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Report to the Secretary of Transportation

November 1997

TRANSPORTATION INFRASTRUCTURE

Highway Pavement Design Guide Is Outdated

GAO/RCED-98-9

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United States
General Accounting Office
Washington, D.C. 20548

Resources, Community, and
Economic Development Division

B-275328

November 21, 1997

The Honorable Rodney E. Slater
The Secretary of Transportation

Dear Mr. Secretary:

The National Highway System encompasses about 155,000 miles of the nation's most important interstate, arterial, and major highways and freeways, which represents about 4 percent of the nation's approximately 4 million miles of public roads. Billions of dollars have been spent to construct these roads and highways, and preserving and maintaining them is estimated to cost billions of dollars more each year. In 1995, the U.S. Department of Transportation (DOT) estimated that the average annual cost to maintain overall highway conditions and performance for this system through the year 2013 to be $44.8 billion.[1]

An American Association of State Highway Officials[2] road test conducted in 1959-60 to obtain pavement performance data showed—among other things—that heavy trucks cause more highway pavement damage than other vehicular traffic. On the basis of this test, the Association developed an initial pavement design guide in 1961, and it has been updated periodically since then. DOT's Federal Highway Administration (FHWA) neither adopts the guide nor requires its use by states. Rather, FHWA—in its working relationship with states—requires that sound engineering and management principles and practices be used in the pavement design process. According to FHWA, one indication of this is the states' use of guides and standards developed by a number of standard-setting industry organizations, including AASHTO.

This report (1) describes the roles of FHWA and others in developing and updating the pavement design guide and (2) examines the use and potential of a computer analysis method known as the nonlinear 3 Dimensional-Finite Element Method (3D-FEM)[3] for improving the design and analysis of highway pavement structures.

[1]1995 Status of the Nation's Surface Transportation System: Condition and Performance, DOT (Washington, D.C.: Oct. 27, 1995), pp. xix, 175.

[2]This organization has since become the American Association of State Highway and Transportation Officials, more commonly known as AASHTO.

[3]The nonlinear 3D-FEM method uses a set of computer programs to analyze engineering problems. It has been used for about 25 years for solving structural problems with complicated geometries, loadings, and material properties associated with aeronautical, biomedical, automotive, naval architecture, nuclear weaponry, off-shore drilling, piping, and seismic engineering.

Results in Brief

The Federal Highway Administration has worked cooperatively with the American Association of State Highway and Transportation Officials in developing and updating the pavement design guide. The current guide is slated to be updated by the year 2002 to better reflect the changing priority of rehabilitating the nation's highways rather than building new ones. In contrast to the current guide that many transportation experts believe is outdated, the new guide is expected to incorporate the use of analytical methods to predict pavement performance under various loading and climatic conditions. Sponsors believe that "a new design approach will more realistically characterize existing highway pavements and improve the reliability of designs."

A promising analytical method to accurately predict pavement response is the nonlinear 3 Dimensional-Finite Element Method. Only with accurate response data can one reliably predict pavement performance. The use of this method has the potential to improve the design of highway pavements—which encompasses their safety, durability, and cost-effectiveness—because values of stresses, strains, and deflections (pavement response) can be calculated accurately from a variety of static, impact, vibratory, and moving mixes of traffic loads. Several state departments of transportation, academicians, and scientists have pioneered the use of the nonlinear 3 Dimensional-Finite Element Method and are using it to solve a variety of complex structural engineering problems, including the design and analysis of highway pavement structures. While this is a promising method for improving highway pavement design and analysis, we could find no evidence that it is being considered for inclusion in the current design guide update.

Background

FHWA is responsible for administering and overseeing various highway transportation programs, including the Federal-Aid Highway Program—which provides financial assistance to the states for improving the efficiency of highway and traffic operations. FHWA relies on AASHTO to (1) provide technical guidance for the design, construction, and maintenance of highways and other transportation facilities; (2) publish manuals, guides, and specifications regarding design, safety, maintenance, and materials; and (3) conduct planning for highways, bridges, and other structures. Active membership in AASHTO is open to the state departments of transportation of the United States, Puerto Rico, and the District of Columbia. DOT is an active, albeit nonvoting, member. FHWA supports AASHTO's manuals, guides, and specifications, which the states can use in designing and analyzing federally funded highway projects. In addition, states can use their own pavement design criteria and procedures for such projects, which generally mirror what is in AASHTO's pavement design guide.

Updating the Pavement Design Guide

Currently, highway pavement design criteria and procedures are documented in AASHTO's 1993 Guide For the Design of Pavement Structures. AASHTO's Joint Task Force on Pavements is responsible for the development and updating of the guide. The guide was first issued in 1961 and then updated in 1972, 1981, 1986, and 1993. Another update of the guide is forthcoming. The task force's efforts to update the guide are overseen by a National Cooperative Highway Research Program (NCHRP) project panel, which functions under the Transportation Research Board (TRB) of the National Academy of Sciences' National Research Council.

While constructing new highways was once the primary goal of state transportation departments, the major emphasis in pavement design in the 1990s has progressed to rehabilitating existing highways. According to NCHRP, the current guide does not reflect this shift in emphasis, and the updated guide is the expected product of an NCHRP/TRB contract with an engineering consulting firm that is expected to be awarded in the near future. Under the contract, the guide would be updated by 2002. In updating the guide, NCHRP intends to improve upon the outdated pavement design procedures contained in the current guide.

The current design guide and its predecessors were largely based on design equations empirically derived from the observations AASHTO's predecessor made during road performance tests completed in 1959-60. Several transportation experts have criticized the empirical data thus derived as outdated and inadequate for today's highway system.[4] [5] In addition, a March 1994 DOT Office of Inspector General report concluded that the design guide was outdated and that pavement design information it relied on could not be supported and validated with systematic comparisons to actual experience or research.[6] In contrast to the current guide, which relied heavily on an empirical approach to derive its design

[4]Kenneth A. Small, Clifford Winston, and Carol Evans, Road Work, The Brookings Institution (Washington, D.C.: 1989), pp. 26-27.

[5]Jerry J. Hajek, General Axle Load Equivalency Factors, Ontario Ministry of Transportation, Downsview, Ontario, Canada, TRB, Transportation Research Record No. 1482 (Washington, D.C.: 1995).

[6]Report on Audit of Cost Comparison of Asphalt Versus Concrete Pavement, DOT Office of Inspector General, FHWA Region 4, Report Number R4, FH-4-008 (Mar. 30, 1994).

equations, the NCHRP contract to update the guide by 2002 calls for the use of an approach that would more realistically characterize existing highway pavement usage and improve the reliability of designs.

Under the first phase of the contract that ended in July 1997, Nichols Consulting Engineers developed a detailed work plan for completing the new pavement design guide. When the project manager resigned in June 1997, NCHRP decided to rebid the contract. The NCHRP program officer stated that he believes that the new guide will be completed as planned.

An Existing Pavement Design and Analysis Method Has the Potential to Improve Highways and Is Being Used by Others

An existing method called nonlinear 3D-FEM has the potential to significantly improve the design and analysis of highway pavement structures. A number of nonlinear 3D-FEM computer programs have been available since the 1970s that can be used for solving complex structural engineering problems, including designing safer, longer-lasting, more cost-effective highway pavement structures.[7] Nonlinear 3D-FEM is considered by many experts to be superior to current design and analysis methods because values of stresses, strains, and pavement deflections can be calculated accurately from a variety of traffic loads—static, impact, vibratory, and moving mixes of traffic loads, including multiaxle truck/trailer loads both within and outside legal weight limits. The nonlinear 3D-FEM analysis allows a level of detail that aids in selecting pavement materials as well as improving the accuracy of determinations of the thickness needed for new, reconstructed, and overlay pavements. This method can be used to analyze pavements for strengthening that may be required for expected traffic loads in the future and for computing the pavements' remaining structural and operational lives.

Several highway departments and academic institutions have already used nonlinear 3D-FEM for various structural analysis applications. The Indiana, Mississippi, and Ohio departments of transportation, for example, have pioneered the use of nonlinear 3D-FEM in pavement design and analysis. Officials of these agencies told us that they are very satisfied with its application on various road systems.

[7]Dr. John Hallquist, formerly of the Lawrence Livermore National Laboratory, Livermore, California, developed the nonlinear 3D-FEM computer programs DYNA-3D in 1976 and NIKE-3D in 1978. Lawrence Livermore used these nonlinear 3D-FEM programs to analyze the effects of nuclear explosive devices underground and the ability of intercontinental ballistic missiles to penetrate hardened military structures. Improved versions called LS-DYNA-3D and LS-NIKE-3D have become available since 1989 and 1995 from Dr. Hallquist, Livermore Software Technology Corporation, 2876 Waverely Way, Livermore, California 94550. The nonlinear 3D-FEM computer program ABAQUS has been available since 1978 from Hibbitt, Karlsson and Sorensen, Inc., 1080 Main Street, Pawtucket, Rhode Island 02860.

In 1995, the University of Mississippi used nonlinear 3D-FEM to analyze jointed concrete pavement for dynamic truck loads and thermal analysis.[8] An official from the Mississippi State Department of Transportation told us that this method enabled the state to determine the conditions causing the rapid deterioration of its concrete pavement. Similarly, a senior scientist from a firm specializing in evaluating the integrity of engineering structures told us that, among other things, the finite element method—combined with statistical theory (which factors in uncertainties in material properties)—has been used to predict the expected life of a concrete runway at Seymour Johnson Air Force Base in North Carolina.

Because it considers AASHTO's pavement design guide to be outdated, the School of Civil Engineering, Purdue University, also has been using nonlinear 3D-FEM to analyze various pavement problems. The university has used this method to analyze responses to moving multiaxle truck/trailer loads within and outside legal weight limits on both flexible and rigid pavements. Studies the university has conducted to verify the analyses have shown a strong correlation between field and predicted pavement responses (strains and deflections).[9]

More recently, Purdue University conducted a study—including the use of field instrumentation, laboratory testing, field data collection, and subgrade and core sampling—of three asphalt pavement sections with different subdrainage configurations on a portion of Interstate 469 in Ft. Wayne, Indiana.[10] Nonlinear 3D-FEM was used to evaluate the subdrainage performance and the analysis of moisture flow through the pavement. The results of the study indicated a strong correlation between the predicted and field-measured outflows of water.

The effects of high moisture conditions on pavement performance include rutting, cracking, and faulting—leading to increased roughness, unsafe conditions, and a loss of serviceability. A pavement design manager with the Indiana Department of Transportation told us that the Purdue study,

[8]Three Dimensional-Finite Element Analysis of Jointed Concrete Pavement, Waheed Uddin, Robert M. Hackett, Ajith Joseph, Zhou Pan, Department of Civil Engineering, University of Mississippi, and A.B. Crawley, Mississippi Department of Transportation, TRB, Transportation Research Record No. 1482 (Washington, D.C.: 1995).

[9]Sameh Zagloul and Thomas D. White, Effect of Overload Vehicles on the Indiana Highway Network, School of Civil Engineering, Purdue University, Joint Highway Research Project (FHWA/IN/JHRP-93-5) (IN47907, June 2, 1994).

[10]Hossam F. Hassan and Thomas D. White, Locating the Drainage Layer for Flexible Pavements, School of Civil Engineering, Purdue University, Joint Highway Research Project (FHWA/IN/JHRP-96/14) (IN 47907, Dec. 1996).

using nonlinear 3D-FEM, confirmed that the Department's previously used subdrainage design procedures resulted in a drainage outflow pipe that was too small—thus limiting moisture outflow. Subdrainage layers with filter layers, a perforated pipe (subdrainage collector pipe), trench material, and an outlet pipe play a key role in reducing the extent and duration of high moisture conditions in pavement structures and their subgrade. The manager said that nonlinear 3D-FEM provided the (1) proper (increased) size of drainage outlet pipe and (2) best, most efficient filter material, which turned out to be less costly than the material previously being used. We were told that Indiana's Transportation Department is now in the process of adopting nonlinear 3D-FEM as its preferred method for designing subdrainage systems. An Indiana research section engineer also told us that he believes that nonlinear 3D-FEM could be used by all state highway departments to design subdrainage systems.

Battelle Memorial Institute recently applied nonlinear 3D-FEM to predict pavement response to a broad range of vehicle loads on 4 miles of newly constructed highway pavement (2 miles southbound and 2 miles northbound) north of Columbus, Ohio. According to a Battelle project scientist and an academician from Ohio University, the results of the heavily instrumented highway test sections showed a strong correlation with the analytical results achieved from nonlinear 3D-FEM.[11] They also told us that nonlinear 3D-FEM is the best computational method to address pavement problems. A chief engineer of the Ohio Transportation Department further told us that the state was pleased with Battelle's efforts to predict pavement response using the nonlinear method.

According to an engineer-advisor with the DOT Inspector General's Office, AASHTO's pavement design guide has changed very little over the years. He was of the opinion that new design procedures are needed, incorporating nonlinear 3D-FEM, if FHWA and the states are going to be better able to ensure that highway pavement is constructed, reconstructed, or overlaid according to current FHWA policy that it be safe, durable, and cost-effective.

We reviewed the scope of work of the contract NCHRP awarded in December 1996 to Nichols Consulting Engineers for the development of the new guide. The scope of the most recent contract work does not directly cite nonlinear 3D-FEM as a technique that can be used in the design

[11]James C. Kennedy, Jr., Pavement Response to Vehicular Roads—A Mechanistic Approach Involving Nondestructive Evaluation Techniques, Battelle Memorial Institute, Columbus, Ohio, Proceedings: International Society for Optical Engineers, Nondestructive Evaluation Techniques for Aging Infrastructure and Manufacturing, Scottsdale, Arizona (Dec. 2-5, 1996).

and analysis of highway pavement. In discussions with Nichols' project manager and with an NCHRP official and in our review of the contractor's work plan for the guide, we did not find any specific reference that nonlinear 3D-FEM would be investigated for inclusion or exclusion in the 2002 update. Through interviews with FHWA, AASHTO, and NCHRP officials, we attempted to determine why the method was not specifically being considered. We did not receive any explanation. However, the program officer said that while the contractual documentation for this particular effort does not contain specific reference to nonlinear 3D-FEM as a pavement design and analysis method, the documentation does not exclude the use of such a method either.

Conclusions

The pavement design guide developed and updated by AASHTO over the years for designing and analyzing highway pavement structures is outdated. NCHRP has undertaken a 5-year effort to update the guide employing improved design approaches. Research on nonlinear 3D-FEM and documented successes in its application suggest that this method could be an important tool for accurately (1) designing and analyzing new highway pavement structures and (2) analyzing the response of deteriorated pavement structures for rehabilitation. We believe it should be considered in NCHRP's ongoing efforts to update AASHTO's current pavement design and analysis guide. The recent decision to rebid the contract for the design guide update provides an opportunity for FHWA to specify the consideration of this method.

Recommendation

To better assist states in designing safer, longer lasting, and more cost-effective new, reconstructed, and overlay highway pavement structures, we recommend that the Secretary of Transportation direct the Administrator, FHWA, to ensure that nonlinear 3D-FEM is considered in the current update of the pavement design guide.

Agency Comments and Our Evaluation

We provided a draft of this report to DOT for its review and comment. In written comments dated October 31, 1997 (see app. II), DOT stated that it has maintained a long- standing commitment to ensuring that the nation's investment in its highway infrastructure is cost-effective. DOT concurred with our recommendation that nonlinear 3D-FEM be considered in the current update of AASHTO's pavement design guide. DOT stated that it would work with NCHRP to encourage full consideration of the method along with other quantitative analytical methods.

As part of its commitment to a cost-effective highway infrastructure, DOT stated that FHWA has supported research efforts at its own Turner-Fairbank Highway Research Center as well as efforts by AASHTO, NCHRP, and TRB. DOT further stated that FHWA is fully aware of and recognizes the potential benefits to highway design offered by 3D-FEM. According to DOT, FHWA has supported the development of this technology at its Turner-Fairbank facility and with individual states through the State Planning and Research program. DOT stated that FHWA considers 3D-FEM to be a very useful research tool for analyzing pavement structures but that it will be up to NCHRP and AASHTO to determine whether the method has achieved the maturity necessary to become a practical engineering tool.

We are pleased to hear of DOT's interest in and acceptance of nonlinear 3D-FEM as an analytical tool for designing and analyzing highway pavement structures. Such interest and acceptance was never made known to us (1) during discussions we had with the Chief, Pavement Division, FHWA; the project manager, AASHTO; a senior program officer, NCHRP; and the initial contractor's project manager for the development of the 2002 pavement guide nor (2) in documentation we gathered and reviewed during the assignment.

We made other clarifying changes to the report as appropriate on the basis of other comments by DOT.

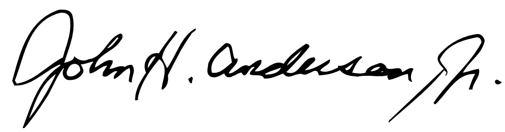
We performed our work from May 1996 through October 1997 in accordance with generally accepted government auditing standards. Appendix I contains details on our objectives, scope, and methodology.

As you know, 31 U.S.C. 720 requires the head of a federal agency to submit a written statement of the actions taken on our recommendations to the Senate Committee on Governmental Affairs and to the House Committee on Government Reform and Oversight not later than 60 days from the date of this letter and to the House and Senate Committees on Appropriations with the agency's first request for appropriations made more than 60 days after the date of this letter.

We are sending copies of this report to the Administrator, FHWA; the Director, Office of Management and Budget; and appropriate congressional committees. We will make copies available to others upon request.

Please call me at (202) 512-2834 if you have any questions. Major contributors to this report are listed in appendix III.

Sincerely yours,



John H. Anderson, Jr.
Director, Transportation Issues

Contents

Abbreviations

AASHTO	American Association of State Highway Transportation Officials
DOT	U. S. Department of Transportation
FHWA	Federal Highway Administration
NCHRP	National Cooperative Highway Research Program
TRB	Transportation Reasearch Board
3D-FEM	3 Dimensional-Finite Element Method

Objectives, Scope, and Methodology

The objectives of this review were to (1) describe the roles of the Federal Highway Administration (FHWA) and others in developing and updating the pavement design guide and (2) examine the use and potential of a computer analysis method known as the nonlinear 3 Dimensional-Finite Element Method (3D-FEM) for improving the design and analysis of highway pavements.

To accomplish these objectives, we first reviewed the American Association of State Highway and Transportation Officials' (AASHTO) highway pavement guide, which is being used by many state departments of transportation as an aid in designing and analyzing pavement structures, federally funded and otherwise. We reviewed available literature and contacted officials from FHWA, AASHTO, and the Transportation Research Board. We also contacted contractor officials responsible for the development and updates of the pavement design guide. We contacted officials from the Transport Research Laboratory, Crawthorne, Berkshire, United Kingdom, and reviewed its pavement design practices. We contacted officials from the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi; Indiana, Mississippi, and Ohio state highway departments; and various engineering consulting firms. We contacted academicians from the University of Arizona, the University of Cincinnati, Florida A&M University-Florida State University, Ohio University, the University of Iowa, the University of Mississippi, the University of Nebraska, and Purdue University, as well as Birmingham University in the United Kingdom. Also, we contacted scientists from Battelle Memorial Institute and Lawrence Livermore National Laboratory.

We selected these educational institutions and nonprofit organizations because all have conducted research and development work related to pavement design and analysis and/or the application of nonlinear 3D-FEM for solving structural engineering problems. Furthermore, we performed a literature and database search to identify any individuals who have authored publications on the applications of nonlinear 3D-FEM to highway pavement design and analysis or other structural engineering problems.

We discussed with FHWA and others their roles in keeping up with and promoting up-to-date techniques regarding pavement design and analysis. We reviewed FHWA's pavement policy issued in December 1996, which states that pavements should be designed to accommodate current and predicted traffic needs in a safe, durable, and cost-effective manner.

More broadly, we used in this review information we obtained through attendance at the Fourth International Conference on the Bearing Capacity of Roads and Airfields held in July 1994 in Minneapolis, Minnesota; the Third Materials Engineering Conference held in November 1994 in San Diego, California; annual Transportation Research Board meetings held in January 1995 and in January 1997 in Washington, D.C.; and the Structures Congress XV held in April 1997 in Portland, Oregon.

Comments From the Department of Transportation

U.S. Department of Transportation

Assistant Secretary
for Administration

400 Seventh St., S.W.
Washington, D.C. 20590

October 31, 1997

Mr. John Anderson
Director, Transportation Issues
U.S. General Accounting Office
441 G Street, N.W.
Washington, D.C. 20548

Dear Mr. Anderson:

Enclosed are two copies of the Department of Transportation's comments concerning the U.S. General Accounting Office draft report, "Transportation Infrastructure: Highway Pavement Design Guide is Outdated." Thank you for the opportunity to review this report. If you have any questions concerning our reply, please contact Martin Gertel on 366-5145.

Sincerely,

Melissa S. Spillenkothen

Melissa Spillenkothen

Enclosures

Department of Transportation
Comments on GAO Draft Report
"Transportation Infrastructure:
Highway Pavement Design Guide is Outdated"

Overview

The Department of Transportation has maintained a long-standing commitment to ensuring that the Nation's investment in its highway infrastructure is cost effective. One part of this commitment involves research into highway design and materials sciences to ensure that highways are safe, durable, and long-lasting. The Federal Highway Administration (FHWA) has supported research efforts at its own Turner-Fairbank Highway Research Center as well as efforts by the American Association of State Highway and Transportation Officials (AASHTO), the National Cooperative Highway Research Program (NCHRP), and the Transportation Research Board (TRB).

FHWA is Pursuing the Development of the Three Dimensional Finite Element Model

Although it is not readily apparent from the discussion in the draft report, the FHWA is fully aware of and recognizes the potential benefits to highway design offered by the Three Dimensional Finite Element Model (3D-FEM). FHWA has supported the development of this methodology at its Turner-Fairbank facility and with individual states through the State Planning and Research program. In fact, one of FHWA's staff, Mr. William Kenis, is an internationally recognized expert in the development and application of three dimensional models for engineering analysis. FHWA considers 3D-FEM to be a very useful research tool for analyzing pavement structures. It will be up to NCHRP and AASHTO to determine whether the method has achieved the maturity necessary to become a practical engineering tool.

Pavement Design Guide is Developed by AASHTO and NCHRP

While FHWA fully supports AASHTO's and NCHRP's efforts to update the 1993 pavement design guide, it is these organizations that should be credited with this action in the heading on page 4 of the draft report. In addition, the various places in the draft report which indicate that FHWA "adopts" the guide are not accurate. FHWA neither adopts the guide nor requires its use by states. Rather, FHWA in its working relationship with states requires that sound engineering and management principles and practices be used in the pavement design process. One indication of this is the states' use of guides and standards developed by a number of standard setting and industry organizations, including AASHTO.

Recommendation and Response

Recommendation: Ensure that the nonlinear 3D-FEM method is considered in the current update of the pavement design guide.

Response: Concur. FHWA will work with the NCHRP to encourage the full consideration of 3D-FEM, along with other quantitative analytical methods, for pavement analysis in the revised AASHTO Highway Pavement Design Guide. We understand that the recently completed Phase I of the NCHRP effort identified 3D-FEM as one of several available procedures to be considered.

Major Contributors to This Report

Resources, Community, and Economic Development Division

Dr. Manohar Singh, P.E., Engineering Consultant
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