channel are moving at reduced speeds than those piers located closer to the navigable channel limits. Aberrant vessels located at large distances from the channel are usually drifting with the current. Aberrant vessels located very near the channel are moving at speeds approaching the speeds of ships and barges in the main channel.

The exact distribution of the speed reduction is unknown. However, a triangular distribution was chosen for the Specifications because of its simplicity, as well as its reasonableness in modeling the aberrant vessel speed situation. As shown in Figure 1, the typical vessel transit speed in the waterway is constant to the edge of the

As a minimum, the design impact speed shall be equal to the yearly mean current for the waterway location. In waterways where seasonal flooding represents a significant portion of the current activity, judgment must be used to establish the basis for determining the minimum impact speed. Judgment must also be used on the effects of prevailing wind acting in the waterway and upon the exposed vessel.

channel at which point it decreases to the minimum design speed value at a distance $3 \times LOA$ from the centerline of vessel transit path. The use of the distance $3 \times LOA$ to define the limits at which the design speed becomes equal to the water current was based on the observation that very few accidents (other than drifting vessels) have historically occurred beyond that boundary. Additional discussion of historical accident data is contained in Article C4.8.3.3.

The 1991 Guide Specifications (Article 3.7 on Design Impact Speed and Article 4.8.3.3 Geometric Probability) required the use of a vessel length overall (LOA) selected in accordance with the Method I criteria for use in estimating the impact speed and geometric probability for all vessel classifications. This provision has been revised in the new Guide Specifications to allow for the LOA of each specific vessel category to be used in determining the vessel speed distribution and geometric probability associated with that specific vessel category.



V = design impact speed (ft/s)

V_T = design impact speed (ft/s)

V_{Min} = minimum design impact speed (ft/s)

x = distance to bridge element from centerline of vessel transit path (ft)

x_C = distance to edge of channel from centerline of vessel transit path (ft)

x_L = distance equal to $3 \times LOA$ from centerline of vessel transit path (ft)

Figure 3.7-1—Design Impact Speed

3.8 VESSEL COLLISION ENERGY

The kinetic energy of a moving vessel to be absorbed during a collision with a bridge pier shall be determined by the following:

$$KE = \frac{C_H W(V)^2}{29.2} \quad (3.8-1)$$

where:

KE = vessel collision energy (kip-ft),

C3.8

Equation 3.8-1 in the 1991 Guide Specifications was developed using the standard relationship for computing the kinetic energy, KE , of a moving body as:

$$KE = \frac{m(V)^2}{2} = \frac{W(V)^2}{2g} \quad (C3.8-1)$$

where:

m = mass of the vessel,

C_H = hydrodynamic mass coefficient,

W = vessel displacement tonnage (tonnes), and

V = vessel impact speed (ft/s).

V = vessel impact speed,

W = vessel displacement tonnage; and

g = acceleration due to gravity (ft/s²).

The vessel displacement tonnage, W , equals the weight of the vessel when empty plus the weight of the ballast and cargo (DWT) being carried by the vessel.

The displacement tonnage for barge tows shall equal the displacement of the tug/tow vessel plus the combined displacement of the number of barges in the length of the tow. The number of barges across the width of the tow are neglected in computing the impact energy of the tow (and therefore the impact force as well) since they are assumed to break away upon impact.

The hydrodynamic mass coefficient, C_H , accounts for the mass of water surrounding and moving with the vessel; therefore, the inertia force from this mass of water has to be added to that of the vessel. C_H varies depending on many factors such as, water depth, underkeel clearance, distance to obstacles, shape of the vessel, vessel speed, currents, position of the vessel, direction of vessel travel, stiffness of bridge and fender systems, and the cleanliness of the vessel's hull underwater. For a vessel moving in a straight forward motion, the following values of C_H shall be used, unless determined otherwise by accepted analysis procedures:

1. for large underkeel clearances ($\geq 0.5 \times \text{Draft}$),

$$C_H = 1.05$$

2. for small underkeel clearances ($\leq 0.1 \times \text{Draft}$),

$$C_H = 1.25$$

The underkeel clearance is the distance between the bottom (keel) of a vessel and the bottom of the waterway. C_H for underkeel clearances between the large and small limits discussed above may be estimated by interpolating.

Expressing KE in kip-ft, W in tonnes (1 tonne = 2.205 kips), V in ft/s, $g = 32.2$ ft/s², and including the hydrodynamic mass coefficient, C_H , in Eq. C1 results in the equation:

$$KE = \frac{2.205 (C_H)(W)(V)^2}{(2)(32.2)} = \frac{(C_H)(W)(V)^2}{29.2} \quad (C3.8-2)$$

Included in this equation is a hydrodynamic mass coefficient, C_H , to account for the influence of the surrounding water upon the moving vessel.

It is difficult to find a single value for C_H because of the many factors which influence its magnitude. PIANC (1984) provides an extensive discussion of the various investigations which have been conducted to measure and compute C_H associated with vessel berthing and fender design, and discusses the wide scatter of the reported results. On the basis of its investigation, PIANC (1984) states that unless the designer has good reasons to adopt other values, to assume C_H to range between 1.5 (for large underkeel clearances) and 1.8 (for small underkeel clearances) for computing the kinetic energy associated with ship berthing. These values apply to ships which are approaching a berthing wharf from a lateral (broadside) direction. During such lateral motions a relatively large mass of water moves with the vessel. For vessels moving in a forward direction however, a smaller mass of water moves with the vessel, and therefore the values of C_H are smaller than those encountered in berthing maneuvers.

One of the basic concepts of the Guide Specifications is that the impact loadings represent the worst-case, head-on collision situation with the vessel moving in a forward direction at relatively high speed. For acceleration in the direction of the ship's length, and for waterways with large underkeel clearances, a constant value of $C_H = 1.05$ may be used (Saul and Svensson, 1980). For waterways with small underkeel clearances, the 1.05 value was increased by the ratio (1.8/1.5) to the approximate value of $C_H = 1.25$, which is similar to the increase in hydrodynamic mass discussed in the previous paragraph for vessel berthing.

While not a requirement in the Specifications, the ability to compute the impact energy due to an oblique collision is often times useful. The collision energy, KE , to be absorbed by either the vessel or the bridge structure during a collision event, E , is a function of the impact angle, α , and the coefficient of friction, μ , between the colliding vessel and the bridge structure. Research by Saul and Svensson (1980) indicates the following relationship:

$$E = \eta(KE) \quad (C3.8-3)$$

Values of η are shown in Figure C1 as a function of the impact angle and coefficient of friction based on research by Woisin, Saul, and Svensson.

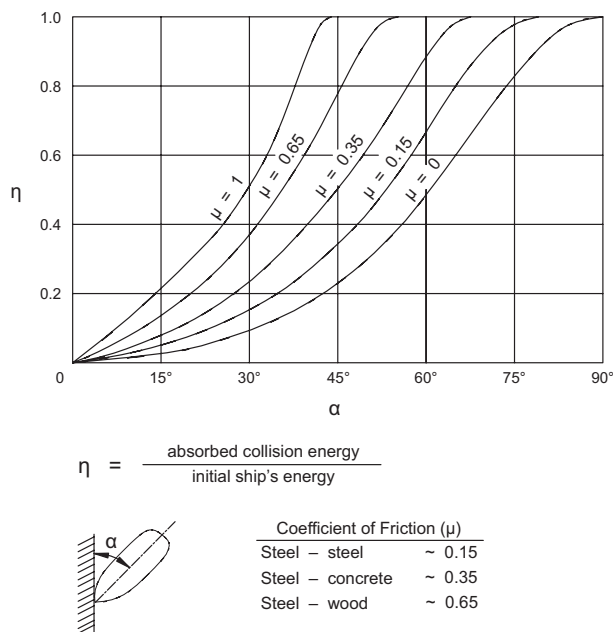


Figure C3.8-1—Portion of Collision Energy to Be Absorbed by the Ship or Bridge Structure in Relation to the Collision Angle and the Coefficient of Friction (Saul and Svensson, 1980)

Studies on multibarge tow impact forces by the University of Kentucky (Yuan, Harik and Davidson, 2005) have indicated that counting the barges in the length of the tow may yield conservative impact forces using the AASHTO equations, particularly in those cases where the width of the pier is smaller (approximately 10 percent) than the width of the barge. Where the width of the pier is about 50 percent of the width of the barge, the barge impact forces are close to the AASHTO values, and where the width of the pier is about the same or greater than the width of the barge, the AASHTO forces are less than those computed using finite element models and dynamic analysis. Their research indicates that an “accordion” type effect occurs where the barges in the tow length buckle upward/downward—which reduces the impact energy being transferred to the pier. The Kentucky studies also indicate that the barges in the width of the tow do not simply break away on impact, but stay connected sufficiently to impart some of their energy in the collision. Interestingly, using dynamic analysis finite element methods applied to the entire multibarge tow (flotilla) resulted in overall impact forces very similar to the forces derived using the AASHTO method (i.e., the reduction of the force by barges buckling in the length of the tow is offset by an increase

3.9 SHIP COLLISION FORCE ON PIER

The ship collision equivalent static impact force associated with a head-on collision with a rigid object shall be computed by the following for Product Carrier/Tanker, Bulk Carrier, and Freighter/Container vessels:

$$P_S = 220 (DWT)^{1/2} \left(\frac{V}{27} \right) \quad (3.9-1)$$

where:

P_S = equivalent static ship impact force (kips),

DWT = deadweight tonnage of ship (tonnes), and

V = ship impact speed (ft/s).

A more rigorous generally accepted dynamic analysis procedure may be used in lieu of the recommended static analysis procedure. Such procedure shall be based on an accepted impact force/damage length relationship established by model testing or structural analysis. If transient or permanent deflections or movements of a bridge component are introduced in the analysis, the force reducing effect must be documented by a dynamic analysis.

A graphic of ship impact forces computed using Eq. 1 is shown in Figure 1.

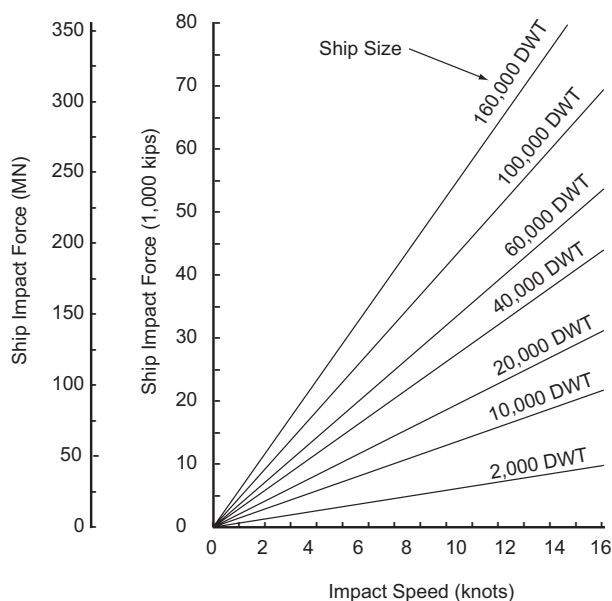


Figure 3.9-1—Ship Impact Forces

in force caused by the influence of the adjacent barges in the width of the tow).

C3.9

The determination of the impact load on a bridge structure during a ship collision is extremely complex and depends on many factors such as the structural type and shape of the ship's bow, the degree of water ballast carried in the forepeak of the bow, the size and speed of the ship, the geometry of the collision, and the geometry and strength characteristics of the bridge pier.

European, Japanese, and U.S. experimentation utilizing physical and mathematical models for collision tests of various types of vessels have resulted in the development of several empirical relationships for estimating the crushing load of a ship's bow, which is an upper limit for the collision force on the bridge (IABSE, 1983).

Equation 3.9-1 of the 1991 Guide Specifications was primarily developed from research conducted by Woisin in Hamburg, West Germany, from 1967–1976 to generate collision data to protect the reactors of nuclear powered ships from collisions with other ships (Woisin, 1976). The ship collision data resulted from a total of 24 collision tests with 12 pairs of physical ship models at scales 1:12 and 1:7.5 as shown in Figure C1. Woisin's results have been found to be in good agreement with research conducted by other ship collision investigators worldwide (IABSE, 1983).

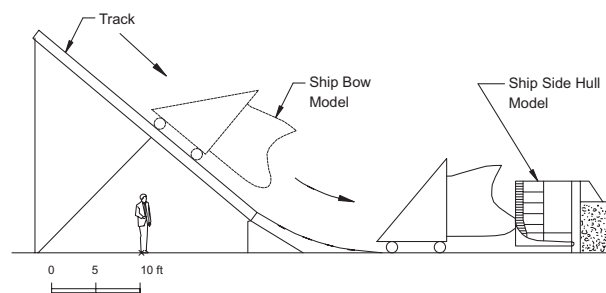


Figure C3.9-1—Elevation View of Set-Up for Woisin's Ship Model Collision Tests at Howldtswerke-Deutsche Werft, Hamburg (Woisin, 1971)

A schematic representation of the typical dynamics of impact force over time is shown in Figure C2 for Woisin's model tests. An oscillation of the striking mass and impact force occurred during the initial phase of the impact with a duration of 0.1 to 0.2 seconds for a real ship. During this phase the amplitude sometimes increased to twice the mean value of the impact force. Unfortunately, however, accurate collision force-time histories were not obtained during the testing due to electronic measuring difficulties in the instrumentation and induced vibrations in the model test set-up. As a result, it was not possible to evaluate the compression phase of the impact over time, $P(t)$.

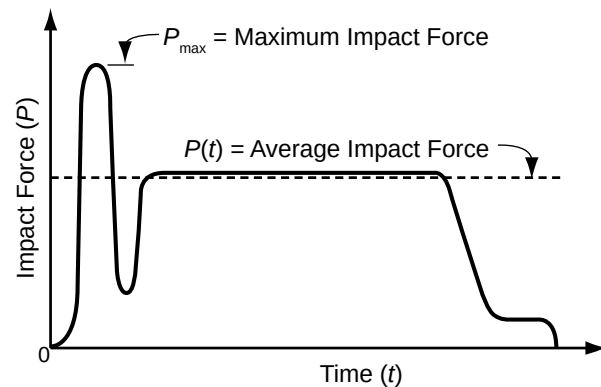


Figure C3.9-2—Schematic Representation of Ship Impact Force History from Collision Tests Conducted by Woisin and Gerlach, 1970

Woisin did compute the mean impact force, $\bar{P}(a)$, averaged over the bow damage depth, a , by dividing the loss in kinetic energy, KE , by the bow damage depth. A typical plot of impact force and energy over the bow damage depth is shown in Figure C3.

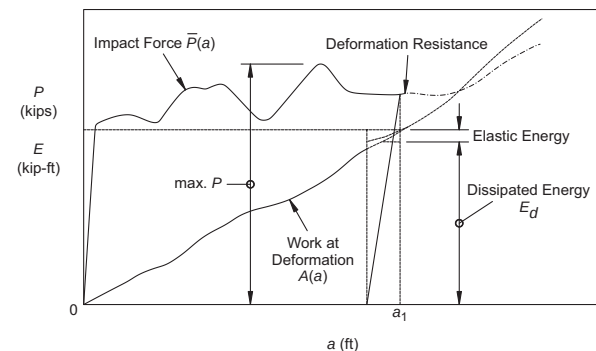


Figure C3.9-3—Impact Force, P , and Energy, E , in Relation to the Vessel Damage Depth, a , (Woisin, 1971)

Based on theoretical and model test results, Woisin developed the following relationship between the mean impact force averaged over time, $\bar{P}(t)$, and the mean impact force averaged over the damage depth, $\bar{P}(a)$:

$$\bar{P}(t) = (1.25) \bar{P}(a) \quad (\text{C3.9-1})$$

The major influences affecting the mean impact force arranged in order of decreasing importance by Woisin were: 1) ship size (DWT), 2) type of ship, 3) shape and structure of bow, 4) amount of ballast water in the bow, and 5) the impact speed. Due to the varying influences, a ± 50 percent scatter in the ship impact force was measured as shown in Figure C4.