BRIDGES of the AASHO Road Test

A Unique and Historic Research Endeavor

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Tests in the early 1920s and later studies showed that the service life of a highway pavement is related to the magnitude and frequency of the wheel loads, to the characteristics of the pavement and its substrate, and to the environment. Efforts to quantify these relationships led the American Association of State Highway Officials[1] (AASHO) to conduct the historic Road Test in the late 1950s.

Contributions from the 48 contiguous states, Hawaii, the District of Columbia, and the territory of Puerto Rico financed this major undertaking. The U.S. Department of Defense provided a unit of 300 to 400 soldiers to drive the test vehicles. The total cost of the project was approximately $27 million, including $12 million for research, $12 million for construction, and $3 million in contributed services.

The Highway Research Board[2] (HRB) was responsible for the project's administration and direction. Advisory committees and panels reported to the National Advisory Committee, chaired by Professor K. B. Woods, Head of the School of Civil Engineering at Purdue University. Day-to-day direction of the work was the responsibility of Project Director Walter B. McKendrick, Jr., and Chief Engineer William N. Carey, Jr.

Technical personnel reporting to Carey included research engineers in charge of the four principal branches: Alvin C. Benkelman, flexible pavements; Frank H. Scrivner, rigid pavements; Ivan M. Viest, bridges; and Paul E. Irick, data processing and analysis. Personnel included permanent staff and engineers-in-training assigned to the project by the Bureau of Public Roads[3] (BPR) for 6 months. Interested agencies and organizations also delegated consultants and observers to the Road Test.

Pouring slab for test bridge.

Adding Bridges

At the request of the AASHO Committee on Bridges and Structures, the plan to test asphaltic and concrete pavements was expanded in scope in December 1951 to include bridges. The structures were to be designed as case studies of the effect of repeated overstress on the service life of highway bridges.

The bridge research was the brainchild of three members of the HRB Bridge Committee: E. L. Erickson, Chief of the BPR Bridge Division; Glen S. Paxson, Bridge Engineer of the Oregon State Highway Commission; and Chester P. Siess, Research Associate Pro-

[1] Now the American Association of State Highway and Transportation Officials.

[2] Now the Transportation Research Board.

[3] Now the Federal Highway Administration.

fessor of Civil Engineering at the University of Illinois. At the HRB 1951 annual meeting, the committee developed the proposal for including case studies of ordinary slab-and-beam highway bridges in the AASHO Road Test.

The final plan for the Road Test included 16 short-span test bridges representing in simplified form the types of bridges commonly built on the U.S. highway system. A Subcommittee on Bridges was appointed as part of the Working Committee of the AASHO Committee on Highway Transport.

The subcommittee selected the design variables and criteria for the test bridges, which included eight bridges with steel beams, four with prestressed concrete beams, and four with reinforced concrete T-beam construction. BPR designed the bridges with steel beams; the Portland Cement Association designed the bridges with concrete beams. The subcommittee reviewed the final designs.

Construction and Adjustments

The AASHO Road Test facility was located a short distance northwest of Ottawa, Illinois, and 80 miles southwest of Chicago, on the right-of-way of the future Interstate 80. Construction of the temporary test facility started in August 1956.

The first concrete for bridge foundations was cast on October 5, 1956, and the last concrete on May 28, 1957. The erection of beams commenced in June and was completed by the end of November. Roadway slabs for bridges with steel and prestressed concrete beams were cast from August 1957 to April 1958. The superstructures for the reinforced concrete bridges were cast in August and September 1957.

Vehicles first crossed over the test bridges on August 29, 1958. Regular test traffic began on November 5, 1958, and ended on December 3, 1960.

Early in the testing, four of the steel beam bridges failed. Safety cribs then were placed for support under all bridges before the beginning of the test traffic, with enough clearance to permit unrestricted deflections under loading, as well as inspection of the underside.

Cribbing placed below test bridges.

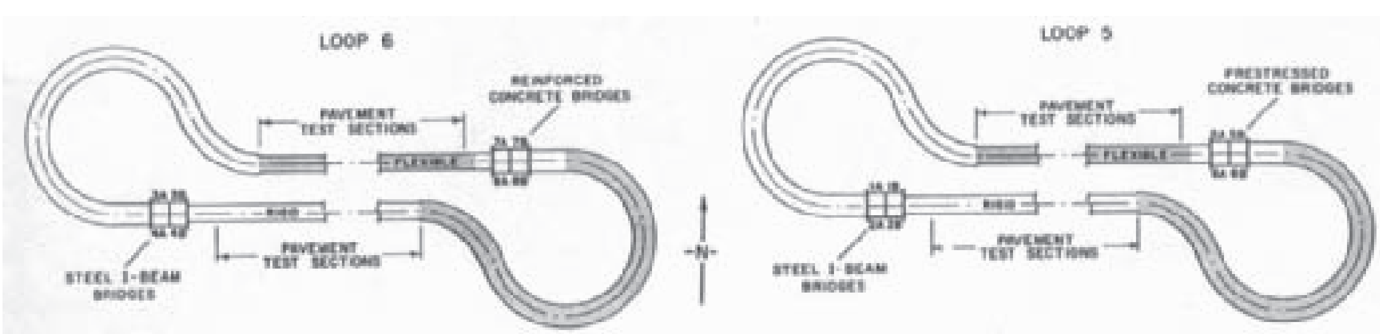
Two of the failed bridges were replaced, increasing the total of the test bridges to 18. Regular test traffic began on the two replacement bridges on June 20, 1959. Both bridges survived the remaining period of the test traffic.

Conducting Additional Tests

Dynamic tests of the bridges were conducted from fall 1958 to October 1960, in cooperation with the University of Illinois. Bridge testing continued after the completion of the regular test traffic, first with accelerated fatigue tests and then with tests that increased the loads until the bridge's failure.

The fatigue tests added to the number of maximum stress cycles accumulated in the regular test traffic. The tests with increasing loads were conducted to determine the greatest loads that could cross a bridge, as well as the mode of failure for each bridge type. All bridge testing was completed by June 12, 1961.

The Advisory Panel on Bridges and the Special Committee on Dynamic Behavior of Test Bridges, both chaired by Paxson, guided the bridge research. Members included Erickson and and state bridge engineers W. C. Hopkins, Maryland State Roads Commission; and O. L. Kipp and A. E. LaBonte, Minnesota Department of Highways; university professors Siess and A. S. Veletsos of Illinois, B. Thürlimann of Lehigh, and J.



Locations of test bridges.

Chronology of Bridge Research at the AASHO Road Test

1951 In December, at the request of AASHO Committee on Bridges and Structures, the scope of the AASHO Road Test is expanded to include bridges.

1952 Types and number of bridges, design variables, and criteria are selected.

1953 Bureau of Public Roads designs the steel bridges; Portland Cement Association designs the concrete bridges.

1954 Cost of bridge research is estimated at $386,000, including construction.

1955 Final scope of the project is limited to slab-and-beam type bridges. Each bridge is to consist of three simple-span beams supporting a concrete slab. Bridges with steel, reinforced concrete, and prestressed concrete beams are included.

1956 National Advisory Committee for the AASHO Road Test and Advisory Panel on Bridges are established.
Construction of the test road starts in August.
First pour of concrete for bridge foundations, October 5.

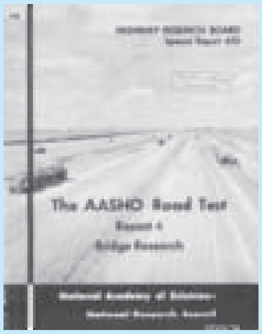
1958 University of Illinois starts cooperative investigation, Dynamic Studies of Bridges on the AASHO Road Test.
Four steel bridges designed to sustain stresses approaching the yield point fail in preliminary tests.
Controlled test traffic is inaugurated, October 15.

1959 Two of the four steel bridges that failed are replaced with two new steel bridges. Regular test traffic on the new bridges starts in June.

1960 Regular test traffic ends November 30.
Accelerated fatigue tests of bridges start in December.

1961 Bridge tests with increasing overloads start in March.
Accelerated fatigue tests are completed by end of May.
Testing of bridges is completed June 12.

1962 Bridge research results published in HRB Special Reports 61D and 71.
Conference on the AASHO Road Test convenes in St. Louis, Missouri, May 16–18.



Removing damaged steel from test bridge.

M. Biggs of Massachusetts Institute of Technology; and Road Test staff Carey and Viest.

Bridge Types

The AASHO Road Test included six test loops of two double-lane tangents with a variety of pavements. Turnarounds at each end of a tangent permitted continuous test traffic. The test bridges were one-lane, single-span structures. Groups of four bridges were placed at the beginning of the pavement test tangents on the two loops that carried the heaviest truck traffic.

All four bridges in a group were supported by a concrete substructure of two abutments and one pier on spread footings. Each superstructure consisted of three identical beams supported on steel bearings, fixed on the center pier, permitting expansion at the abutments. The 50-foot beams carried a reinforced concrete slab 6.5 inches thick and 15 feet wide. A 12-by-12-inch timber curb—two pieces spliced loosely at midspan—was bolted to the outside edge of the slab.

The steel beams varied from bridge to bridge in the size of the cross section, in the presence or absence of partial-length cover plates on the bottom flange of the I-section, and in the presence or absence of composite interaction with the slab. The cover plates were terminated according to the requirements of the stress analysis—that is, they were cut off short of the supports. In bridges with composite action, the slab was connected to the beams, eliminating differential movement along the interface of the two elements. The physical properties of the structural steel were close to the minimum specified values.

According to tension tests of coupons—or steel test strips—taken from the flanges of the delivered beams, the mean yield point varied from 34.7 to 37.9 thousand pounds per square inch (ksi) for the original bridges and was 32.5 ksi for the two replacement bridges. To preclude bonding with the slab on noncomposite bridges, the top surfaces of the steel beams were coated with a mixture of graphite and linseed oil. Channel shear connectors were welded to the top flanges of composite bridges. On the replacement bridges, a partial-length cover plate was welded on the bottom and also on the top flanges of the steel beams.

As noted, in composite bridges, differential movement does not occur along the interface of the slabs and the supporting beams. In noncomposite bridges, however, the slab deforms independently of the supporting beams and is free to slide along the top surfaces of the beams.

A commercial precaster in Springfield, Illinois, manufactured the prestressed concrete beams. All had the same cross section but with differences in prestressing steel and in the details of the end anchorages. Two bridges were posttensioned and two were pretensioned.

The beams of the posttensioned bridges were reinforced with draped parallel-wire cables. The cables were made up of ten 0.192-inch wires enclosed in a flexible steel conduit, secured by Freyssinet anchorages, and grouted. Each beam had four of these tendons in the lower-stressed bridge and six in the higher-stressed one.

The pretensioned beams were reinforced with straight 3/8-inch, 7-wire strands anchored by bond. Each beam had 16 strands in the lower-stressed and 20 in the higher-stressed bridge. All other features—such as the reinforcement of the relatively thin web connecting the two flanges of an I-section, the connection of the beams to the slab, and the slabs—were the same in all of the prestressed concrete bridges.

Loaded truck crosses test bridge. Bridge trailer that housed data recorders is at right.

The reinforced concrete bridges were constructed with monolithic T-beams. The cross section of the four bridges differed only in the details of the principal reinforcement. The stems of the T-beams were reinforced in tension with two layers of standard deformed reinforcing bars: three No. 11 bars in the bottom layer and two No. 9 bars in the upper layer. In addition, one No. 8 bar was placed in the upper layer of each stem on the lower-stressed bridges. The web reinforcement, slabs, and diaphragms were the same for all the reinforced concrete bridges.

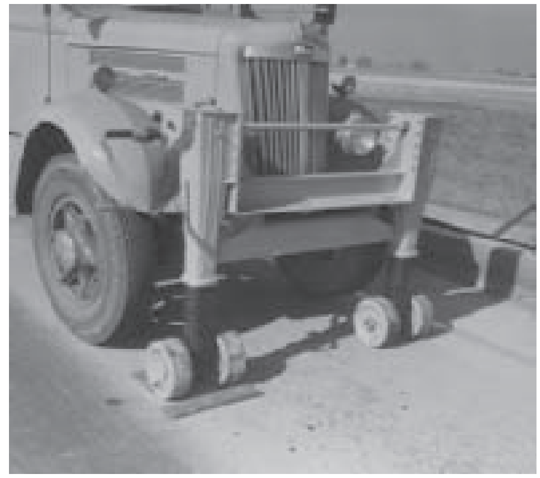
Tests with Repeated Stresses

Before the test traffic, regular test vehicles made special runs over all bridges to collect initial data on stresses and deformations. These reference tests were repeated at 6-month intervals.

Generally only small changes were observed in the stresses; nonetheless, the deflections of all bridges

Installing sensor beneath a bridge. Sensors were connected to data recording equipment in trailer.

Amplifiers and recording oscillographs in bridge trailer.



Above, left: Mechanical oscillator on a bridge. *Above, right*: Vibrating truck on bridge.

increased with time. The increase was generally 5 to 16 percent in steel bridges and 18 to 35 percent in concrete bridges. The changes in deflections indicated decreasing stiffness, probably the result of cracking in the concrete slabs and concrete beams. Progressive cracking was observed as the test vehicle trips accumulated.

Tests of steel beams with partial-length cover plates demonstrated that the section at the end of a cover plate—and by implication at other stress raisers of similar configuration—can be critical in fatigue cracking. By the end of the regular test traffic, all steel bridges with partial-length cover plates had at least one fatigue crack.

In the reinforced concrete bridges designed for high stress, two bars broke in the exterior beam after 730,000 cycles. The fractures seemed to occur suddenly. An examination of the reinforcing bars after bridge failure, however, revealed incipient cracks short distances away from the breaks. The crack growth, therefore, must have been gradual, leading to the fractures.

In the prestressed concrete bridges subjected to tensile stress lower than the modulus of rupture, some fatigue cracking of concrete was detected during the test traffic. This fatigue cracking, however, had no observable effects on the overall behavior of the test bridges, except for an increase in deflections.

The number of stress cycles for the fatigue cracking of steel beams with partial-length cover plates and for the fracture of reinforcing bars in reinforced concrete bridges was compared with laboratory fatigue data for similar specimens. The results indicated that with an estimate of the magnitude and the number of repetitions of stress, laboratory fatigue data for component elements can forecast—within reasonable limits—the service life of a bridge until fatigue failure.

Special vehicle during test to failure with increasing loads.

Accelerating Fatigue

The AASHO Road Test bridge research demonstrated that consideration of fatigue should be integrated into the design requirements for bridges on the highway system. Furthermore, the findings suggested a simplified method for fatigue design, but systematic laboratory tests were needed to develop practical requirements. The tests were performed later at Lehigh University under the National Cooperative Highway Research Program (NCHRP).

After the conclusion of the regular test traffic in December 1960, 7 of the 13 surviving test bridges were subjected to accelerated fatigue tests. A mechanical oscillator was applied to the bridges at an amplitude that approximated the maximum stress and the range of the fluctuating stress at the critical section during the test traffic. The vibration continued until bridge failure or until 1.5 million stress cycles—comparable to the number of cycles accumulated during the test traffic, with each trip of a regular test vehicle counted as one stress cycle.

The accelerated fatigue tests were equivalent to laboratory fatigue tests and differed from the tests under regular test traffic. Most of the differences, however, could be interpreted analytically or were minor.

For the bridges that failed by fatigue, the number of stress cycles applied in the accelerated tests was small in relation to the number of vehicle trips. The effect of the differences between the two types of tests on the findings, therefore, was negligible.

Dynamic Load Tests

The dynamic amplification—or impact—of vehicle loads has been a longstanding concern in bridge design. A simple formula relates the impact factor to the length of the bridge.

Research to develop comprehensive, yet easy-to-use, impact provisions for highway bridges has a long history. The AASHO Road Test site, only a 3-hour drive from the University of Illinois at Urbana, provided the Civil Engineering Department the opportunity to extend an active program of research on bridge impact from model tests and numerical simulations to full-size vehicles running on nearly full-size bridges.

The university and HRB established a cooperative research project, with Siess and Veletsos as principal investigators. Assistant Professor Robert K. L. Wen served as the first program manager, succeeded in the fall of 1958 by Steven J. Fenves, an instructor.

Implementing Dynamic Tests

The University of Illinois team developed the tests, which were reviewed and approved by the Special Committee on Dynamic Behavior of the Test Bridges and were performed by the Bridge Research group. The group ran approximately 1,900 tests from October 1958 through October 1960 on all bridge types, using 14 types of vehicles at speeds from 10 to 50 miles per hour.

The dynamic tests explored a range of parameters for bridge vehicles—such as speed, weight, frequency, and deflection ratios—and examined influencing factors, such as initial bridge and vehicle oscillations, eccentric loading, and the effect of inoperative vehicle springs. Qualitative and quantitative evaluations and comparisons were made in two formats: time histories, with the dynamic amplification of displacement and strain plotted against the vehicle position; and spectra, with the peak responses of interest plotted against the speed parameter.

Additional characterization tests on the bridges examined static loads and loads on vehicles traveling at a crawl speed of 3 miles per hour. Characterization tests of static loading on pavements included vehicles with normal and inoperative springs. The behavior models and testing methods for bridges were well established then, but the behavior of vehicles was largely unknown.

The static loading tests established the bilinear load-deflection characteristics of the vehicle leaf springs—initially the springs act as a single beam, then after overcoming the interleaf friction, each leaf deforms independently. The dynamic tests of vehicles on pavements primarily served to evaluate and calibrate the tire pressure gauges and the trailer-mounted recording mechanism developed by the Road Test instrumentation staff.

The analytical model for comparison with the experimental test results was sophisticated at the time, running on the University of Illinois' high-speed automatic computer, ILLIAC, which had 1,000 words—or 5 kilobytes—of storage.

Load testing.

Test Results

The dynamic tests confirmed all of the theoretical predictions about the bridges: that the bridges acted as simply supported beams; that noncomposite steel, prestressed, and reinforced concrete bridges exhibited different characteristics under load than in free vibration; and that age—that is, the number of regular load applications—reduces structural stiffness, except in composite steel bridges. Surface irregularities on the approaches and on the bridge had pronounced effects.

The major accomplishment of the dynamic tests on the AASHO Road Test bridges was the calibration of the analytical model to functioning bridges and vehicles.

AASHO Road Test Project Director Walter B. McKendrick, Jr. (*right*) joins National Academy of Sciences officials on an inspection tour of the bridge project.

Two prestressed concrete bridges after failure under increasing loads.

Other Tests and Studies

Four steel bridges, four prestressed concrete bridges, and two reinforced concrete bridges survived the tests with repeated loads and were available for tests that increased the loads until the bridge's failure. The tests studied the bridge's response to loads that approached capacity, to determine the bridge's manner of failure under moving loads, and to provide data for checking theories about ultimate strength.

In each test, the load would cross the bridge 30 times. The load then was increased for another 30 crossings. The procedure was repeated until the concrete slab was crushed, or the principal tension steel was fractured, or an already extreme permanent set—or deformation—at midspan continued to increase with each successive trip of the vehicle.

The tests with increasing loads were unique. No tests similar in scope have been performed since then on individual bridges. As Erickson observed, "[The] bridge tests in the Road Test program…have given information [about] the effect of overload on highway structures. Certainly it was demonstrated that overloading bridges sufficiently is going to wreck them."

HRB Special Report 61D, *The AASHO Road Test Report 4: Bridge Research*, describes seven additional tests and studies carried out during the project. The special post-traffic tests, for example, were carried out on pavements and bridges at the request of the Department of Defense, which was actively involved in the testing, to study the effects on bridge response of (*a*) tire pressure and tire design, (*b*) commercial construction equipment, (*c*) special suspension systems, and (*d*) military vehicles.

Other studies considered the properties of the concrete and steel in the test bridges and the development of a bond-breaking agent to allow treatment of the top flanges of the steel beams in noncomposite steel bridges. A mixture of linseed oil and graphite was found effective for preventing a bond.

The materials tests investigated the outdoor creep and shrinkage of concrete in prestressed concrete

When Does a Bridge Fail from Fatigue?

The Road Test's composite steel beam bridge was designed to sustain the stress of 35,000 pounds per square inch at the ends of the partial-length cover plates that were welded to the bottom flanges of the rolled steel sections. The bridge sustained all 558,400 trips of the assigned test vehicles.

By the end of the test traffic, fatigue cracks were visible at five locations. Three were confined to the areas around the toe of the welds connecting the cover plates. One extended from the weld to the near edge of the flange and another extended the full depth of the bottom flange from the edge to the web.

Additional applications of critical stress with a mechanical oscillator caused further growth in the cracks. One crack extended slowly toward the web. At 25,800 oscillator cycles, the crack reached about 6 inches into the web; a complete fracture of the steel section occurred after 47,500 oscillator cycles—that is, a total of 605,900 cycles of critical stress.

Two reinforced concrete bridges designed for a tensile stress of 40,000 pounds per square inch also were subjected to additional critical stresses with an oscillator. The tests proceeded smoothly for more than 170,000 post-traffic cycles. The response of the strain gages at midspan of one of the bridges became erratic at 172,600 cycles. An inspection after 174,000 cycles revealed two fractured reinforcing bars.

Fatigue failure of reinforcing bars in a reinforced concrete bridge.

In the other bridge, the bar fracture was signaled by a loud noise at 172,200 post-traffic cycles. One reinforced concrete bridge sustained a total of 730,100 and the other 728,300 critical stress cycles.

beams; relaxation and fatigue tests of the prestressing steel; fatigue tests of the reinforcing bars in the stems of the reinforced concrete bridges; and determination of the residual stresses and fatigue strength of structural steel in the rolled sections of the steel bridges.

The results of the creep and shrinkage tests of concrete cylinders, made from the same mix and at the same time as the prestressed concrete beams, were not published.

Follow-Up

The development of fatigue cracks at the ends of partial-length cover plates on steel test bridges demonstrated the need for comprehensive experimental studies. At that time, only approximate design relationships were available, relying on limited laboratory tests of small-scale samples. NCHRP initiated comprehensive research to provide data for the design of welded bridges. A series of research projects was carried out at Lehigh University starting in 1967.

Additional studies followed in the 1970s, when fatigue cracking was discovered in bridges on the highway system. Some of the cracking in beams with partial-length cover plates occurred in bridges with as little as 13 years of service. Furthermore, fatigue cracks were discovered frequently at the ends of web stiffeners, when stopped short of the beam flange.

The new studies included variable-cycle loading, full-scale bridge attachments, detection and repair of fatigue cracks, and an examination of large-scale experiments carried out worldwide in the 1970s and 1980s. NCHRP published these studies in nine reports—seven on the tests carried out at Lehigh University and two on tests at United States Steel Corporation. A new set of design requirements appeared in the 1986 American Association of State Highway and Transportation Officials (AASHTO) specifications.

Research on bridge dynamics has continued at the University of Illinois, at the Federal Highway Administration's Turner-Fairbank Highway Research Center, and elsewhere. The analytical bridge model for the Road Test bridges has been extended to continuous bridges and to two-dimensional modeling. Two-dimensional modeling has allowed the consideration of bridge skew, lateral stiffness distribution, superelevation, the effect of centrifugal forces, and many other parameters.

Dynamic tests are performed sporadically as a part of other full-scale bridge tests, but no program has matched the scale and comprehensiveness of the AASHO Road Test. With the veracity and reliability of analytical models today, if the bridge behavior can be verified by static and low-speed crawl tests, the full dynamic behavior predicted by the analytical models is accepted, at least for conventional dynamic effects on linearly elastic bridges.

AASHO Road Test Bridge Engineering Researchers

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A Unique Experiment

The bridge experiment at the AASHO Road Test provided insights into the behavior of highway bridges under the stresses caused by

- Large volumes of truck traffic,
- Moving loads, and
- Extreme overloads.

Extensive fatigue tests conducted after the completion of the Road Test studies have resulted in simple, but comprehensive, design requirements that should ensure the satisfactory long-term performance of welded steel bridges.

Because details of bridge dynamic behavior now can be ascertained by static and low-speed crawl tests combined with predictions from analytical models for all but the most unusual bridges, another experimental program of the scale and comprehensiveness of the dynamic load tests at the AASHO Road Test is unlikely. The bridge experiment at the AASHO Road Test nearly 50 years ago remains unique.