ERRATA

THE CORRECTIONS BELOW ARE *INCLUDED*
IN THIS REVISED VERSION OF THE DOCUMENT

HIGHWAY SAFETY RECOMMENDATION LETTER
SAFETY RECOMMENDATIONS H-10-17 AND -18

RECOMMENDATIONS CONCERNING NONDESTRUCTIVE EVALUATION OF CONCRETE BRIDGE RAILINGS FOLLOWING AN ACCIDENT ON THE WILLIAM PRESTON LANE, JR., MEMORIAL BRIDGE (CHESAPEAKE BAY BRIDGE) NEAR ANNAPOLIS, MARYLAND, AUGUST 10, 2008

The last sentence of page 3 was corrected to read as follows (corrections shown in boldface type):

Such was the case at the time of the accident; the northern span was closed, and the southern span—the original bridge span—was carrying **westbound** traffic in its northern lane and **eastbound** traffic in its southern lane.

National Transportation Safety Board

Washington, D.C. 20594

Safety Recommendation

Date: November 23, 2010

In reply refer to: H-10-17 and -18

The Honorable Mr. Victor M. Mendez
Administrator
Federal Highway Administration
1200 New Jersey Avenue, SE
Washington, D.C. 20590

As a result of information learned during its investigation of an August 10, 2008, accident that occurred on the William Preston Lane, Jr., Memorial Bridge that crosses the Chesapeake Bay near Annapolis, Maryland, the National Transportation Safety Board (NTSB) is making recommendations to the Federal Highway Administration (FHWA) concerning nondestructive evaluation (NDE) of concrete bridge railings. Information supporting these recommendations is discussed below.

Background

On August 10, 2008, at 3:55 a.m., the driver of a tractor-trailer took evasive action to avoid a Chevrolet Camaro passenger vehicle that had departed its travel lane on the William Preston Lane, Jr., Memorial Bridge (Chesapeake Bay Bridge) near Annapolis, Maryland.[1] The Camaro struck the tractor-trailer and rotated 180 degrees but remained on the bridge; the tractor-trailer, traveling at a police-reported speed of more than 40 mph, crossed to the opposite side of the bridge, striking the bridge barrier at a 40-degree angle and departing the bridge. The tractor-trailer's impact to the bridge railing caused an approximately 24-foot length of the barrier to dislodge and a 12-foot length of the displaced barrier to completely separate and fall into the Chesapeake Bay. The driver of the commercial vehicle was killed; the driver of the Camaro sustained serious injuries and the Camaro's passenger sustained minor injuries; and the driver and passenger of a third vehicle, a Toyota Prius that was struck by the trailer, were uninjured.

[1] For further information, see the public docket for accident number HWY-08-FH-023 <http://dmssvr/dms/public/search/hitlist.cfm?docketID=47293>.

When this accident occurred in August 2008, the NTSB was completing its investigation of the I-35W highway bridge collapse in Minneapolis,[2] which included consideration of corrosion damage, bridge inspection practices, and inspection technology. Also in August 2008, the NTSB began investigating another bridge accident, which involved a charter motorcoach that departed a bridge near Sherman, Texas. The Sherman accident examined the failure of the bridge railing to retain the motorcoach on the roadway and the need for criteria for the selection of appropriate bridge railing designs.[3] The NTSB conducted a limited investigation of the Chesapeake Bay Bridge barrier failure for the opportunity to examine components of the bridge railing that could not be monitored by visual inspection. However, neither the bridge design nor the corrosion issues that led the NTSB to make the recommendations in this letter were factors in the Annapolis, Maryland, accident. The investigation, nonetheless, revealed safety issues related to corrosion that merit further evaluation.

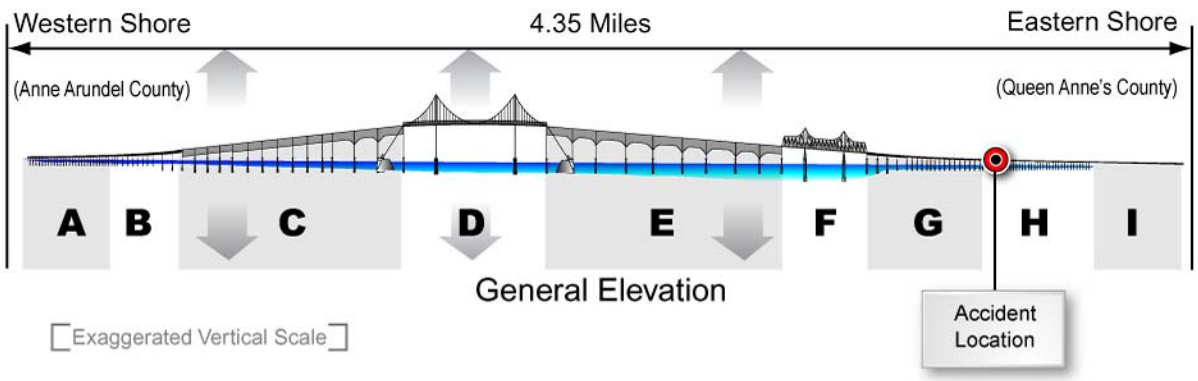
Bridge Description

The Chesapeake Bay Bridge is owned by the Maryland Transportation Authority (MdTA) and operated as a toll facility.[4] Since 1971, the MdTA has been responsible for managing, operating, and improving the state's toll facilities, as well as for financing new revenue-producing transportation projects. The Chesapeake Bay Bridge consists of two separate bridge spans with five different types of structural components, including prestressed concrete beams at each end, steel girders, two steel deck trusses, a three-span suspension unit, and a three-span steel through truss unit. (See figure 1.) The accident occurred on the eastbound span of the bridge at mile marker 36.1, approximately 0.5 mile west of the bridge's eastern terminus. The bridge superstructure at the site of the accident was of beam span construction.

[2] *Collapse of I-35W Highway Bridge, Minneapolis, Minnesota, August 1, 2007*, Highway Accident Report NTSB/HAR-08/03 (Washington, DC: National Transportation Safety Board, 2008).

[3] *Motorcoach Run-Off-the-Bridge and Rollover, Sherman, Texas, August 8, 2008*, Highway Accident Report NTSB/HAR-09/02 (Washington, DC: National Transportation Safety Board, 2009).

[4] The MdTA's 2004 *Transportation Needs Report* indicated that the average daily traffic (ADT) count on a summer weekend day is 95,000 vehicles, as compared with an ADT count on an average weekday of 61,000 vehicles. Heavy traffic, defined as single-unit trucks and larger, accounted for 5 percent of traffic on an August weekend day and for 14 percent on an October weekday. The capacity of the existing bridge, as modeled by the Task Force on Traffic Capacity Across the Chesapeake Bay, is 82,500 vehicles per day.



LEGEND		
A	1,841	Feet of Beam Spans
B	1,319	Feet of Girder Spans
C	4,296	Feet of Deck Truss Spans
D	2,923	Feet of Suspension Spans
E	4,665	Feet of Deck Cantilever Truss Spans
F	1,719	Feet of Through Cantilever Truss Spans
G	2,231	Feet of Girder Spans
H	2,272	Feet of Beam Spans
I	1,756	Feet of Filled Causeway

Figure 1. Diagram of eastbound span of Chesapeake Bay Bridge showing the different types of superstructures.

Construction of the original two-lane bridge span began in November 1949;[5] the bridge was opened to traffic in July 1952. The bridge has a shore-to-shore length of 4.35 miles, a vertical clearance of 186 feet, and a suspension bridge height of 354 feet. When it opened in 1952, it was the world's largest continuous over-water steel structure. A second, three-lane span, located parallel to and 450 feet north of the original span, was constructed from 1969–1973. This addition was designed to carry westbound traffic, and the original span became a two-lane roadway for eastbound traffic. In addition to increasing the capacity of the bridge, this roadway configuration allowed for two-way traffic to be routed along a single span while scheduled bridge maintenance was accomplished on the closed span. Such was the case at the time of the accident; the northern span was closed, and the southern span—the original bridge span—was carrying westbound traffic in its northern lane and eastbound traffic in its southern lane.

[5] 1949 was also the year that the first Bridge Committee of the Highway Research Board, the predecessor to the Transportation Research Board (TRB), was organized.

Bridge Barrier Design

The barriers in the beam span portion of the Chesapeake Bay Bridge at the time of the accident were similar in size and shape to "New Jersey" barriers used throughout the United States. These barriers extended 34 inches above the bridge deck. Each section on the eastbound span had a longitudinal measurement of approximately 61.5 feet between the expansion joints. Within each section, four 1-inch-wide control joints separated the barrier into five segments; the middle three segments were 13 feet 6 inches long, and the two end segments were 10 feet 6 inches long. Drainage slots at the base of the barrier conveyed water from the bridge deck.

In 1951, as part of the original construction, the concrete barrier was attached to the bridge deck using a U-bolt anchorage system. Each section contained five segments and each segment was anchored to the deck at four locations using two U-bolts, threaded and attached with nuts and washers above and below the deck. The U-bolts were aligned perpendicularly across the barrier with one bolt closer to the traffic side of the barrier and the other near the bay side. The U-bolts were oriented "upside-down," such that the bolt attached around the reinforcement bars inside the base of the barrier and the ends of the "U" extended down through the bridge deck and were bolted to the underside of the deck. (See figure 2.) A U-bolt anchorage system was used on all portions of the bridge barrier except the suspension span, which had a steel barrier bolted directly to the steel floor beams, independent of the bridge deck. The use of a U-bolt anchorage system would be considered "nonstandard" today; however, it conformed to the bridge railing designs contained in the 1944 American Association of State Highway Officials (AASHO) *Standard Specifications for Highway Bridges*.[6]

[6] *Standard Specifications for Highway Bridges*, 4th edition (Washington, DC: American Association of State Highway Officials, 1944). In 1973, this organization changed its name to the American Association of State Highway and Transportation Officials (AASHTO).

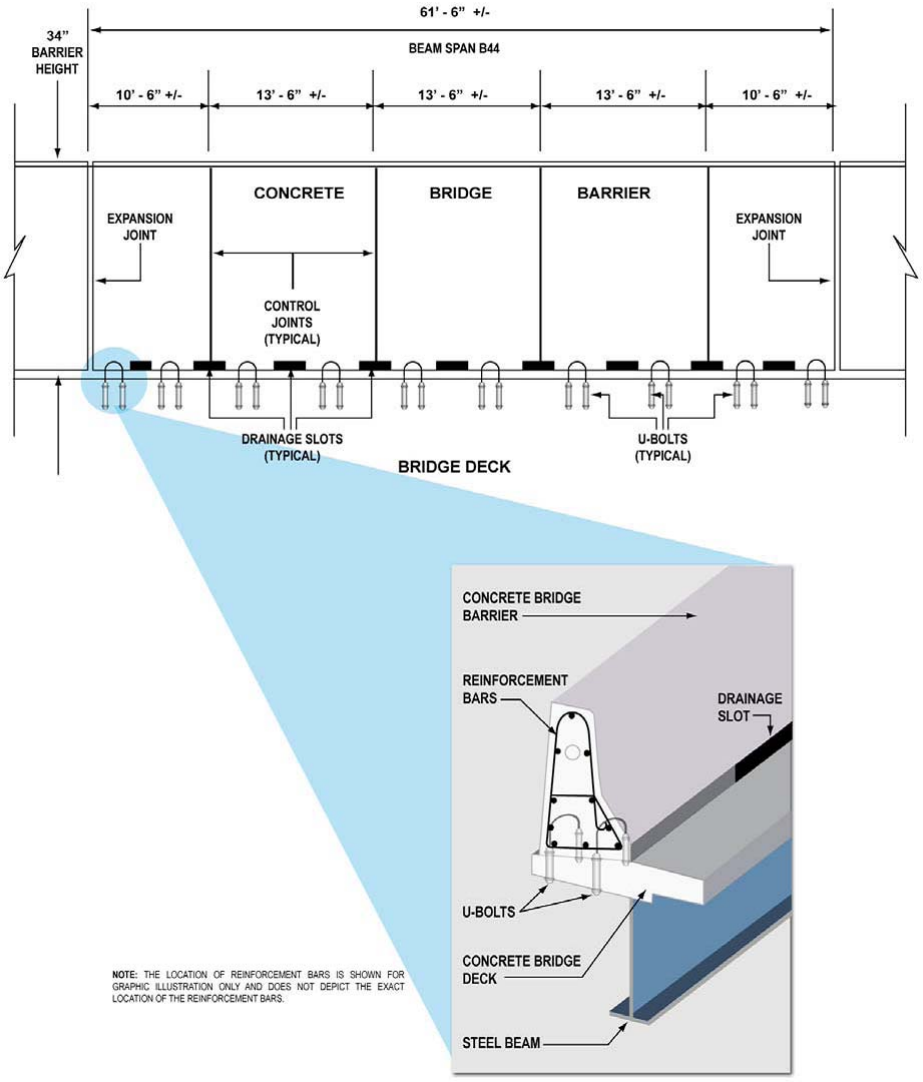


Figure 2. Bridge deck concrete barrier attachment detail.

In 1973, the MdTA undertook a deck replacement in the beam span sections of the southern span of the bridge that included an upgrade of the concrete barrier. The remaining span portions of the bridge (girder, deck truss, and through truss spans) were not rehabilitated at that time. The concrete barriers for the beam span sections were precast and attached to the bridge deck using a U-bolt anchorage system similar to the original design. The U-bolt anchorage system was acceptable in 1973 and satisfied the horizontal load criteria, as specified in the

1965 AASHO *Standard Specifications for Highway Bridges*.[7] In 1986, a rehabilitation project replaced the bridge deck and barriers on the girder, deck truss, and through truss portions of the bridge but not on the beam span sections. Because the deck and barriers were replaced at the same time in these portions of the bridge, the new concrete barriers were cast in place and attached to the deck using a standard anchorage detail consisting of reinforcement bars extending through the base of the barriers and into the deck. The beam span sections of the bridge received a deck overlay (not a deck replacement) and new barriers. The new steel-reinforced concrete barriers for the beam span sections were attached to the existing bridge deck structure using the existing U-bolt anchorage system, which was originally installed in 1973. The result was that the anchorage detail on the beam span sections of the bridge was the same as for the original bridge but different from the other portions of the bridge.

The 1986 engineering drawings called for replacing the existing U-bolts installed between the barriers and the bridge deck in 1973 with 7/8-inch (0.875-inch) epoxy-coated bolts conforming to American Society for Testing and Materials (ASTM) A449-00. However, because the existing U-bolts (installed in 1973) were grouted into the deck, their removal and replacement proved too damaging to the bridge deck. Most of the existing 1973 U-bolt attachments were reused in 1986 to attach the new concrete barriers, which were cast in place using a "slip form" method.[8]

Following the accident, the MdTA engaged a consultant engineering contractor to analyze the strength of the as-built barriers on the beam span section of the bridge. That analysis, which was predicated on as-specified bolt size with no corrosion of bolt strength, determined that the U-bolt anchorage system satisfied the design criteria contained in the 1983 AASHTO *Standard Specifications for Highway Bridges*.[9] The analysis was reviewed and confirmed by an independent peer group organized at the request of the Governor of Maryland.[10] The NTSB concludes that the bridge barrier design satisfied the design specifications that were in effect at the time of original construction and those in effect during the 1973 and 1986 rehabilitation projects.

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[7] *Standard Specifications for Highway Bridges*, 9th edition, section 1.2.11(D)(1), "Traffic Railing" (Washington, DC: American Association of State Highway Officials, 1965). The performance of bridge barriers, as defined in specifications, was determined by precedent and engineering judgment, not by crash testing, as is the case today.

[8] In *slip form* construction, concrete is poured into a sliding form that moves along at a set rate, allowing the concrete structure to be cast in place.

[9] *Standard Specifications for Highway Bridges*, 13th edition (Washington, DC: American Association of State Highway and Transportation Officials, 1983). The 9th edition (issued in 1965) applied to the 1973 design, and the 13th edition (issued in1983) applied to the 1986 design. The 10-kip transverse design force requirement remained the same in both specifications.

[10] As a result of the August 2008 accident, the Governor of Maryland called for a panel of experts to review the accident bridge and advise the MdTA on its bridge management practices. In September 2008, the Maryland Secretary of Transportation appointed a seven-member peer group to examine the MdTA's overall inspection practices for bridges and tunnels, as well as the particular issues surrounding the Chesapeake Bay Bridge barriers.

Bridge Barrier Performance

Due to differences in the scope of past rehabilitation projects on the Chesapeake Bay Bridge, the beam span sections of the bridge (4,113 feet or 0.80 mile, representing 18 percent of the bridge's barrier system) had a different barrier anchor design than the rest of the span sections (girder, deck truss, and through truss spans). Bridge barriers designed before 1964, as discussed in the current AASHTO *Roadside Design Guide*,[11] generally do not meet current standards because they were not crash-tested.

The 2007 AASHTO *Load and Resistance Factor Design (LRFD) Bridge Design Specifications*[12] describes the six test levels for bridge railings. Section C13.7.2 states that:

> The individual tests are designed to evaluate one or more of the principal performance factors of the bridge railing, which include structural adequacy, occupant risk, and post-impact behavior of the test vehicle. In general, the lower test levels are applicable for evaluating and selecting bridge railings to be used on segments of lower service level roadways and certain types of work zones. The higher test levels are applicable for evaluating and selecting bridge railings to be used on higher service level roadways or at locations that demand a special, high performance bridge railing. In this regard, test level 4 (TL-4) railings are expected to satisfy the majority of interstate highway design requirements.

The most recent criteria for crash testing barriers is contained in the *Manual for Assessing Safety Hardware* (MASH), which was adopted in October 2009 and is scheduled to be fully implemented by January 1, 2011.[13] Under MASH, TL-4 barriers are tested with a single unit truck weighing 22,000 pounds, traveling 56 mph, at an impact angle of 25 degrees.[14] The impact angle for the test was determined based on the 85th percentile of crash data analysis.[15]

The tractor-trailer involved in the Chesapeake Bay Bridge accident weighed approximately 80,000 pounds. The Chesapeake Bay Bridge barrier was not designed to prevent a vehicle weighing 80,000 pounds and striking the barrier at an angle of impact of approximately 40 degrees from departing the bridge. A postaccident report issued by the state-appointed peer group echoed this assessment with a finding that bridge barriers are not typically designed to withstand the crash forces of a large tractor-trailer truck striking the barrier at angles greater than

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[11] *Roadside Design Guide*, 3rd edition, section 7.7.1, "Identification of Potentially Deficient Systems," (Washington, DC: American Association of State Highway and Transportation Officials, 2006), p. 7–8.

[12] *LRFD Bridge Design Specifications*, 4th edition (Washington, DC: American Association of State Highway and Transportation Officials, 2007), p. 13–9.

[13] MASH, which will replace National Cooperative Highway Research Program (NCHRP) Report 350 (*Recommended Procedures for the Safety Performance Evaluation of Highway Features*, NCHRP Report 350 [Washington, DC: Transportation Research Board, 1993]), on January 1, 2011, is an update to and supersedes NCHRP Report 350 for the purposes of evaluating new safety hardware devices. It is not a design standard, however, and does not supersede the criteria for design of roadside safety hardware contained within the AASHTO *Roadside Design Guide*.

[14] *Impact angle* refers to the crash test vehicle's approach path angle relative to the barrier's longitudinal surface. MASH criteria increased the small car impact angle from 20 to 25 degrees to match the impact angle used in light truck testing.

[15] Crash data analysis determined that 85 percent of crashes occur at an impact angle of 25 degrees or less.

25 degrees. The group also stated that "impact forces may become so great that it is impossible to contain a vehicle without serious injury to occupants and damage to the vehicle."[16] Crash forces to vehicle occupants at more extreme angles approach conditions that are not survivable, regardless of containment.

Immediately following the accident, in August–September 2008, the MdTA installed temporary tie-down straps at the base of the barriers along the eastbound beam span sections of the bridge, at an approximate cost of $4.1 million. This installation had a limited capacity to resist the force of a barrier impact but, rather, served to prevent uplift and overturning of the barrier. From June 2009–March 2010, the MdTA completed a $1.4 million permanent barrier retrofit to the beam span sections of the bridge, adding bolts that extended down through the traffic-side face of the barriers and through the roadway slab. Following the addition of these bolt anchors to the barriers, the steel tie-down straps were removed. The permanent barrier retrofit used 1-inch-diameter anchoring bolts with hexagonal nuts and washers. The exposed portions of the core hole were filled with epoxy grout. In a February 4, 2010, letter to the NTSB, the MdTA provided design plans for the permanent barrier retrofit and stated that the retrofitted barrier met the equivalent of a TL-4 test level, as determined by engineering analysis. The MdTA also surveyed all of its other bridge assets and determined that the barrier anchorage system in the Chesapeake Bay Bridge was unique.

Corrosion Evidence

The NTSB materials laboratory examined the displaced barriers and retained eight concrete core samples, four U-bolts, and eight threaded U-bolt ends cut from the lower side of the deck for testing. Figure 3 shows U-bolts with threaded ends. The diameters of the U-bolts near the upper middle sections where there was no corrosion measured 0.994–1.002 inches. The lower ends of the U-bolts were reduced in diameter, and the smallest cross-sectional diameter was measured near the fractured ends. All of the bolts had reduced cross-sectional area due to corrosion; minimum diameter measurements were 0.648, 0.530, 0.415, 0.509, 0.378, and 0.305 inch. In one instance, the bolt diameter had corroded to the extent that it had decreased to a point. The fracture surfaces were covered in red, black, and orange oxides and exhibited reverse bending fatigue and environmental exposure. (See figure 3.)

[16] *Task Force Report: Review of the Maryland Transportation Authority's Bridge and Tunnel Inspection Practices, June 1, 2009* (finding 9, p. 18).



Figure 3. Photograph of U-bolts after removal from barrier.

Diameters were measured in the eight samples cut from the U-bolt threaded ends extending from the lower side of the deck. Samples from the traffic side of the barrier had diameters of 0.99–1.00 inch; samples from the bay side had diameters of 0.87–0.89 inch. The NTSB found that the attachment U-bolts for the barrier dislodged by the accident showed reduced cross-sectional area due to corrosion. The NTSB concludes that, based on the degree of corrosion, the attachment U-bolts for the barriers in the accident location were substantially degraded at the time of the accident.

MdTA Postaccident Nondestructive Evaluation

Once the accident investigation revealed evidence of barrier corrosion, postaccident testing was conducted to determine the extent of the problem. To survey the beam span sections, the MdTA conducted postaccident NDE of the bridge barriers in the southeast quadrant of the bridge. According to the state-appointed peer group, “Nondestructive evaluation techniques have been found to be effective in specific applications. These techniques are not routinely used in bridge inspection by agencies around the country except in selected situations where there are reasons to suspect problems.” Of the 5,376 U-bolts existing in the beam span sections of the

bridge, 2,459 bolts (45 percent) were tested; of these, 10 percent (247 bolts) were identified by ultrasonic testing (UT) method as being broken. Although the condition of many more bolts may be degraded, as used in this application, UT cannot determine the loss in U-bolt diameter due to corrosion. Destructive testing was conducted at six bridge locations to confirm the UT procedure's results. In this case, UT testing was a viable NDE option because of the barrier's unusual anchorage design, which used exposed, accessible bolts below the deck. The NTSB concludes that the condition of the U-bolt anchorages in the bridge barriers along the entire beam span section of the bridge had degraded but to an unknown degree.

Ground penetrating radar (GPR), which uses electromagnetic waves to assess subsurface flaws, was used to scan the barrier attachment areas for voids in the cast-in-place concrete barriers.[17] The GPR findings revealed that voids were prominent along the southeast concrete barrier of the beam span sections of the bridge and were evident to a lesser degree in the remaining three quadrants (barriers along the northeast, northwest, and southwest beam spans). Concrete barriers along the girder, deck truss, and through truss span portions of the bridge showed few to no voids. The GPR results described by the MdTA characterized the concrete as "sound" or containing "small random voids" or "void present" but did not quantify void size. The MdTA, in its presentation of UT and GPR data to the state-appointed peer group in December 2008, stated that GPR could locate voids but could not easily determine their sizes. Voids provide an opportunity for the internal collection of moisture which, in turn, can cause corrosion of the steel reinforcement bars and U-bolts. Voids are consistent with insufficient compaction of concrete at the time of installation.

The MdTA noted that deicing materials (mainly salt) are applied to the bridge deck after the start of frozen precipitation. Corrosion of the U-bolts was most likely the result of exposure to environmental conditions, such as salt, moisture, and oxygen. The vertical grade of the bridge drains to the beam span sections, and the small joint between the bottom of the barrier and the surface of the bridge deck, allowed salt and water to infiltrate the joint. This phenomenon occurred for approximately 35 years, from the time the U-bolts were originally installed in 1973.

The Chesapeake Bay Bridge underwent three types of bridge inspections: routine inspections conducted annually (the *National Bridge Inspection Standards* [NBIS] requirement is for inspections at 24-month intervals); fracture-critical member inspections conducted annually (NBIS requirement is for 24-month intervals); and underwater inspections conducted every 60 months (NBIS requirement is for 60-month intervals). NTSB investigators reviewed reports for routine inspections of the eastbound bridge span conducted by the MdTA during fiscal years 1998–2009. Those reports did not identify any problems with corrosion of the U-bolts attaching the barriers to the bridge deck. However, examination by the NTSB materials laboratory documented internal U-bolt anchorage corrosion. The NTSB concludes that annual routine visual inspections could not have identified the hidden corrosion of U-bolt anchorages in the concrete. Although Maryland officials determined that the design of the Chesapeake Bay Bridge barriers is unique to Maryland bridges, it is possible that bridges in other states may have similar barrier attachment details that would be susceptible to corrosion; however, the FHWA's National Bridge Inventory does not contain this information. Therefore, the NTSB recommends that the FHWA

[17] Scans were conducted with a Geophysical Survey Systems SIR-3000 handheld unit with a 1.6-gigahertz antenna.

inform state Departments of Transportation (DOT) of the risks of steel reinforcement corrosion and voids in concrete barriers and barrier attachment points and of the NDE methods used by the MdTA to identify internal corrosion problems.

National Bridge Inspection Program

As authorized by the National Bridge Inspection Program,[18] the NBIS were adopted in April 1971, following the collapse of the Silver Bridge into the Ohio River on December 15, 1967.[19] The Surface Transportation Assistance Act of 1978 extended NBIS requirements to bridges greater than 20 feet in length on all public roads and, in 1987, the scope was again expanded to include special inspection procedures for fracture-critical members and underwater inspection.[20]

The NBIS, which incorporate by reference inspection procedures from AASHTO's *Manual for Bridge Evaluation*,[21] address proper safety inspection and evaluation of all highway bridges and establishes qualifications and training for highway bridge inspectors. The NBIS also require states to maintain and report inventory data (23 *Code of Federal Regulations* 650.315) on their inspection findings; the resulting National Bridge Inventory contains more than 25 years of information on the U.S. bridge population.

The most common practices used to evaluate bridge decks include inspecting the deck condition visually, sounding a bare deck with a chain or hammer, comparing electrochemical measurements over time, and taking core samples.[22] NCHRP Synthesis Report 375 summarizes the formal bridge inspection practices of state DOTs in the United States and of other countries. The executive summary states that "These are primarily visual inspections and they provide data to bridge registries and databases."[23] All of these methods may require lane closure and have limited ability to determine the internal condition of the deck over the entire deck area.

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[18] 23 *United States Code* (U.S.C.) 151 and U.S.C. 650, subpart C, 1971.

[19] The NTSB's history of investigating bridge accidents begins with the accident on the Silver Bridge in West Virginia that killed 46 people. For further information, see *Collapse of U.S. Highway Bridge, Point Pleasant, West Virginia, December 15, 1967*, Highway Accident Report NTSB/HAR-71/01 (Washington, DC: National Transportation Safety Board, 1971).

[20] Surface Transportation and Uniform Relocation Assistance Act of 1987.

[21] *Manual for Bridge Evaluation*, 1st edition, with 2010 interim revisions, AASHTO. This manual provides guidelines for determining the physical condition, maintenance needs, and load capacity of highway bridges and was developed to assist bridge owners in establishing inspection procedures and evaluation practices that meet the NBIS. Rating examples are also included. The manual supersedes both the *Guide Manual for Condition Evaluation* and *Load and Resistance Factor Rating (LRFR) of Highway Bridges*, 1st edition, with 2005 interim revisions, and the *Manual for Condition Evaluation of Bridges*, 2nd edition, with 2001 and 2003 interim revisions.

[22] Bridge inspectors must complete Safety Inspection of In-Service Bridges (FHWA-NHI-130055), a comprehensive 2-week training course on bridge inspection methods offered through the FHWA's National Highway Institute (NHI).

[23] G. Hearn, *Bridge Inspection Practices*, NCHRP Synthesis 375 (Washington, DC: Transportation Research Board, 2007), p. 1.

In 2001, the FHWA's Turner-Fairbank Highway Research Center (TFHRC) completed a study of the reliability of bridge inspections,[24] focusing on two common types of inspections: (1) routine, regularly scheduled inspections and (2) in-depth inspections.[25] Ten inspection tasks were performed on 7 test bridges using 49 state inspectors from 25 state agencies. The results illustrated considerable variability in inspection ratings, with the FHWA noting:

> A number of important conclusions were developed from the experimental study and are summarized in the final report. As an example, it was found that Routine Inspections are completed with significant variability. This variability is found in all aspects of the inspection process but is most prominent in the assignment of Condition Ratings, where bridge owners can expect 95% of Condition Ratings to be spread over five rating points.[26] With respect to In-depth Inspection, it appears unlikely that In-depth Inspections will correctly detect and identify the types of defects for which those types of inspections are typically prescribed. Further, a significant proportion of In-depth Inspections will not reveal deficiencies beyond those that could be noted during a Routine Inspection.[27]

The Highway Bridge Program (HBP) is the primary source of Federal funding for bridges, providing over $4.5 billion to the states per year.[28] States may use HBP funds to reduce the number of defective bridges, to conduct systematic preventive maintenance projects, or to conduct selected bridge projects, such as seismic retrofitting. In January 2005, the FHWA updated the NBIS to reflect the increasing complexity and cost of bridge inspection activities with more advanced equipment. Concerned that the absence of funding for new inspection equipment may be adversely impacting the National Bridge Inspection Program, the FHWA issued a memorandum on October 5, 2005, to clarify that Highway Bridge Replacement and Rehabilitation Program funds could be used for the purchase of specialized bridge inspection equipment, such as NDE equipment and data collection and analysis equipment.

Some states select projects based on bridge management systems and state-specific bridge condition rating systems. Bridge management systems provide a systematic process for cost-effectively maintaining, upgrading, and replacing physical assets. Systems approaches to asset management have been used in the bridge community for two decades.[29] Bridge inspection is one component of bridge condition monitoring, which, in turn, is one aspect of a

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[24] M. Moore and others, *Reliability of Visual Inspection for Highway Bridges*, FHWA-RD-01-020 (Washington, DC: Federal Highway Administration, 2001).

[25] Federal regulations define eight types of inspections: initial, routine, in-depth, special, damage, fracture-critical member, hands-on, and underwater. The standard interval for fracture-critical member inspections and routine inspections is 24 months.

[26] Condition ratings describe the current condition of the bridge, ranging from 0 (failed) to 9 (excellent). The ratings are an overall assessment of the deck, superstructure, and substructure.

[27] For more information, see <http://www.tfhrc.gov/hnr20/nde/visual.htm>, accessed May 23, 2010.

[28] For more information on the 1998–2007 funding average, see <http://www.aashtojournal.org/pages/072310bridges.aspx>, accessed July 23, 2010.

[29] R. de Neufville, *Applied Systems Analysis: Engineering Planning and Technology Management* (New York: McGraw Hill, 1990).

comprehensive bridge management program.[30] The current trend in bridge management is performance-based management, which incorporates an array of information concerning the design and condition of the bridge, traffic and environmental operating conditions, construction and maintenance history, and structural health monitoring. The objective of performance-based management is to guarantee that the bridge will meet an objective set of lifecycle performance metrics. Bridge management programs and the sophisticated analyses that are used to support business decisions about highway assets require quantitative data.[31] However, performance-based management of bridge assets is weakened by an inspection program that is primarily conducted through visual inspection methods. The NTSB concludes that although bridge management systems may make use of sophisticated and elaborate analysis techniques, their reliance on visual inspection data is a clear limitation.

Nondestructive Evaluation Methodologies

NDE can be used to measure material characteristics of damage, such as corrosion, in structures or their components without compromising structural integrity. NDE methodologies quantitatively collect condition data on different properties of the structure—mechanical, electrical, optical, thermal, or chemical—by means of:

- **Eddy current testing.** Uses electromagnetic induction to assess surface flaws, material thickness, and coating thickness. Typically used on metals with painted or untreated surfaces.

- **Ultrasonic testing (UT).** Uses high frequency sound energy to assess flaws (surface and subsurface) and make dimensional measurements, typically on metals with untreated or cleaned surfaces.

- **Infrared thermography.** Measures the amount of infrared energy emitted by an object to calculate temperature. Typically used to assess deterioration damage, surface and subsurface flaws, and moisture intrusion.

- **Impact echo testing.** Uses impact-generated stress waves to assess subsurface flaws and material thickness in concrete and masonry.

- **Ground penetrating radar (GPR).** Uses electromagnetic waves to assess subsurface flaws and to image embedded reinforcement or tendons in concrete, asphalt, timber, or earthen structures.

[30] For a thorough discussion of bridge management, see M. Markow and W. Hyman, *Bridge Management for Transportation Agency Decision Making*, TRB Synthesis Report 397 (Washington, DC: Transportation Research Board, 2009).

[31] Authorization of the FHWA's Long-Term Bridge Performance (LTBP) Program was enacted by Congress in 2005 in the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). The objective of the LTBP program is to compile a comprehensive database of quantitative information from a representative set of bridges, looking at factors that specifically affect performance.

The more common NDE tools include GPR, UT, laser scanning, and infrared thermography.[32] Although NDE methods have existed more than three decades,[33] much of the research and development concerning highway applications has occurred in recent years.[34]

NDE is used across a wide variety of industries, as evidenced by the varied membership of the American Society for Nondestructive Testing (ASNT), which sets certification standards for NDE training and qualification.[35] There are three qualification levels:

- Level I and II certification is based on training hours, work experience, and passing both written and practical examinations related to the testing method.

- Level III certification is based on initial training (ranging from 40–120 hours, depending on testing method), 1–4 years of experience using the testing method (depending on the educational qualifications of the trainee), and successful completion of a series of written and practical examinations. Level III certification is available in six areas: magnetic particle testing, liquid penetrant testing, radiographic testing, UT, visual and optical testing, and electromagnetic testing.[36]

The FHWA established the TFHRC NDE Center laboratory in 1998 to improve practices for highway bridge inspections. The NDE Center laboratory is charged with providing independent evaluation of the reliability of NDE technologies, developing new NDE technologies to solve specific problems that are critical to maintaining safety, and providing technical assistance to states exploring the use of these advanced technologies. The laboratory includes a structural loading floor for constructing mockups of field conditions, a radiological capability for creating x-ray images of defects, a computed tomography facility for characterizing materials, and an instrumentation facility for manufacturing prototypes and developing new NDE tools.[37] In addition to the laboratory, the NDE program uses a series of field tests on bridges in northern Virginia and southern Pennsylvania to collect field data and component test specimens.

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[32] H. Song and V. Saraswathy, "Corrosion Monitoring of Reinforced Concrete Structures–A Review," *International Journal of Electrochemical Science*, vol. 2 (2007), pp. 1–28.

[33] S. Li, V. Ramakrishnan, and J. Russell, "Advances in Nondestructive Testing of Concrete," *Fifth International Bridge Engineering Conference, June 1972*.

[34] A TRB report (A. Wimsatt, *A Plan for Developing High-Speed Nondestructive Testing Procedures for Both Design Evaluation and Construction Evaluation*, Second Strategic Highway Research Program [SHRP 2] Report S2-R06-RW [Washington, DC: Transportation Research Board, 2009]) includes a literature review of over 400 publications on NDE. A standing committee, AFF40–Field Testing and Nondestructive Evaluation of Transportation Structures, and international symposiums and ASNT conferences have focused on NDE for highways and bridges. More than a decade ago, the FHWA funded the development of HERMES (High-Speed Electromagnetic Roadway Measurement and Evaluation System) at the Lawrence Livermore National Laboratories.

[35] Recommended Practice SNT-TC-1A, first published by ASNT in 1968.

[36] Persons certified by examination through their employer or contracted agencies are "certified in accordance with Recommended Practice No. SNY-TC-1A." Persons certified by ASNT are "ASNT Certified." Since 1988, Level III certification can be granted only by ASNT.

[37] One such tool is a GPR system (HERMES) that can reliably detect, quantify, and image delaminations in bridge decks while operating at normal highway speeds, eliminating the need for lane closure. The HERMES system includes a computer workstation and storage device, survey wheel, control electronics, and an array of 64 antenna modules or transceivers mounted in a towable trailer. A prototype was delivered to the FHWA in October 1998.

The NDE Center laboratory and program are part of the Infrastructure Inspection and Management (II&M) Team in the FHWA's Office of Infrastructure. The NDE program staff is small, currently comprising a Federal program manager and contractor support staff consisting of three research engineers, one technician, a technical manager, and a project manager. The staff has been supplemented in recent years by a National Research Council (postdoctorate) Fellow and visiting professors on interagency agreement. Over the years, funding for research conducted at the NDE Center laboratory has been provided primarily by set-aside programs within transportation legislation, along with AASHTO state pooled-fund projects. In the most recent transportation legislation (SAFETEA-LU), only one funding designation supported research at the NDE Center laboratory. The Steel Bridge Testing Program was authorized $1.25 million per year (FY06–FY09). Although the NDE program has its own identity within the II&M team, other program elements within that team (the LTBP as well as the Coating and Corrosion Program) conduct NDE research and development specific to bridge inspection.

Following the Minneapolis bridge collapse, the FHWA focused on advancing NDE techniques and promoting their use by bridge owners. In March 2008, the NDE Center laboratory developed a Bridge Inspectors NDE Showcase (BINS), which was a 1-day demonstration-based seminar designed to expose state DOT bridge inspection staff to basic NDE tools and methodologies; to knowledge of how, when, and where to apply NDE tests during a bridge inspection; and to the capabilities and limitations of each methodology. BINS was funded with discretionary sources from the TFHRC and the Office of Bridge Technology. Thus far, BINS has addressed five different NDE test methods:[38] eddy current, UT, infrared thermography, impact echo, and GPR.

The FHWA's BINS training on NDE systems has been well received, with approximately 100 inspectors completing the 1-day showcase. However, that number represents a small fraction of bridge inspectors; and many, if not all, need exposure to NDE practices.[39] Although not all state bridge inspectors need to be NDE qualified, inspectors and those responsible for inspection should be aware of the types of testing methods that can be applied to specific types of infrastructure. In July 2010, the FHWA announced to its Division Bridge Engineers the availability of BINS (NHI course #130099). NHI is providing one session of the course to each state DOT at no cost,[40] as long as it is the DOT's first offering of the course and is scheduled to be hosted before August 2011. Although NHI classes normally have approximately 30 participants, BINS will be structured to allow for a class size of approximately 100 participants. The NTSB commends the FHWA's Office of Bridge Technology on this training effort.

[38] Distinguishing between testing methods explains why the six areas of ASNT certification differ from those demonstrated in BINS. BINS demonstrates specific testing methods while ASNT testing methods refer to more general physical testing mechanisms, such as electromagnetic testing or UT.

[39] According to a survey of state bridge inspection personnel, as documented in NCHRP Synthesis 375, individual states typically have several executive level managers; a staff of regional bridge inspection managers (for example, New York=18, Michigan=7, Kentucky=12, and Virginia=9); team leaders (for example, Virginia=33, New York =27 + consultants, North Carolina=18, and Pennsylvania=25 + consultants); and a staff of inspectors and consultants (for example, Virginia=45, North Carolina=21, and Pennsylvania=24). Not all states responded to survey requests summarized in that report, and a national total was not given. However, by extrapolating the staffing numbers that were reported, bridge inspectors and those in direct supervision of inspections can be estimated at 3,000.

[40] The FHWA NHI website lists a registration fee of $13,000.

The transfer of NDE techniques from research and development to field applications has been gradual. The TRB recognizes that "implementation is more challenging than the original development of the technology."[41] Moving new inspection technologies from a controlled, laboratory environment into field operations is challenging. Variations in operator skill, differing techniques, asset structural differences, and environmental factors all affect the quality of evaluation results. Testing standards—as defined by the ASTM, the American National Standards Institute, or the American Society of Mechanical Engineers—describe validated methods for conducting materials testing. State DOTs recognize the need to develop validated NDE methods, and some have proceeded to develop their own validation facilities and capabilities.[42] Such standards provide guidance on the critical aspects of conducting tests and standardize test execution by different evaluators. NDE programs and the standards used to conduct evaluations are not as advanced for concrete as they are for steel structures; only a few standards exist for concrete materials.[43] The NTSB concludes that few standards currently exist for NDE in highway applications and very few for concrete materials.

The *Bridge Inspector's Reference Manual*[44] (BIRM) contains information about programs, procedures, and techniques for inspecting and evaluating various types of highway bridges. The BIRM is used as the basis for the NHI's 3-week training program on bridge inspections, which consists of a 1-week course, "Engineering Concepts for Bridge Inspectors," and a 2-week course, "Safety Inspection of In-Service Bridges." When combined, these courses meet the FHWA's definition of a comprehensive training program in bridge inspection as defined in the NBIS. Although the BIRM contains a very limited discussion of advanced techniques,[45] it offers one of the best tools for introducing inspectors to NDE techniques and their appropriate use based on type of bridge material.

The NTSB recognizes the training efforts of the FHWA with regard to NDE, but also sees opportunities for an expanded treatment of NDE methods in the BIRM; a focus on developing test standards for bridge inspection applications; a more robust treatment of NDE methods in infrastructure asset management programs, such as the LTBP program; and the acceptance of quantitative NDE data into the National Bridge Inventory. The NTSB concludes that the FHWA's efforts to promote NDE technology for bridge inspectors have been limited and that NDE inspection practices are not widely used by the states because of their complexity and cost. The NTSB recommends that the FHWA (1) expand the research and development of NDE technologies to develop bridge inspection methods that augment visual inspections; offer reliable

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[41] TRB SHRP 2 Report S2-R06-RW, p. 2.

[42] D. Algernon, D. Hiltunen, and C. Ferraro, *Validation of Nondestructive Testing Equipment for Concrete*, Final Report, contract BD545-80 (Tallahassee, Florida: Florida Department of Transportation, July 2010).

[43] ASTM C876-91, regarding half-cell potential mapping, is a field-tested technique used to evaluate the probability of corrosion of reinforcing steel in concrete. ASTM C597-97 is a testing method used for determining pulse velocity through concrete. There are also a few AASHTO standards for testing concrete materials (T260-97, Sampling and Testing for Chlorine Ion in Concrete and Concrete Raw Materials, and T277-07, Electrical Indication of Concrete's Ability to Resist Chlorine Ion Penetration).

[44] *Bridge Inspector's Reference Manual*, FHWA NHI 03-001 (vol. 1) and FHWA NHI 03-002 (vol. 2) (Washington, DC: Federal Highway Administration, 2002, rev. 2006).

[45] Section 13 covers advanced techniques in the areas of timber, concrete, and steel, along with a section on advanced asset assessment.

measurement techniques; and are practical, both in terms of time and cost, for field inspection work; and (2) promote the use of these technologies by bridge owners.

Recommendations

As a result of its investigation, the National Transportation Safety Board makes the following recommendations to the Federal Highway Administration:

> Inform state Departments of Transportation of the risks of steel reinforcement corrosion and voids in concrete barriers and barrier attachment points and of the nondestructive evaluation methods used by the Maryland Transportation Authority to identify internal corrosion problems. (H-10-17)

> Expand the research and development of nondestructive evaluation technologies to develop bridge inspection methods that augment visual inspections; offer reliable measurement techniques; and are practical, both in terms of time and cost, for field inspection work; and promote the use of these technologies by bridge owners. (H-10-18)

In response to the recommendations in this letter, please refer to Safety Recommendations H-10-17 and -18. If you would like to submit your response electronically rather than in hard copy, you may send it to the following e-mail address: correspondence@ntsb.gov. If your response includes attachments that exceed 5 megabytes, please e-mail us asking for instructions on how to use our Tumbleweed secure mailbox. To avoid confusion, please use only one method of submission (that is, do not submit both an electronic copy and a hard copy of the same response letter).

Chairman HERSMAN, Vice Chairman HART, and Members SUMWALT, WEENER, and ROSEKIND concurred in these recommendations.

[Original Signed]

By: Deborah A.P. Hersman
Chairman