March 18, 2025 MIR-25-10

Safeguarding Bridges from Vessel Strikes: Need for Vulnerability Assessment and Risk Reduction Strategies

1. Introduction

The National Transportation Safety Board (NTSB) is providing the following information to urge owners of bridges over navigable waterways frequented by ocean-going vessels, the Federal Highway Administration (FHWA), the US Coast Guard, and the US Army Corps of Engineers to act on the safety recommendations in this report.[1] We identified the need to safeguard bridges from vessel strikes as part of our ongoing investigation of the March 26, 2024, containership *Dali*'s collision with the Francis Scott Key Bridge, and the bridge's subsequent collapse.[2] We completed a vulnerability assessment—a mathematical risk model calculated using data on bridge/span geometry and design, pier protection and lateral capacity, the characteristics of vessel traffic transiting the main navigation channel, waterway characteristics, and other factors—to determine how susceptible the Key Bridge was to collapse from a vessel collision and found that it was above the acceptable level of risk established by the American Association of State Highway and Transportation Officials (AASHTO) for such a collision.[3] We also identified 68 other bridges frequented by ocean-going vessels that were constructed before the AASHTO

[1] An *ocean-going vessel* is a large ship that transits international routes and/or the Great Lakes. Examples include containerships, general cargo ships, tankers, dry bulk carriers, passenger ships, cable-laying ships, research ships, support ships, training ships, and US Navy ships.

[2] (a) Although the maritime definition of *collision* involves two moving vessels striking one another, the findings and recommendations in this report mainly concern bridge design. Therefore, this report uses the term *collision* when discussing a vessel striking a bridge. (b) Visit ntsb.gov to find additional information in the public docket for this NTSB investigation (case number DCA24MM031). Use the CAROL Query to search safety recommendations and investigations.

[3] A *vulnerability assessment* 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. (AASHTO, 2009, *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges*, 2nd ed., 180.)

NOTE: This report was reissued on March 24, 2025, with corrections to the footnotes in Table B-1 on pages 22–25.

guidance was issued in 1991, have not undergone a vulnerability assessment based on recent vessel traffic, and, therefore, have an unknown level of risk of collapse from a vessel collision.

In this interim report, we urge the FHWA, Coast Guard, and Corps of Engineers to form a dedicated, interdisciplinary team that provides guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision. We also urge the owners of the 68 identified bridges to calculate whether the probability of a bridge collapse from a vessel collision is above the acceptable risk threshold established by AASHTO. If so, we urge them to develop and implement a risk reduction plan that includes input from the interdisciplinary team, identifies short- and long-term strategies to reduce risk, and considers the safety of the vessels and structures in the waterways.

2. Background and Analysis

2.1 *Dali* Collision with Francis Scott Key Bridge and Subsequent Bridge Collapse

On March 26, 2024, about 0129 eastern daylight time, the 984-foot-long Singapore-flagged cargo vessel (containership) *Dali* was transiting out of Baltimore Harbor in Baltimore, Maryland, when it experienced a loss of electrical power and propulsion and struck Pier 17, the southern pier that supported the central span of the continuous through-truss of the Francis Scott Key Bridge.[4] A portion of the bridge subsequently collapsed into the river, and portions of the pier, deck, and truss spans collapsed onto the vessel's forward deck (see figure 1).[5] A seven-person road maintenance crew and one inspector were on the bridge when the vessel struck it. The inspector escaped unharmed, and one of the construction crewmembers survived the collapse with serious injuries. Six construction workers died as a result of the bridge collapse. One of the 23 persons aboard the *Dali* sustained a minor injury.

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[4] (a) A *pier* is "a substructure unit that supports the spans of a multi-span superstructure at an intermediate location between its abutments." (FHWA, 2022, *Bridge Inspector's Reference Manual*, Report Number FHWA-NHI-21-002, FHWA National Highway Institute.) (b) A *span* is the horizontal space between two supports of a bridge structure. (b) A *truss* is a "jointed structure made up of individual members primarily carrying axial loads arranged and connected in triangular panels" (FHWA 2022).

[5] A bridge *deck* is "the portion of a bridge that provides direct support for vehicular and pedestrian traffic, supported by the superstructure" (FHWA 2002).

Figure 1. The *Dali*, with portions of the collapsed Key Bridge across its forward deck and in the Patapsco River, on March 28, 2024.

2.2 Francis Scott Key Bridge and Fort McHenry Federal Channel

2.2.1 Francis Scott Key Bridge

The Key Bridge was located in Baltimore, Maryland, and carried Maryland 695 over the Patapsco River, from Baltimore to Dundalk, Maryland.[6] The bridge was owned and operated by the Maryland Transportation Authority (MDTA) and opened to traffic on March 23, 1977. According to the MDTA, the overall length of the bridge was about 9,086 feet between the north and south abutments.[7] The maximum vertical clearance for the Key Bridge above the main navigational channel, the 700-foot-wide Fort McHenry Federal Channel, was 185 feet.[8]

[6] On April 29, 2024, the FHWA approved a request from the State of Maryland to redesignate a segment of Maryland 695, including the Francis Scott Key Bridge, as part of the interstate highway system.

[7] An *abutment* is a structure designed to support the vertical and lateral forces from the ends of an arch or span, such as a bridge.

[8] *Vertical clearance* is the vertical distance between the water level at mean high water and the lowest point of the bridge structure span over a navigation channel, indicating how much space a vessel has to pass underneath without hitting the bridge. Also known as "charted height."

The Key Bridge was designed according to the 1969 edition of the AASHTO *Standard Specifications for Highway Bridges* (1970 and 1971 Interim Specifications).[9] Although this guidance did not mention the risk of vessel collisions or a need for bridge protections, the Key Bridge was designed and built with physical protection systems to protect portions of the bridge exposed to possible damage by marine traffic. These protection systems (including four 28-foot-diameter dolphin structures, each with rubber fenders, and crushable concrete and timber fendering systems around Pier 17 and Pier 18) were in place when the bridge opened in 1977 (see figure 2).[10] Dolphins are frequently used to protect bridge piers because they can slow, stop, or redirect an aberrant vessel.[11]

The Key Bridge dolphins were constructed according to project-specific design criteria and, according to the MDTA, have retained these original specifications. The centers of Dolphin 1 and Dolphin 2 were located 489 feet west of the centers of Pier 17 and Pier 18, respectively (see figure 3). All dolphins were about 550 feet clear of the centerline of the Fort McHenry Federal Channel. None of the four dolphins were contacted by the *Dali* during the collision.

[9] AASHTO, 1969, *Standard Specifications for Highway Bridges*, 1970 and 1971 Interim Specifications, 10th ed. Note that in 1969, AASHTO was called the American Association of State Highway Officials.

[10] (a) A *bridge dolphin* is "a group of piles driven close together, or a caisson placed to protect portions of a bridge exposed to possible damage by collision with river or marine traffic" (FHWA 2022). (b) A *fender* (or *fendering system*) is a protective structure located directly on a bridge or on a protective element independent of the bridge (such as a dolphin), designed to fully or partially absorb the design impact loads, or deflect or redirect an aberrant vessel away from the bridge. (c) *Rubber fenders* are "usually placed on the outer perimeter of the dolphin to act as an anti-sparking surface to prevent metal-to-metal contact in the event of collision with a steel-hulled vessel carrying flammable products." Further, "the circular shape of the dolphins can help deflect aberrant vessels away from the pier." Finally, *crushable concrete* and *timber fendering systems*, such as those around Pier 17 and Pier 18, have been frequently used for protecting piers from minor vessel impact forces "because of their relatively low cost." (AASHTO, Article C7.3.3, "Dolphin Protection," *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges* (2009), 114.)

[11] (a) For more information, see Article C7.3.3, "Dolphin Protection" in AASHTO's 2009 *Guide Specifications*. (b) An *aberrant vessel* is a vessel that has lost control or has unexpectedly gone off course.

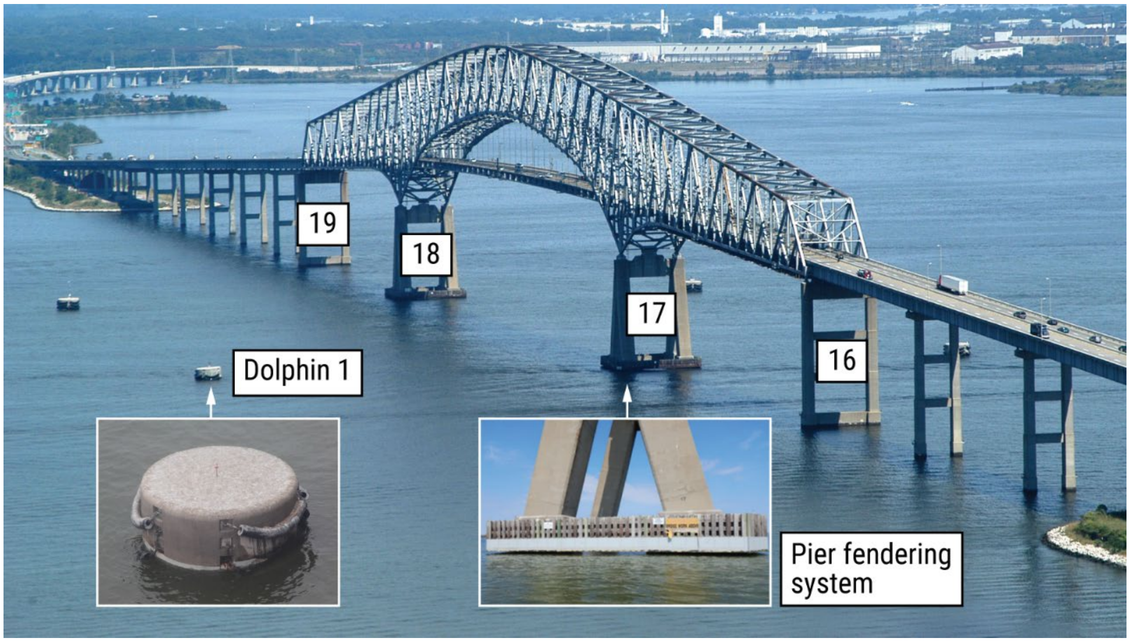

Figure 2. The Key Bridge and the physical protection systems (Dolphin 1 and the pier fendering system) protecting Pier 17 from vessels transiting outbound under the Key Bridge. (Background source: MDTA)

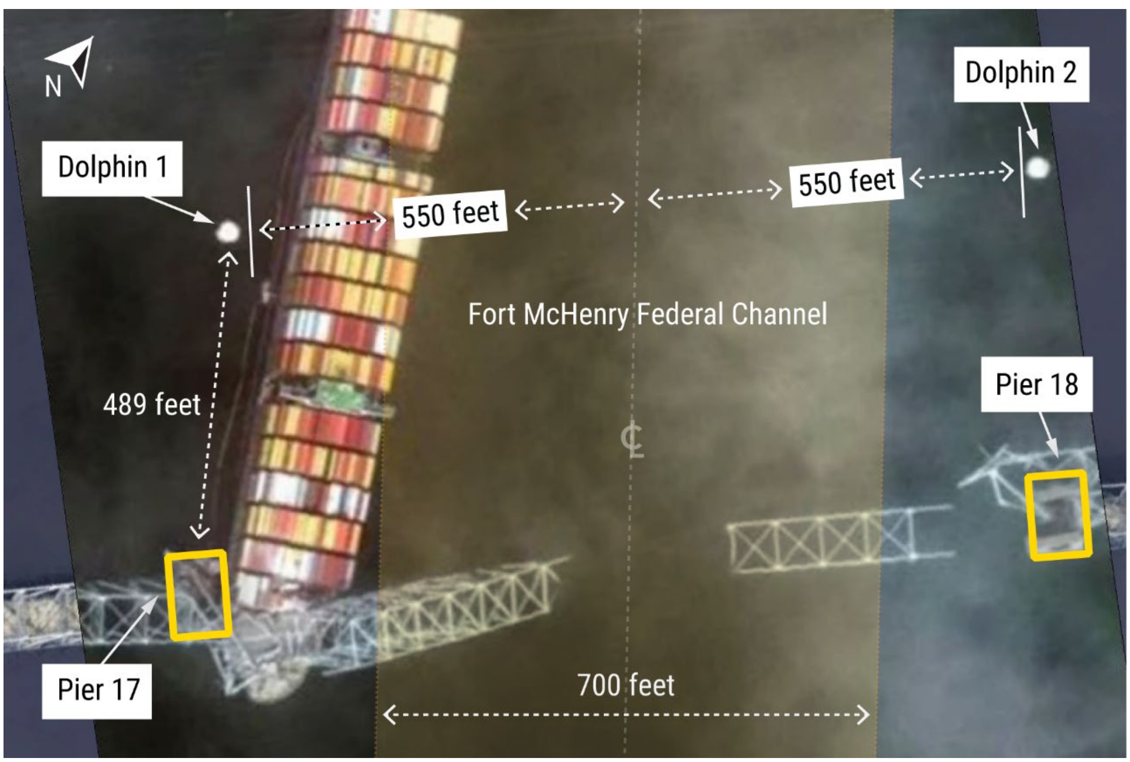

Figure 3. Overhead view of the collapsed Key Bridge and the *Dali*. Locations of Dolphin 1 and Dolphin 2 relative to the vessel, bridge, and Fort McHenry Federal Channel are depicted. (Background sources: MAXAR and Google Earth)

In accordance with the National Bridge Inspection Standards, the Key Bridge and its pier protection systems were subject to regular safety inspections by nationally certified bridge inspectors.[12] These periodic safety inspections, which included the dolphins for the Key Bridge, are intended to assess and document the physical and functional condition of a bridge and its components, and identify any changes from previously recorded conditions to ensure that any structural deficiencies posing an imminent threat to public safety are corrected.[13] These inspections are "necessary to maintain safe bridge operation and prevent structural and functional failures."[14] The Key Bridge's most recent inspections in March 2021 and May 2023 found the condition of the deck, the superstructure, and the substructure as being in satisfactory condition, and the pier protection was rated as in place and functioning properly.[15]

The Key Bridge's pier protection was struck in 1980 when the 390-foot-long Japan-flagged containership *Blue Nagoya*, which had a displacement or weight about one-tenth that of the *Dali*, collided with Pier 17 following a loss of steering about 600 yards from the bridge; see figure 4 for a size comparison of the *Blue Nagoya* to the *Dali*. The vessel was stopped by the crushable concrete and timber fendering system at Pier 17, and the bow overhang contacted the pier's A-frame.[16] As a result of the collision, minor surface damage occurred on Pier 17's columns and the pier's fender was destroyed. The crushable concrete and timber fendering around the pier was reconstructed according to the original project-specific design criteria, and the minor damage to the columns was repaired.

[12] See Title 23 *Code of Federal Regulations* (*CFR*) Part 650 Subpart C.

[13] (a) See 23 *CFR* 650.313(q)(1)(i). (b) FHWA, "Questions and Answers on the National Bridge Inspection Standards, 23 *CFR* Part 650, Subpart C." Updated April 5, 2024.

[14] FHWA, "National Bridge Inspection Standards." Updated November 7, 2024.

[15] (a) A *superstructure* is a bridge structure that receives loads from the deck, such as traffic or pedestrian loads, and in turn, transfers those loads to the substructure. (b) A *substructure* is a bridge structure that supports the superstructure and transfers loads from it to the foundation; main components are abutments, piers, footings, and pilings.

[16] See National Research Council, *Ship Collisions with Bridges: The Nature of the Accidents, Their Prevention, and Mitigation* (National Academy Press, 1983), 26. See also AASHTO 2009, 102.

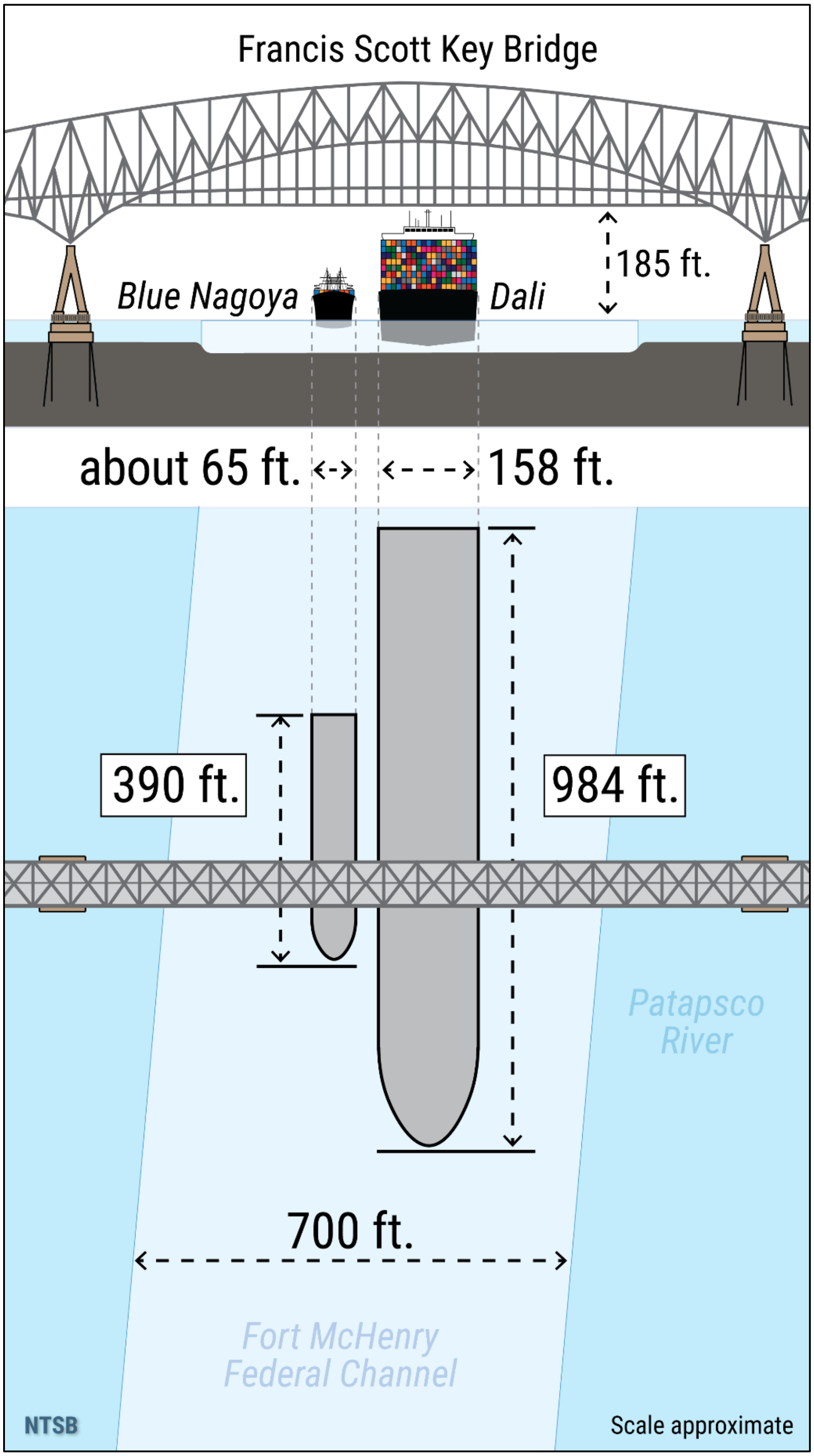

Figure 4. The comparative sizes of the *Blue Nagoya* and the *Dali* relative to the Key Bridge.

2.2.2 Fort McHenry Federal Channel

The Fort McHenry Federal Channel, which runs within the Patapsco River along the length of the Port of Baltimore and under the Key Bridge, is a navigation channel maintained by the Corps of Engineers (see figure 5). The channel is 700 feet wide, 50 feet deep, and 4 miles long, with a vertical clearance of 185 feet under the Key Bridge. The main navigational channel near the bridge is straight, and there are no bends or turns.

Ocean-going vessels passed under the bridge at the centerline of the Fort McHenry Federal Channel and were required to have a Maryland State Pilot aboard.[17] In 2023, a total of 3,775 transits between Pier 17 and Pier 18 were recorded (1,902 inbound and 1,873 outbound).[18]

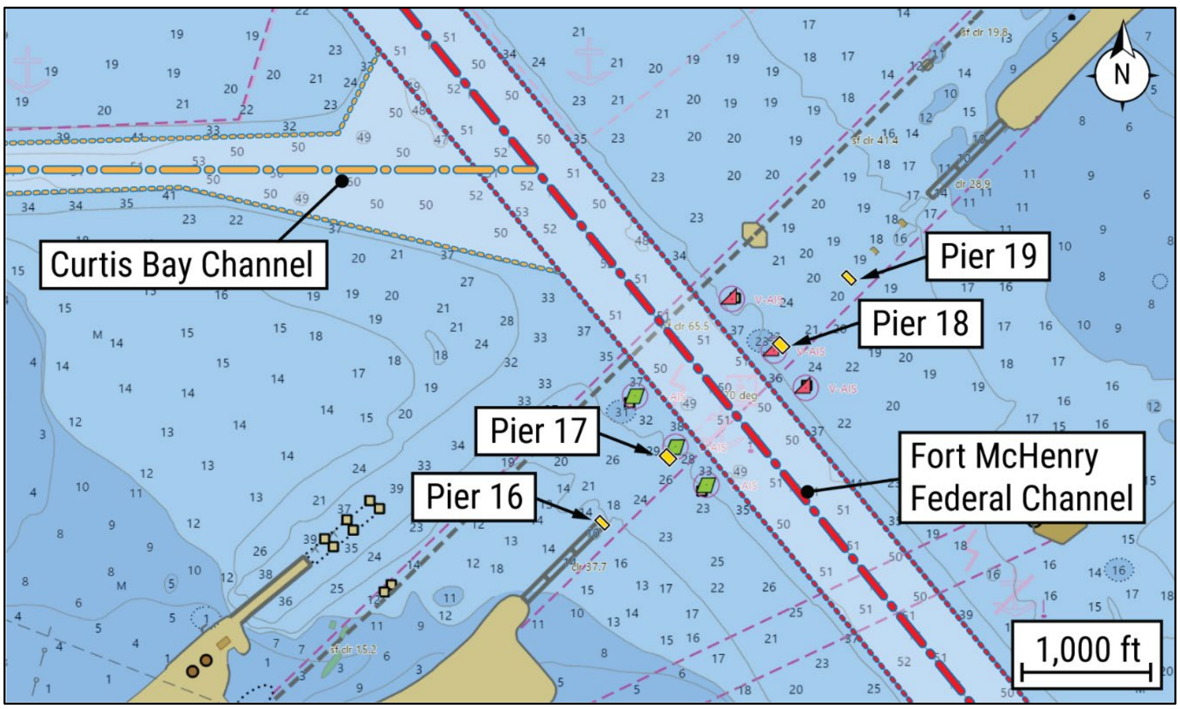

Figure 5. Nautical chart used to evaluate the channel layout. (Background source: National Oceanic and Atmospheric Administration electronic navigational chart US5BALBB)

[17] A *pilot* is retained by the ship to provide local knowledge of the waterway, familiarity with tides and currents in the area, understanding of local procedures, and a thorough knowledge of the topography of the waterway. Pilots usually operate by issuing maneuvering instructions (such as heading, rudder angle, and speed orders) to the vessel's crew under the supervision of the master, the officer in charge of the navigation watch, or both.

[18] Per National Oceanic and Atmospheric Administration AccessAIS data. Further details can be found in the public docket for this investigation.

2.3 Vessel Collision Vulnerability Assessment

2.3.1 Background

As a result of the NTSB's investigation of the May 9, 1980, Liberia-flagged bulk carrier *Summit Venture*'s collision with the Sunshine Skyway Bridge, Tampa Bay, Florida, we issued multiple recommendations to address identified safety concerns.[19] Among those recommendations, we asked the FHWA, in cooperation with the Coast Guard, to "develop standards for the design, performance, and location of structural bridge pier protection systems which consider that the impact from an off-course vessel can occur significantly above as well as below the water surface" (Safety Recommendation M-81-20). In response to this recommendation, the FHWA shared an existing research study, "The State of the Art: Bridge Protective Systems and Devices," and indicated that a follow-up study to perform laboratory tests of bridge protection models had been initiated and was nearly complete.[20] In 1988, a pooled-fund research project sponsored by 11 states and the FHWA led to the development of a proposed design code for bridge engineers to use in evaluating structures for vessel collision. This effort resulted in AASHTO's adoption of its first edition of the *Guide Specification and Commentary for Vessel Collision Design of Highway Bridges* in 1991.[21] The second edition, titled *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges*, was released in 2009.[22]

The FHWA requires that new bridges on the National Highway System be designed to minimize the risk of a catastrophic bridge collapse from a vessel collision given the size, speed, and other characteristics of the vessels navigating the channel under the bridge; the requirements were adapted from AASHTO's *Guide*

[19] *Ramming of the Sunshine Skyway Bridge by the Liberian Bulk Carrier* Summit Venture*, Tampa Bay, Florida, May 9, 1980*, MAR-81-03.

[20] (a) The NTSB classified Safety Recommendation M-81-20 Closed—Acceptable Response in December 1984. (b) "The State of the Art: Bridge Protective Systems and Devices." Final Report 1979. Report no. CG-N-1-80. Prepared for US Department of Transportation, sponsoring agency US Coast Guard Office of Navigation, performing organization University of Maryland Department of Civil Engineering. Washington, DC.

[21] AASHTO, *Guide Specification and Commentary for Vessel Collision Design of Highway Bridges*, Volume I: Final Report, 1991.

[22] AASHTO 2009.

Specifications using a vulnerability assessment calculation.[23] AASHTO's 1991 *Guide Specification* introduced the vulnerability assessment calculation, and AASHTO reiterated the value of performing this calculation in its 2009 *Guide Specifications*. AASHTO also recommended that bridge owners use the vulnerability assessment calculations to evaluate bridges built before 1991 to identify bridges at risk of a catastrophic collapse in the event of a vessel collision and 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."[24]

Neither the FHWA nor AASHTO can require a bridge owner to complete a vulnerability assessment for a bridge designed before the release of the 1991 guidelines.[25] The MDTA had not performed, nor was it required to perform, a vulnerability assessment to evaluate the Key Bridge's risk of a catastrophic collapse from a vessel collision. However, as previously stated, AASHTO recommended that states, like Maryland, perform such vulnerability assessments to evaluate and address risk.

[23] a) This requirement applies to bridges on the National Highway System (23 *CFR* 625.3(a)(1)). Bridges not on the National Highway System are designed in accordance with State law (23 *CFR* 625.3(a)(2)). b) Requirements contained within the AASHTO *LRFD* [Load and Resistance Factor Design] *Bridge Design Specifications*, which are defined in 23 *CFR* 625.4, were adapted from the *Guide Specifications* using the Method II vulnerability assessment. Method II is discussed further in section 2.3.2 of this report. The *LRFD Bridge Design Specifications* are intended for the design, evaluation, and rehabilitation of both fixed and movable highway bridges. The Method II risk acceptance has been included in the *LRFD Bridge Design Specifications* since their inception in 1994. c) The NTSB has addressed the AASHTO *Guide Specifications*' vulnerability assessments in two prior investigation reports related to vessel/bridge collisions. See *U.S. Towboat* Robert Y. Love *Allision With Interstate 40 Highway Bridge Near Webbers Falls, Oklahoma, May 26, 2002*, NTSB/HAR-04/05, and *Allision of Hong Kong-Registered Containership M/V* Cosco Busan *with the Delta Tower of the San Francisco–Oakland Bay Bridge, San Francisco, California, November 7, 2007*, NTSB/MAR-09/01.

[24] AASHTO 2009, 2.

[25] Per Title 23 *United States Code* 144(h)(3)(A)(ii), the FHWA's authority to require bridge assessment extends only to the evaluation of live load carrying capacity (commonly referred to as a bridge load rating).

2.3.2 AASHTO *Guide Specifications*

The 2009 AASHTO *Guide Specifications* provide three methods for conducting bridge vulnerability assessments.[26] Unless a bridge over a navigable waterway with commercial vessel traffic was "designed in accordance with the previous 1991 edition of the AASHTO *Guide Specification*," the bridge "should be evaluated using a vulnerability assessment in accordance with the Method II risk analysis procedures contained in the current guide specifications."

The AASHTO Method II vulnerability assessment calculation is used to determine the annual frequency of collapse (AF), which is the probability of a bridge collapse due to vessel collision in a year's time. The total AF is based on the sum of the AFs for each pier that is vulnerable to a vessel collision from both inbound and outbound traffic. This vulnerability assessment calculation allows bridge owners to calculate their bridge's level of risk and determine whether that risk is below the acceptable threshold established by AASHTO. A bridge design with a risk level below the acceptable threshold would minimize the risk of a collapse but does not guarantee that a collapse from a vessel collision will not occur. Likewise, a risk level above the acceptable threshold does not mean a collapse from a vessel collision is a certainty. The Method II vulnerability assessment calculation, shown in Appendix A, uses data specific to each bridge and waterway, including:

- characteristics of the vessel traffic passing under the bridge,
- vessel transit speeds,
- vessel loading characteristics,
- waterway and navigable channel geometry (including intersecting channels),
- water depths,
- environmental conditions,
- bridge geometry,
- pier protection systems, and

[26] "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" (AASHTO 2009, 2). Further, "a prerequisite for using Method III is that the annual frequency of bridge collapse is computed in accordance with Method II and brought to the attention of the [bridge] owner" (AASHTO 2009, 62).

- ultimate lateral capacity of the bridge piers.[27]

The AASHTO *Guide Specifications* further define how these data are used to calculate each factor in the vulnerability assessment calculation related to:

- the vessel frequency distribution transiting under the bridge,
- the probability that a vessel will go off course,
- the probability that a vessel will hit a bridge pier if it is off course,
- the probability of a bridge collapse once a collision has occurred, and
- the protection factor due to the presence of structures, such as dolphins or islands, that may protect a pier from collision.

The AASHTO *Guide Specifications* classify bridges over navigable waterways as either critical/essential or typical. Bridges that "serve as important links" in the Strategic Highway Network are classified as critical/essential; the Key Bridge had this classification.[28] Bridges not deemed critical/essential are classified as typical. The 2009 AASHTO *Guide Specifications* provide acceptable threshold values for a bridge's vulnerability assessment calculation. For bridges classified as critical/essential, the threshold is computed as an AF value of 0.0001. For bridges classified as typical, the threshold is computed as an AF value of 0.001.

2.3.3 Francis Scott Key Bridge Vulnerability Assessment Acceptable Threshold

As noted previously, bridges built before 1991 were not required to undergo a vulnerability assessment; such an assessment had not been performed for the Key Bridge, which was constructed in 1977. Following the *Dali* collision, the NTSB conducted a vulnerability assessment of the bridge using the AASHTO Method II calculation to understand its level of risk at the time of its collapse. The calculated AF considered the factors listed above to assess whether this value was below AASHTO's acceptable threshold value for a critical/essential bridge's probability of collapse. We calculated and summed the AFs for both inbound and outbound vessel traffic for Piers 16, 17, 18, and 19, which are shown in table 1.[29] These piers provided support

[27] *Lateral capacity* is the maximum horizontal load a pier can withstand before failing.

[28] AASHTO 2009, 21. The Strategic Highway Network "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." (US Department of Transportation, updated July 27, 2024.)

[29] Details of the vulnerability assessment calculations to determine the Key Bridge's AF can be found in the public docket for this investigation.

to the portion of the bridge over the Fort McHenry Federal Channel.[30] A comparison of the AFs of the piers in table 1 shows that a vessel collision with Pier 17 or Pier 18 was the largest contributor to the Key Bridge's overall AF.

Table 1. AF Summary for the Key Bridge.

Pier	Inbound AF	Outbound AF	Total AF
16	0.000024	0.000024	0.000048
17	0.000687	0.000743	0.001430
18	0.000693	0.000749	0.001442
19	0.000001	0.000000	0.000001
Total	0.001405	0.001516	0.002921

Since the Key Bridge's opening in 1977, engineering and shipping advances—such as the 2016 Panama Canal expansion—have led to far larger vessels visiting, and increased vessel traffic volume to and from, the Port of Baltimore. Therefore, incorporating current vessel traffic parameters (and other environmental/waterway factors) into the AASHTO Method II vulnerability assessment calculation to evaluate the Key Bridge's specifications, the NTSB determined that if the MDTA had calculated the AF for the Key Bridge before the collapse, it would have identified that the bridge's risk level was almost 30 times greater than the AASHTO risk threshold for critical/essential bridges (0.0001). Therefore, the NTSB concludes that had the MDTA conducted a vulnerability assessment of the Francis Scott Key Bridge based on recent vessel traffic, as recommended by the 1991 and 2009 AASHTO *Guide Specifications*, the MDTA would have been aware that this critical/essential bridge was above the AASHTO threshold of risk for catastrophic collapse from a vessel collision when the *Dali* collision occurred.

The 2009 AASHTO *Guide Specifications* are a resource for state Departments of Transportation (DOTs) and other bridge owners to better understand the overall safety of bridges within their inventory to "minimize their susceptibility to damage from vessel collisions."[31] For the Key Bridge, factors that contributed to this risk in the calculated vulnerability assessment included the piers adjacent to the main navigation channel and the channel size, which provided off-course vessels with little

[30] The calculation focused on ocean-going vessels, including containerships, general cargo ships, tankers, dry bulk carriers, and other vessels (passenger ships, cable laying ships, research ships, support ships, training ships, and US Navy ships).

[31] AASHTO 2009, ix.

time for path correction before colliding with the bridge. Further, the locations and size of the dolphins did not fully protect Pier 17 and Pier 18 from a collision from an off-course vessel, and the speed and size (dimensions and weight) of modern vessels such as the *Dali* highlighted that the bridge piers were not strong enough to withstand a collision from a large ocean-going vessel.

Although some factors are challenging to modify for existing bridges, the process of calculating vulnerability assessments enables owners to make informed decisions to manage their assets, identify their bridges that may be susceptible to damage from a vessel collision, and appraise and prioritize vessel collision protection projects alongside other projects addressing highway asset needs and risks. When a bridge owner performs vulnerability assessments of structures in its inventory in accordance with the Method II calculation outlined by the 2009 AASHTO *Guide Specifications*, it is better equipped to understand the overall vulnerability of the bridges within its inventory. Therefore, the NTSB concludes that had the MDTA conducted a vulnerability assessment of the Key Bridge using AASHTO's Method II vulnerability assessment calculation, the MDTA would have had information to proactively identify strategies to reduce the risk of a collapse and loss of lives associated with a vessel collision with the bridge.

2.4 Other US Bridges over Navigable Waterways Frequented by Ocean-Going Vessels

Like the Key Bridge, other bridges throughout the United States were designed before AASHTO's 1991 *Guide Specification* for bridge design was issued. To understand the scope of the risk posed by bridges nationwide with designs predating AASHTO's *Guide Specification*, the NTSB requested that the FHWA identify bridges that cross navigable waterways and are used by ocean-going vessels like the *Dali*, as well as gather information about protection devices in place for those bridges (if any). The FHWA coordinated with state DOTs to identify 176 bridges in 26 states that cross waterways used by ocean-going vessels.[32]

The NTSB subsequently filtered the results according to whether a bridge:

- Was built before 1996. We recognized that although the AASHTO *Guide Specification* was available in 1991, bridges under design or initial construction at that time were likely not built to its specifications.

[32] The FHWA sent questionnaires to state DOTs, regarding engineering studies on pier protection and what standards were used during those studies. The FHWA used the responses to produce the report, *FHWA Bridges Crossing Waterways Utilized by Ocean-Going Vessels*, which can be found in the public docket for this investigation.

Therefore, we determined that bridges placed into service before 1996 were likely not designed and built to the current specifications.

- Had a vertical clearance of at least 80 feet. We used the typical vertical clearance height for ocean-going vessels (80 feet) based upon the typical minimum mast clearance height of a loaded bulk carrier and loaded tanker.[33]
- Had substructures (such as piers) in a waterway. The only bridges considered in this report were those with piers in a waterway, because piers on land have natural protection from a horizontal vessel impact.[34]

Applying these conditions to the 176 bridges reduced the number to 95. The NTSB also queried the FHWA Long-Term Bridge Performance (LTBP) InfoBridge web portal to identify 224 bridges owned by the Corps of Engineers.[35] The same parameters used to filter the 176 bridges in the FHWA report were applied to these 224 bridges, resulting in 6 bridges that met the above criteria. Therefore, a total of 101 bridges—95 identified in the FHWA report and 6 owned by the Corps of Engineers—met the NTSB criteria.[36]

Next, we evaluated the vessel traffic transiting under the 101 bridges between January 1, 2019, and September 31, 2024, to determine whether a bridge's average annual transits by ocean-going vessels were sufficient to result in a measurable amount of risk in the vulnerability assessment calculation.[37] This evaluation was accomplished using a similar methodology to the one used to determine the vessel traffic for the

[33] (a) AASHTO 2009. (b) *Mast clearance height* is the vertical distance from the top of a vessel's highest point down to its waterline. Also known as "air draft." (c) The NTSB used the vessel types listed in the AASHTO 2009 *Guide Specifications*, which had a minimum mast height of 80 feet (AASHTO 2009, 32).

[34] A total of 14 bridges built before 1996 had piers that were constructed only on land.

[35] Federal Highway Administration Office of Research, Development and Technology at the Turner-Fairbanks Highway Research Center, "Long-Term Bridge Performance (LTBP) InfoBridge." Updated November 10, 2022.

[36] Additional details about how the data were filtered can be found in the public docket for this investigation.

[37] Engineering judgement was used to determine a conservative value of 100 annual transits by ocean-going vessels as the minimum number sufficient to provide risk in the vulnerability assessment calculation. For comparison, the Key Bridge had 3,775 ocean-going vessel transits in 2023.

Key Bridge.[38] As a result, we identified 72 bridges (in 19 states, managed by 30 separate bridge owners) over navigable waterways frequented by ocean-going vessels that were likely not designed and built to the AASHTO *Guide Specifications*. The information that the FHWA collected in coordination with state DOTs regarding protection devices helped us to identify that the owners of 4 of the 72 bridges had performed a recent vulnerability assessment and were either implementing a plan to reduce their bridge's vulnerability or would be doing so in the near future. Appendix B lists the remaining 68 bridges that have not undergone a vulnerability assessment based on recent vessel traffic and therefore have an unknown level of risk of collapse from a vessel collision.

Calculating a bridge's AF can help owners understand their bridges' vulnerability of collapse from a vessel collision and the aspects of bridge design or vessel traffic that contribute to this vulnerability, especially for bridges with an AF above the AASHTO threshold. As noted, we identified 68 bridges over navigable waterways frequented by ocean-going vessels that have an unknown level of risk of collapse. Therefore, the NTSB concludes that the 30 owners of 68 bridges over navigable waterways frequented by ocean-going vessels are likely unaware of their bridges' risk of catastrophic collapse from a vessel collision and the potential need to implement countermeasures to reduce the bridges' vulnerability. The NTSB recommends that the 30 owners of the bridges identified in appendix B of this report calculate the AASHTO Method II AF for the bridge(s) identified in appendix B of this report for which they are responsible and inform the NTSB whether the probability of collapse is above the AASHTO threshold.

Awareness of which aspects of bridge design or vessel traffic affect the probability of a collapse can aid in the development of risk reduction strategies. Each of the strategies must be evaluated as part of a holistic safety evaluation of potential benefits and unintended negative outcomes. The bridge owners are in the best position to assess potential strategies for reducing the risk of a bridge collapse from a vessel collision, but they would also benefit from the guidance of the federal agencies that oversee the overlapping aspects of bridge infrastructure, vessel operations, and waterway management. Per the 2009 AASHTO *Guide Specifications*,

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[38] (a) More information can be found in the public docket for this investigation. (b) The differences between our assessment of the Key Bridge traffic and that of the 101 bridges were the use of National Oceanic and Atmospheric Administration's AccessAIS tool and that duplicate records that were transmitted within 15 minutes of each other for the same vessel were not removed and, therefore, the number of transits may have been overestimated. Generally, vessels transmit automatic identification system [AIS] data at specific intervals. There were instances where the same ship transmitted automatic identification system data because the transmission intervals were short and, as the vessel traveled through the established geofence, it transmitted multiple times (duplicate records).

bridge risk reduction evaluations should be developed by an interdisciplinary team that includes representatives from the Coast Guard, the Corps of Engineers, and other federal agencies.[39] The FHWA plays a key role in risk reduction based on its expertise and technical guidance in bridge design, construction, inspection, evaluation, management, and preservation. The Coast Guard has a role in the regulation of vessel operations, including controlling or supervising vessel traffic (when necessary). Finally, the Corps of Engineers is responsible for maintaining the navigability of waterways leading to and within ports by planning, constructing, and managing dredging projects to ensure sufficient channel depths for vessels.

Because of the need to ensure a holistic safety approach and timely guidance to bridge owners on the risks posed by these interconnected factors, the NTSB recommends that the FHWA, in coordination with the Coast Guard and Corps of Engineers, establish an interdisciplinary team—including representatives from the FHWA, Coast Guard, and Corps of Engineers—and provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision. The NTSB also recommends that the Coast Guard and Corps of Engineers support the FHWA in establishing an interdisciplinary team—including representatives from the FHWA, Coast Guard, and Corps of Engineers—and provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision.

Finally, to ensure a comprehensive approach to the safety of the traveling public, bridges and structures, waterways, and vessel traffic, the NTSB recommends that the 30 owners of the bridges identified in appendix B of this report, if the calculations that they performed in response to Safety Recommendation H-25-3 indicate that a bridge has an AF greater than the AASHTO threshold, develop and implement a comprehensive risk reduction plan that includes, at a minimum:

- guidance and assistance from the FHWA, Coast Guard, and Corps of Engineers interdisciplinary team identified in Safety Recommendations H-25-1 and H-25-2, and
- short- and long-term strategies to reduce the probability of a potential bridge collapse from a vessel collision.

[39] AASHTO 2009, 1.

3. Findings

1. Had the Maryland Transportation Authority (MDTA) conducted a vulnerability assessment of the Francis Scott Key Bridge based on recent vessel traffic, as recommended by the 1991 and 2009 American Association of State Highway and Transportation Officials (AASHTO) *Guide Specifications*, the MDTA would have been aware that this critical/essential bridge was above the AASHTO threshold of risk for catastrophic collapse from a vessel collision when the *Dali* collision occurred.

2. Had the Maryland Transportation Authority (MDTA) conducted a vulnerability assessment of the Francis Scott Key Bridge using the American Association of State Highway and Transportation Officials' Method II vulnerability assessment calculation, the MDTA would have had information to proactively identify strategies to reduce the risk of a collapse and loss of lives associated with a vessel collision with the bridge.

3. The 30 owners of 68 bridges over navigable waterways frequented by ocean-going vessels are likely unaware of their bridges' risk of catastrophic collapse from a vessel collision and the potential need to implement countermeasures to reduce the bridges' vulnerability.

4. Recommendations

To the Federal Highway Administration:

> In coordination with the US Coast Guard and US Army Corps of Engineers, establish an interdisciplinary team—including representatives from the Federal Highway Administration, US Coast Guard, and US Army Corps of Engineers—and provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision. (H-25-1) (Urgent)

To the US Coast Guard and the US Army Corps of Engineers:

> Support the Federal Highway Administration in establishing an interdisciplinary team—including representatives from the Federal Highway Administration, US Coast Guard, and US Army Corps of Engineers—and provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision. (H-25-2) (Urgent)

To the Bay Area Toll Authority, the California Department of Transportation, the Golden Gate Bridge Highway and Transportation District, the US Army Corps of Engineers, the Florida Department of Transportation, the Georgia Department of Transportation, Skyway Concession Company LLC, the Louisiana Department of Transportation and Development, the New Orleans Public Belt Railroad, the Maryland Transportation Authority, the Massachusetts Department of Transportation, the Mackinac Bridge Authority, the New Hampshire Department of Transportation, the Delaware River Port Authority, the New Jersey Turnpike Authority, Metropolitan Transportation Authority Bridges and Tunnels, the New York City Department of Transportation, the New York State Bridge Authority, the Ogdensburg Bridge and Port Authority, the Port Authority of New York and New Jersey, the Seaway International Bridge Corporation, the Thousand Islands Bridge Authority, the Ohio Department of Transportation, the Oregon Department of Transportation, the Pennsylvania Turnpike Commission, the Rhode Island Turnpike and Bridge Authority, the Harris County Toll Road Authority, the

Texas Department of Transportation, the Washington State Department of Transportation, and the Wisconsin Department of Transportation:

Calculate the American Association of State Highway and Transportation Officials (AASHTO) Method II annual frequency of collapse for the bridge(s) identified in appendix B of this report for which you are responsible and inform the National Transportation Safety Board whether the probability of collapse is above the AASHTO threshold. (H-25-3) (Urgent)

If the calculations that you performed in response to Safety Recommendation H-25-3 indicate that a bridge has an annual frequency of collapse greater than the American Association of State Highway and Transportation Officials threshold, develop and implement a comprehensive risk reduction plan that includes, at a minimum:

- guidance and assistance from the Federal Highway Administration, US Coast Guard, and US Army Corps of Engineers Interdisciplinary Team identified in Safety Recommendations H-25-1 and H-25-2, and
- short- and long-term strategies to reduce the probability of a potential bridge collapse from a vessel collision. (H-25-4) (Urgent)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

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Appendixes

Appendix A: American Association of State Highway and Transportation Officials Method II Vulnerability Assessment Calculation

The Method II calculation determines the annual frequency of collapse (AF), which is the probability of a bridge collapse due to vessel collision in a year's time. The equation for this calculation is as follows:

$$AF = (N)(PA)(PG)(PC)(PF)$$

where:

N = annual number of vessels classified by type, size, and loading condition which can strike the bridge element

PA = probability of vessel aberrancy

PG = geometric probability of a collision between an aberrant vessel and bridge pier or span

PC = probability of bridge collapse due to a collision with an aberrant vessel

PF = adjustment factor to account for potential protection of the piers from vessel collision due to upstream or downstream land masses, or other structures, that block the vessel

An AF is "computed for each bridge element and vessel classification. The summation of all bridge element AFs equals the annual frequency of collapse for the entire bridge structure."[40]

[40] AASHTO 2009, 69.

Appendix B: US Bridges Over Navigable Waterways Frequented by Ocean-Going Vessels with Unknown Levels of Risk of Collapse from a Vessel Collision

Table B-1. US Bridges Over Navigable Waterways Frequented by Ocean-Going Vessels with Unknown Levels of Risk of Collapse from a Vessel Collision.[a]

State	Bridge Name	Bridge Owner	Classification	Year Built
California	Richmond-San Rafael Bridge	Bay Area Toll Authority	Critical/Essential	1956
California	Carquinez Bridge	Bay Area Toll Authority	Critical/Essential	1958
California	Benicia-Martinez Bridge	Bay Area Toll Authority	Critical/Essential	1962
California	Antioch Bridge	Bay Area Toll Authority	Typical	1978
California	San Mateo-Hayward Bridge	Bay Area Toll Authority	Typical	1967
California	Coronado Bridge	Caltrans	Critical/Essential	1969
California	Golden Gate Bridge	Golden Gate Bridge Highway and Transportation District	Critical/Essential	1937
Delaware	Summit Bridge	US Army Corps of Engineers	Typical	1959
Delaware	Saint Georges Bridge	US Army Corps of Engineers	Typical	1941
Delaware	Reedy Point Bridge	US Army Corps of Engineers	Typical	1969
Florida	Sunshine Skyway Bridge	Florida DOT	Critical/Essential	1986
Florida	Napoleon Bonaparte Broward Bridge (Dames Point Bridge)	Florida DOT	Critical/Essential	1989
Georgia	Talmadge Bridge	Georgia DOT	Typical	1991
Illinois	Chicago Skyway Calumet River Bridge	Skyway Concession Company LLC	Critical/Essential	1958
Louisiana	Huey P. Long Bridge	Louisiana DOT and Development and New Orleans Public Belt Railroad	Typical	1936
Louisiana	Greater New Orleans Bridge	Louisiana DOT and Development	Critical/Essential	1957

State	Bridge Name	Bridge Owner	Classification	Year Built
Louisiana	Israel LaFleur Bridge	Louisiana DOT and Development	Critical/Essential	1964
Louisiana	Crescent City Connection Bridge	Louisiana DOT and Development	Critical/Essential	1985
Louisiana	Hale Boggs (Luling) Bridge	Louisiana DOT and Development	Critical/Essential	1983
Louisiana	Horace Wilkinson Bridge	Louisiana DOT and Development	Critical/Essential	1968
Louisiana	Gramercy (Veterans Memorial) Bridge	Louisiana DOT and Development	Typical	1989
Louisiana	Sunshine Bridge	Louisiana DOT and Development	Typical	1963
Maryland	William Preston Lane Jr. (Bay) Bridge (eastbound)	Maryland Transportation Authority	Critical/Essential	1951
Maryland	William Preston Lane Jr. (Bay) Bridge (westbound)	Maryland Transportation Authority	Critical/Essential	1973
Maryland	Chesapeake City Bridge	US Army Corps of Engineers	Typical	1948
Massachusetts	Tobin Bridge (southbound upper)	Massachusetts DOT	Typical	1950
Massachusetts	Tobin Bridge (northbound lower)	Massachusetts DOT	Typical	1950
Massachusetts	Bourne Bridge	US Army Corps of Engineers	Critical/Essential	1935
Massachusetts	Sagamore Bridge	US Army Corps of Engineers	Typical	1935
Michigan	Mackinac Bridge	Mackinac Bridge Authority	Critical/Essential	1957
New Hampshire[b]	Memorial Bridge	New Hampshire DOT	Typical	1921
New Jersey[c]	Commodore Barry Bridge	Delaware River Port Authority	Typical	1974
New Jersey	Vincent R. Casciano (Newark Bay) Bridge	New Jersey Turnpike Authority	Critical/Essential	1955
New York	Verrazano Narrows Bridge (eastbound)	MTA Bridges and Tunnels	Critical/Essential	1961
New York	Verrazano Narrows Bridge (westbound)	MTA Bridges and Tunnels	Critical/Essential	1961

State	Bridge Name	Bridge Owner	Classification	Year Built
New York	Brooklyn Bridge	New York City DOT	Typical	1883
New York	Manhattan Bridge	New York City DOT	Typical	1909
New York	Williamsburg Bridge	New York City DOT	Typical	1903
New York	Newburgh-Beacon Bridge (eastbound)	New York State Bridge Authority	Critical/Essential	1980
New York	Newburgh-Beacon Bridge (westbound)	New York State Bridge Authority	Critical/Essential	1963
New York	Rip Van Winkle Bridge	New York State Bridge Authority	Typical	1935
New York	Ogdensburg-Prescott International Bridge	Ogdensburg Bridge and Port Authority	Typical	1960
New York[d]	George Washington Bridge	Port Authority of New York and New Jersey	Critical/Essential	1962
New York[d]	Outerbridge Crossing Bridge	Port Authority of New York and New Jersey	Typical	1928
New York	Seaway International Bridge	Seaway International Bridge Corporation	Typical	1958
New York	Thousand Islands Bridge	Thousand Islands Bridge Authority	Critical/Essential	1938
Ohio	CUY-00490-0010 (I-490) Bridge	Ohio DOT	Critical/Essential	1990
Ohio	CUY-00002-1441 (Main Avenue) Bridge	Ohio DOT	Typical	1939
Ohio	CUY-00006-1456 (Detroit Avenue) Bridge	Ohio DOT	Typical	1917
Ohio	CUY-00010-1613 (Carnegie Avenue) Bridge	Ohio DOT	Typical	1932
Ohio	LUC-01W02-0002 (Dr. Martin Luther King Jr. Memorial) Bridge	Ohio DOT	Typical	1914
Ohio	LUC-00002-1862 (Anthony Wayne) Bridge	Ohio DOT	Typical	1931
Oregon[e]	Astoria-Megler Bridge	Oregon DOT	Critical/Essential	1966
Oregon	St. Johns Bridge	Oregon DOT	Typical	1931
Pennsylvania[d]	Walt Whitman Bridge	Delaware River Port Authority	Critical/Essential	1957

State	Bridge Name	Bridge Owner	Classification	Year Built
Pennsylvania[d]	Benjamin Franklin Bridge	Delaware River Port Authority	Critical/Essential	1926
Pennsylvania[d]	Betsy Ross Bridge	Delaware River Port Authority	Typical	1976
Pennsylvania[d]	Delaware River Turnpike Bridge	Pennsylvania Turnpike Commission and New Jersey Turnpike Authority	Critical/Essential	1956
Rhode Island	Claiborne Pell Newport Bridge	Rhode Island Turnpike and Bridge Authority	Typical	1969
Texas	Buffalo Bayou Toll Bridge	Harris County Toll Road Authority	Typical	1980
Texas	Sidney Sherman Bridge	Texas DOT	Critical/Essential	1973
Texas	Rainbow Bridge	Texas DOT	Critical/Essential	1939
Texas	Veterans Memorial Bridge	Texas DOT	Critical/Essential	1991
Texas	Hartman Bridge (eastbound)	Texas DOT	Typical	1995
Texas	Hartman Bridge (westbound)	Texas DOT	Typical	1995
Texas	GulfGate Bridge	Texas DOT	Typical	1970
Washington[f]	Lewis and Clark Bridge	Washington State DOT	Critical/Essential	1929
Wisconsin	Leo Frigo Bridge	Wisconsin DOT	Critical/Essential	1979

[a] As discussed in the report, the four bridges with active or near-term plans are the west span of the Oakland-San Francisco Bay Bridge (owned by the Bay Area Toll Authority); the east and west spans of the Delaware Memorial Bridge (owned by the Delaware River & Bay Authority); and the Blatnik Bridge (co-owned by the Wisconsin and Minnesota DOTs).

[b] Crosses into Maine.

[c] Crosses into Pennsylvania.

[d] Crosses into New Jersey.

[e] Crosses into Washington.

[f] Crosses into Oregon.

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