ROADHOG—A Flexible Pavement Overlay Design Procedure

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ROADHOG, a practical, easy-to-use system for selecting flexible pavement overlay thicknesses, was developed for the Arkansas State Highway and Transportation Department. ROADHOG is an NDT-based structural design procedure that follows the 1986 *AASHTO Guide* structural deficiency approach to overlay design with structural capacities expressed as structural numbers (SNs). Major departures from the 1986 *AASHTO Guide* are the methodologies for determining the effective structural number of the existing pavement (SN_{eff}) and for estimating the in situ subgrade resilient modulus (M_r). SN_{eff} is determined by a relationship between two falling weight deflectometer (FWD) surface deflections: the deflection at the center of loading and the deflection at a distance from loading equal to the pavement thickness. M_r is estimated using a regression algorithm developed from the ILLI-PAVE finite element structural pavement model. ROADHOG is contained in a user friendly, stand-alone (executable) computer program that directly uses the FWD field data files. In addition to determining overlay thicknesses, the program can subdivide a project into statistically similar analysis units on the basis of the overlay thickness required at each NDT test site.

In recent years, highway programs nationwide have shifted their emphasis from new construction to rehabilitation, maintenance, and preservation. With this shift, a major deficiency in pavement design technology became more significant. That deficiency was the lack of practical, proven design procedures for selecting the thickness of pavement overlays. The need for a flexible pavement overlay design procedure was particularly significant in Arkansas, where, except for the Interstates, most highways have flexible pavements. Research Project TRC-8705 was initiated by the Arkansas Highway and Transportation Department (AHTD) and the University of Arkansas to correct this deficiency.

From the beginning, the major objective of the project was to develop a practical, easy-to-use design procedure that was compatible with other AHTD pavement design practices and that consistently produced reasonable design thicknesses. AHTD designs pavements using the AASHTO Guide (*1*). When the 1986 guide became available, AHTD adopted it in place of the previous guide. Unlike the previous guide, the 1986 guide contained procedures for overlay design. These were not complete but did provide a framework around which a complete design procedure could be developed that would be compatible with the new pavement portions of the guide and, thus, be compatible with AHTD's other pavement design practices.

The completed design procedure developed under TRC-8705 was named ROADHOG to designate that it is a roadway design tool developed at the University of Arkansas (the "Hogs"). The computerized version of the design procedure is a stand-alone (executable) program that is extremely flexible and user friendly. The programming was done in CLIPPER, a data base management language accessible to data base file formats, to facilitate the handling of nondestructive testing data. (All product names are registered trademarks of their respective development corporations.) AHTD stores and manipulates field NDT results using the dBASE data base management software. An attractive feature of the ROADHOG program is its modular construction. Each major function of the procedure is contained in a separate program module. This will facilitate upgrading the program as technology improves with little visible effect on the system as a whole.

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OVERLAY DESIGN METHODOLOGY

The AASHTO approach to flexible pavement design uses a structural number (SN) to reflect the combined structural contribution of all the pavement layers (surface, base, and subbase). SN is defined by

$$SN = a_1 * D_1 + a_2 * D_2 + \dots + a_n * D_n \quad (1)$$

where a_n is the layer coefficient of layer n and D_n is the thickness of layer n.

The 1986 guide uses SN in a "structural deficiency" approach to overlay design. In its simplest terms, the structural deficiency approach states that the overlay required is the difference between the total structure needed and the structure that currently exists. The guide expresses this with the following equation:

$$SN_{ol} = SN_y - F_{rl}(SN_{eff}) \quad (2)$$

where

SN_{ol} = required structural number of overlay,
SN_y = structural number required to carry future projected traffic,
F_{rl} = remaining life factor, and
SN_{eff} = effective structural number of existing pavement.

Determination of the required overlay thickness involves converting the required structural number of the overlay into a thickness of asphalt concrete using the appropriate material coefficient:

$$D_{o1} = SN_{o1}/a_{ac} \quad (3)$$

where

D_{o1} = thickness of overlay,
SN_{o1} = structural number of overlay, and
a_{ac} = material coefficient of asphalt concrete.

Within this general approach, the major components lacking for a complete, workable design procedure are specific methodologies for determining SN_{eff} and the subgrade resilient modulus (M_r) needed for calculating SN_y. Although ROADHOG uses the general AASHTO approach to overlay design, the methods used by ROADHOG for determining SN_{eff} and M_r are radically different.

In the AASHTO method the values for SN_{eff} and M_r are interdependent. Both values are determined on the basis of backcalculated moduli from the NDT deflection data. M_r is determined from the deflection at a point some distance from the center of NDT loading. This value is then used in the determination of modulus values for the pavement layers. SN_{eff} is calculated using these moduli. As a result, an error in the determination of M_r will result in an error (although opposite in sign) in SN_{eff}.

In ROADHOG the determination of SN_{eff} and M_r are independent. As in the AASHTO method, SN_{eff} is assumed to be a function of pavement stiffness. However, instead of backcalculating layer moduli (or a single overall equivalent modulus), ROADHOG uses a relationship between SN and a deflection differential called delta D. Delta D is the difference between the deflection measured at the center of loading and the deflection at a point equal to the total pavement thickness (surface + base + subbase). M_r is determined from the deflection measured 36 in. from the center of loading using an analysis algorithm developed by Elliott and Thompson (*2*) using the ILLI-PAVE finite element pavement model.

In addition to independence, these methods of SN_{eff} and M_r determination have other advantages over the AASHTO methods. SN_{eff} determination is relatively independent of depth to bedrock, a major concern in a backcalculation scheme such as that used by AASHTO. Also, the M_r value determined by ROADHOG is consistent with the value used in the *AASHTO Guide* design equation to represent the AASHO Road Test subgrade. As discussed by Elliott (*3*), the M_r value backcalculated by the AASHTO method must be modified to be consistent with the AASHO Road Test subgrade value. The methods of SN_{eff} and M_r determination are discussed in greater detail later.

Another component of the AASHTO design methodology modified in the ROADHOG procedure was F_{r1}, the remaining life factor. F_{r1} is an adjustment factor for the effective structural capacity of the existing pavement. The factor attempts to "reflect a more realistic assessment of the weighted effective capacity during the overlay period" (*1*). Elliott (*4*) investigated the concept and application of remaining life in overlay design as presented in the *AASHTO Guide*. He demonstrated that the F_{r1} relationship is flawed. Elliott's analyses demonstrated that for all practical purposes, 1.0 is the appropriate value for F_{r1}. The concept of remaining life should not be completely ignored in a comprehensive overlay design methodology; however, its inclusion within the structural deficiency design approach used in ROADHOG was not found to be reasonable or practical. Thus, for ROADHOG Equation 2 is reduced to

$$SN_{o1} = SN_y - (SN_{eff}) \quad (2a)$$

OVERVIEW OF THE ROADHOG PROCEDURE

The basic framework for a structural deficiency overlay design procedure is summarized in the following steps. The ROADHOG procedure was constructed upon such a framework.

1. Analysis unit delineation,
2. Traffic analysis,
3. Materials and environmental study,
4. Effective structural capacity analysis (SC_{xeff}),
5. Future overlay structural capacity analysis (SC_y), and
6. Overlay thickness selection.

Step 1, analysis unit delineation, identifies subsections of an overlay project (analysis units) with similar features such as cross section, subgrade support, and pavement condition. Unit delineation helps to optimize an overlay design by identifying varying overlay requirements along a project, rather than recommending a single "average" overlay requirement. Unit delineation should be performed both before the overlay thickness selection on the basis of existing conditions and after the required overlay is calculated for each NDT point along the project. ROADHOG includes methodology for the second unit delineation; that is, methodology for breaking the project into units based on the overlay thicknesses. Unit delineation based on existing conditions needs to be done by the designer before using ROADHOG. Further discussion of this is given later.

Steps 2 and 3, traffic analysis and materials and environmental study, respectively, generate input parameters for use in subsequent steps. These parameters may include design (future) traffic, traffic history, material coefficients, and data concerning current material condition. The designer must have completed these tasks before using the ROADHOG structural design procedure.

Steps 4 and 5 determine the values of the variables (SN_y and SN_{eff}) appearing in Equation 2a. From the values generated in these steps, the required structural capacity (SN_{o1}) of the overlay is calculated.

Step 6, overlay thickness selection, finalizes the overlay design. Equation 3 is used in this step to determine overlay thicknesses for the project.

ROADHOG uses nondestructive testing (NDT) data to evaluate the existing pavement system (pavement and subgrade). NDT-based design procedures have several potential advantages over other procedures, including speed at which data may be obtained, cost of obtaining data, and the amount of data available for a particular project. In addition, NDT-based procedures attempt to evaluate existing pavement systems in situ instead of attempting to relate laboratory test results to field conditions.

The ROADHOG overlay design procedure uses NDT data generated by a falling weight deflectometer (FWD). The FWD applies a load pulse to a pavement and measures the resulting surface deflection. Details of the setup and operation of the FWD are available elsewhere (*5*). The FWD attempts to simulate the effect of a moving wheel load on the pavement surface (*6*). Studies have indicated that the FWD generates load responses comparable with those produced by moving wheel loads (*5,7*). This effect is a major advantage over static tests when attempting to evaluate the pavement as it exists in the field.

ROADHOG uses NDT data taken directly from the FWD field storage file. The program reads the file from the floppy disk and creates a data base file that holds both the field data and the calculated overlay design parameters. Each record in the data base represents a single FWD test performed for the overlay project. A required overlay thickness is determined for each FWD test along the project. The project may be (designer's option) divided into recommended analysis units based on the required overlay thickness at each NDT site. Output options allow the designer to choose whether to use the recommended analysis units and to choose any combination of available data stored in the data base file. User inputs, in addition to the NDT data file from the FWD, include the existing thickness of asphalt concrete surface, the total existing pavement thickness, new pavement design parameters (reliability, standard deviation, delta PSI, and design traffic), asphalt concrete (overlay) material coefficient, and the minimum acceptable length of an analysis unit.

Figure 1 is a flow diagram showing the primary modules of the ROADHOG design procedure. A brief synopsis of the ROADHOG modules follows. Subsequent sections detail the procedures and algorithms used by each respective module.

1. XFORM—The FWD device stores data generated during a nondestructive test in ASCII format on a floppy disk; XFORM transforms these data into a data base file (dBASE format) for use in later modules.
2. SNEFF—The SNEFF module uses a relationship between the deflection basin and structural capacity of a pavement system to generate SN_{eff} for each FWD deflection basin.
3. MRCALC—The MRCALC module uses the deflection measured at 36 in. from the load to estimate the in situ M_r of the subgrade at each test point.
4. NEWFLEX—The NEWFLEX module uses designer input and the subgrade M_r determined in MRCALC to calculate the structural number required to carry future traffic (SN_y).
5. OVLTHICK—The OVLTHICK module calculates the overlay thickness required to strengthen the existing pavement to carry future projected traffic.
6. UNIDEL—The UNIDEL module uses the cumulative difference approach with the required overlay thickness at each FWD test site to subdivide the overlay project into analysis units.
7. OUTPUT—The OUTPUT module allows the user to see the results of the design procedure, sending the results to either the screen, a printer, or a file.

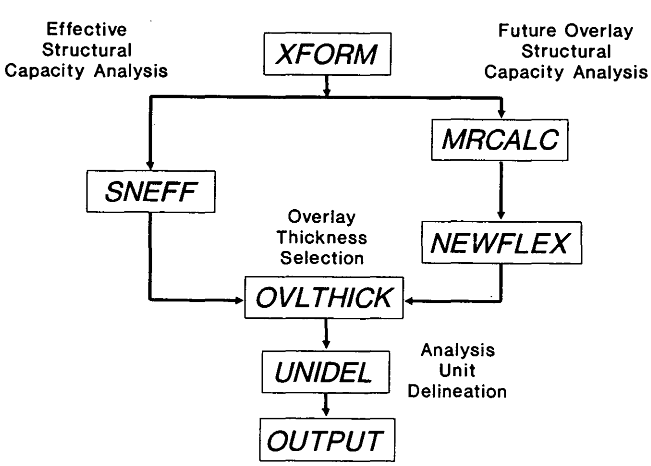

FIGURE 1 ROADHOG flow diagram.

EFFECTIVE STRUCTURAL CAPACITY ANALYSIS

A number of methods currently exist to estimate the effective structural capacity of a pavement, primarily falling into three categories: (*a*) component analysis procedures, (*b*) deflection-based procedures, and (*c*) analytically based, or mechanistic, procedures. An excellent synopsis of each type of procedure is available elsewhere (*8*).

ROADHOG uses a deflection-based procedure in which the effective structural capacity of the existing pavement system is related to the deflection basin generated and measured by the FWD. The ROADHOG module that performs the effective structural capacity analysis is termed "SNEFF." The algorithm forming the basis of SNEFF was developed at the University of Arkansas by Kong (*9*). The salient features of Kong's procedure are reproduced here.

The development of the SN_{eff} algorithm began with the concept that at sufficient distances from the center of loading the surface deflection is almost entirely due to deformation within the subgrade. As shown in Figure 2, the zone of influence due to loading extends with depth. Directly below the loading plate, all materials "feel" the effect of the load and deform. At locations beyond the loading plate, only those materials within the zone of influence are deformed. At some distance, only the subgrade deforms. This concept serves as

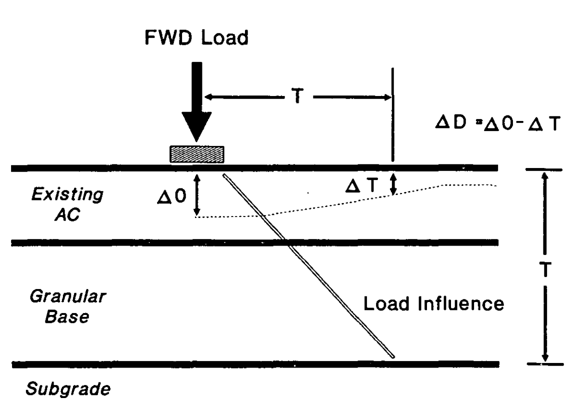

FIGURE 2 Conceptual basis for SNEFF.

the basis for most subgrade resilient modulus backcalculation methods.

Viewed from the perspective of the pavement, this concept suggests that the difference between two deflections could be used as measure of the pavement stiffness. Using the AASHTO assumption that SN_{eff} is a function of stiffness, the deflection difference becomes a measure of SN_{eff}. If the deflection at distance *T* in Figure 2 is due to subgrade deformation and the deflection at the center of loading is due to pavement and subgrade deformation, the difference between the two deflections, delta D, should represent the deformation within the pavement alone. If the zone of influence spreads at an angle of about 45 degrees, the distance *T* would be equal to the pavement thickness.

A relationship between the pavement stiffness (delta D) and the effective structural capacity of the pavement (SN_{eff}) was developed using elastic layer theory. Deflection basins were generated for a variety of pavement cross sections using the elastic layer program ELSYM5 (*10*). Delta D was calculated for each deflection basin and plotted against the structural number of the associated pavement cross section. The structural number of a pavement was calculated using Equation 1. Layer coefficients for new pavements were used in the determination: AC coefficient = 0.44; crushed stone base coefficient = 0.14. Plots of delta D versus SN_{eff} resulted in curves like those shown in Figure 3.

Total pavement thicknesses were 8, 12, and 24 in. Asphalt thicknesses ranged from 1 to 17 in. The elastic modulus values used in ELSYM5 to represent the asphalt and granular materials were 500 ksi and 30 ksi, respectively. These represent typical values for AC at about 70°F and dense graded granular base. They also are consistent with the layer coefficients and modulus relationships used by AASHTO. Subgrade resilient modulus values of 3.5 ksi, 7 ksi, 14 ksi, and 21 ksi were used for the analyses. These were selected as representative of the range of values for Arkansas subgrades expected on the basis of previous work (*11*). The results of the analyses (Figure 3) show the delta D−SN_{eff} relationship to be reasonably independent of the subgrade modulus.

These analyses, however, incorporated the standard elastic layer assumption of a semi-infinite depth of subgrade. Subgrade thickness (depth to bedrock) is believed to be one of the complicating factors in the backcalculation of subgrade resilient modulus (*6*). Additional analyses were performed to determine whether this factor might also be significant relative to the delta D−SN_{eff} relationship. Subgrade depths ranging from 8 ft to semi-infinite were considered. The delta D−SN_{eff} relationship was found to be reasonably independent of the subgrade depth (Figure 4). These findings indicate that this approach provides a practical method for the determination of SN_{eff} that is independent of the subgrade.

For the method to be complete, a means was needed for temperature adjustment. Asphalt concrete is quite temperature sensitive, exhibiting modulus increases at lower temperatures and modulus decreases at higher temperatures. As a result, delta D is also temperature sensitive. The elastic modulus used in the delta D−SN_{eff} analyses was selected as typical of the resilient modulus of an Arkansas asphalt concrete at 70°F.

Additional ELSYM5 analyses were conducted to examine the effect of other AC temperatures on delta D. The AC-modulus temperature relationship shown in Figure 5 was used to select modulus values for other temperatures. From these analyses temperature adjustment curves were established. The temperature correction factor is the ratio of delta D at a given temperature to delta D at 70°F. For testing temperatures other than 70°F, delta D from the given test is multiplied by the temperature correction factor to yield a corrected value of delta D. The corrected delta D value is used with the curves in Figure 3 to estimate SN_{eff} of the existing pavement. The temperature adjustment was reasonably independent of the subgrade but depended on both total pavement thickness and AC thickness. The temperature adjustment factors for an 8-in. pavement are shown in Figure 6.

The SNEFF module uses a second-order polynomial equation (r^2 = 0.98) to approximate the delta D/SN_{eff} relationship. For pavement thicknesses other than those shown in Figure 3, SNEFF uses linear interpolation to generate the points necessary to define a delta D/SN_{eff} curve. For the temperature adjustment, SNEFF approximates each curve with two straight-line segments joined at the 70°F point. For pavement thicknesses other than those analyzed by Kong, SNEFF calculates a temperature correction using linear interpolation.

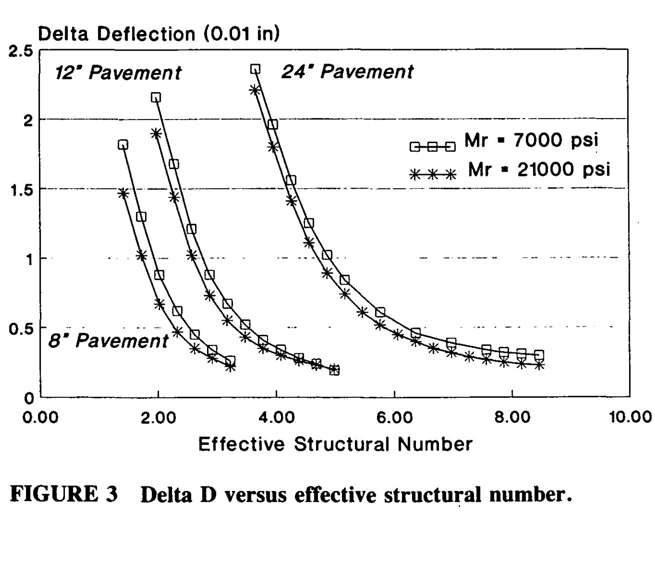

FIGURE 3 Delta D versus effective structural number.

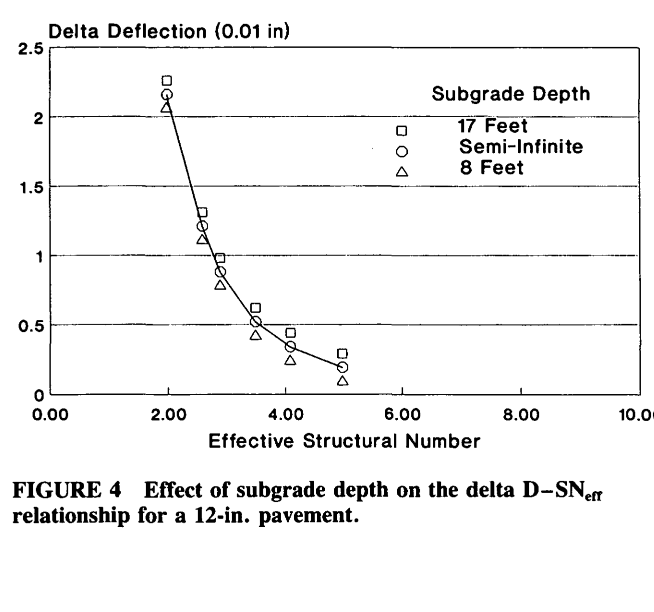

FIGURE 4 Effect of subgrade depth on the delta D−SN_{eff} relationship for a 12-in. pavement.

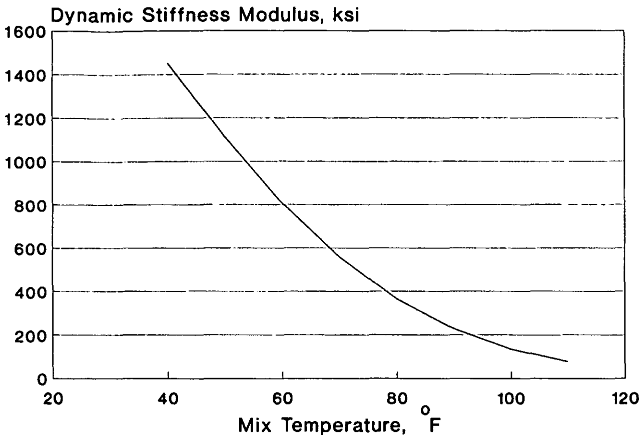

FIGURE 5 AC temperature modulus relationship used in SNEFF (*2*).

The delta D/SN_{eff} relationship developed using elastic layer theory (e.g., ELSYM5) was verified using an alternate approach—the ILLI-PAVE finite element method (*12*). The relationship between delta D and SN_{eff} generated using ILLI-PAVE was virtually identical to that generated using ELSYM5.

FUTURE OVERLAY STRUCTURAL CAPACITY ANALYSIS

In the ROADHOG design procedure, future overlay structural capacity analysis consists mainly of two steps: (*a*) determination of the in situ subgrade resilient modulus and (*b*) calculation of the structural capacity required to carry future traffic. The subgrade resilient modulus, used in the structural capacity calculation, is determined from NDT data. The required structural capacity calculation is identical to a new pavement design. A discussion of the procedure used by ROADHOG in each of these steps follows.

Estimation of elastic properties (e.g., modulus) of pavement layers and subgrade from NDT data has received much attention. A number of procedures for backcalculating the subgrade resilient modulus from deflection data have been developed (*5,7,8,13*). As part of the ROADHOG development effort, Morrison (*6*) studied the types of backcalculation procedures available and their applicability to the soils and environmental conditions found in Arkansas. Morrison identified three general backcalculation procedures for determining subgrade modulus: iterative techniques, direct solution, and empirical response algorithms. Each type of backcalculation technique has strengths and weaknesses.

The primary goals is selecting a procedure for use in ROADHOG included accuracy, simplicity, and speed. Some published backcalculation techniques are extremely elegant but were not yet considered practical for use in an everyday design procedure due to the equipment and time necessary to run the analyses. In addition, the inherent variability of resilient modulus associated with in situ soils makes the expenditure of large amounts of time and energy to backcalculate a modulus value to the nearest psi seem unproductive. The value of subgrade resilient modulus backcalculated using data from an FWD test represents the state of the subgrade soil at that particular point along the project and at prevailing moisture and stress-state conditions. Because of the variability of soil properties in horizontal construction, the procedure selected for estimating E_{ri} for overlay design should be practical and yield reasonable E_{ri} estimates.

Another consideration in selecting a backcalculation procedure is the appropriateness of using the modulus in the AASHTO design equation for flexible pavements. The original performance equations developed from AASHO Road Test data did not include any measure of soil support. To modify the AASHO performance equation for design, the 1986 guide incorporated a subgrade resilient modulus function in which a value of 3,000 psi was assigned to the subgrade at the AASHO Road Test site. This value seems to agree with the breakpoint resilient modulus values obtained by Thompson and Robnett (*14*) using Road Test soils. The breakpoint resilient modulus is defined as the point at which the slope of the resilient modulus–repeated deviator stress curve (Figure 7) typical of a fine-grained soil "breaks," or changes.

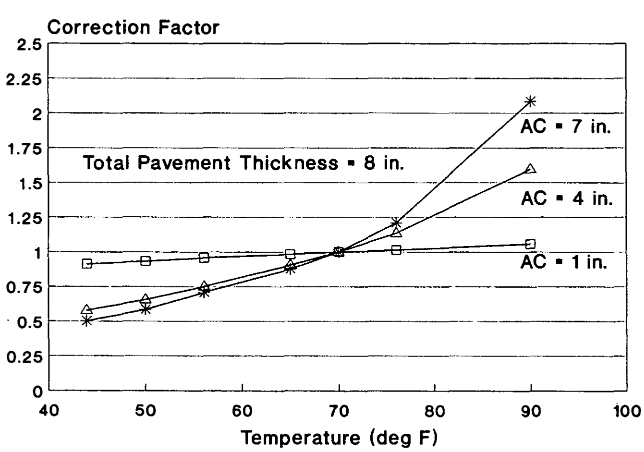

FIGURE 6 Temperature adjustment factors for 8-in. pavement in SNEFF.

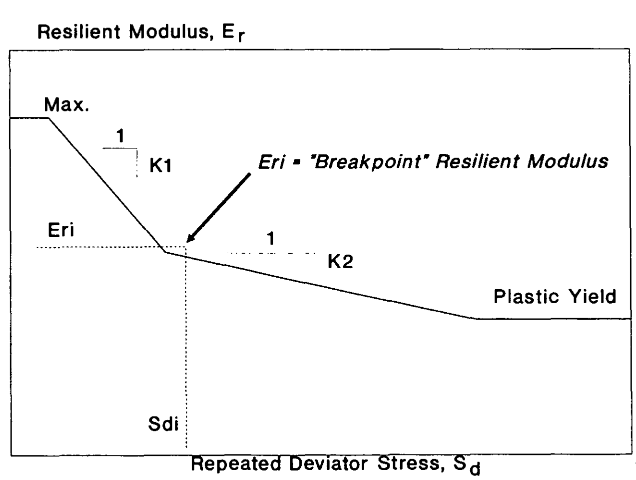

FIGURE 7 Typical representation of the resilient modulus–repeated deviator stress relationship for fine-grained soils (*2*).

To be consistent with the development of the AASHTO design equation, the subgrade modulus value used in the equation should be E_{ri}, the breakpoint resilient modulus. Of the backcalculation methods available, only some empirical response algorithms based on the finite element pavement model ILLI-PAVE calculate the breakpoint subgrade resilient modulus. Modulus values calculated by other methods must be adjusted to remain consistent with the AASHTO design equation (*3*).

ROADHOG uses an empirical response algorithm developed by Elliott and Thompson (*2*) to estimate the subgrade resilient modulus. The algorithm was developed from data generated by the finite element structural pavement model ILLI-PAVE. Finite element-based backcalculation procedures have several advantages over elastic layer- and numeric-based procedures (*6*). However, a major obstacle to using a finite element analysis in routine design is the complexity of the calculations involved. To date, mini- or mainframe computers are needed to fully exploit the advantages gained by using the finite element method. Empirical response algorithms like those developed by Elliott and Thompson help to bring finite element methods to the routine design level.

A finite element model used to generate a response algorithm must be valid for the conditions under which it is used. The data base used to develop the empirical response algorithm discussed here was comprehensive, covering a wide range of asphalt concrete and granular base thicknesses and subgrade strengths. Elliott and Thompson actually developed three equations for estimating the subgrade modulus beneath existing flexible pavements: (*a*) surface treatments—asphalt concrete thickness equal to 0.0 in., (*b*) conventional flexible pavements—asphalt concrete thicknesses ranging from 3 to 16 in., and (*c*) full-depth pavements—asphalt concrete ranging from 4 to 16 in. The three equations are nearly identical and produce practically the same subgrade modulus prediction. Therefore for practical purposes the equation selected for use in ROADHOG covers the range of AC thicknesses from 0 to 16 in. The ranges of material properties used in the analysis agree with observed material properties in the state of Arkansas, validating the use of the response algorithm for the ROADHOG procedure.

The calculation of in situ subgrade resilient modulus for the ROADHOG procedure is contained in the module MRCALC. The finite element-based response algorithm uses a single measured deflection to estimate the subgrade resilient modulus. The regression equation takes the form

$$E_{ri} = 25.0346 - 5.2454D_3 + 0.2864D_3^2 \quad (4)$$

where E_{ri} is the breakpoint subgrade resilient modulus and D_3 is the surface deflection at 3 ft from load.

Deflection data from sensors spaced at 0, 1, 2, and 3 ft from the load were analyzed during the development of the response algorithms. The data from the sensor at 3 ft had the highest correlation coefficient (0.99) with the calculated resilient modulus. The standard error of estimate for the response algorithm was 0.64 ksi. The comprehensive data base and an excellent fit make the algorithm a powerful computational tool.

The determination of the structural capacity (structural number) required to carry future traffic is identical to new pavement design. ROADHOG uses the AASHTO flexible pavement design procedure in the module NEWFLEX to determine structural requirements (*1*). User input for the NEWFLEX module includes the design reliability, design standard deviation, design change in serviceability index (delta PSI), and the number of ESALs for the design period. The subgrade resilient modulus, calculated by the MRCALC module, is supplied by ROADHOG.

OVERLAY THICKNESS SELECTION

Thickness selection of a flexible (structural) overlay for an existing flexible pavement is straightforward. The ROADHOG procedure uses the structural number relationships shown in Equations 2a and 3 for thickness selection.

In the ROADHOG procedure, overlay thickness selection is performed by the module OVLTHICK. OVLTHICK obtains the values of effective and required structural number from the data file and prompts the user for the asphalt concrete material coefficient. A value of a_{ac} equal to 0.44 is recommended to the user; however, the user may elect to use another value if it is deemed to be more appropriate. The 0.44 value is the average material coefficient for asphalt concrete as determined from the AASHO Road Test.

ANALYSIS UNIT DELINEATION

Analysis unit delineation is a process by which a length of pavement slated for rehabilitation (e.g., overlay) is subdivided into homogenous sections. Homogeneous sections or analysis units have been defined as "sections of pavement that can be considered nearly alike in terms of performance, age, traffic, structural capacity, etc., and for which a single treatment is appropriate" (*8*). Subdividing a project into analysis units can greatly increase the efficiency and cost-effectiveness of an overlay design. The use of analysis units can help to ensure that the optimum amount of overlay is placed where it is needed.

The subdivision of an overlay project into analysis units may be performed at a number of occasions in the overlay design process. Unit delineation should be performed before any pavement testing or design analysis based on construction records, visible pavement distress, known subgrade conditions, and so forth The overlay design would then be performed separately on each predetermined analysis unit. Analysis units may also be defined by a material sampling program or NDT data such as maximum deflection under load, and the overlay design performed separately on each predetermined analysis unit. ROADHOG performs analysis unit delineation on the basis of the actual required overlay thickness determined at each NDT test site, making unit delineation the final step in the ROADHOG overlay design procedure.

The ROADHOG procedure uses the "cumulative difference method" outlined in the 1986 *AASHTO Guide* to perform unit delineation in the module UNIDEL. A full discussion of the statistical method is contained in Appendix J of the *AASHTO Guide* (*1*). ROADHOG uses the required overlay thickness calculated for each measured deflection basin as the response variable in the procedure. The actual required overlay thickness is the most reasonable estimate of the structural deficiency of the pavement at each NDT test site.

The UNIDEL module allows the designer to set the minimum length of an analysis unit. For long projects, a recommended minimum length of analysis unit is 1,000 ft (*8*). The minimum length should be based on economics and practicality. UNIDEL establishes "calculated analysis units" based solely on the statistical procedure outlined above. "Recommended analysis units" are determined by combining calculated units shorter than the minimum with adjacent units. After recommended units are determined, UNIDEL assigns each station along the project a unit number. Output of results according to analysis units is based on the assigned unit numbers.

DESIGN RELIABILITY

One difficulty in making meaningful comparisons between ROADHOG and other overlay design procedures is the method of applying a reliability level to the design. Reliability is the probability that a design will perform as intended for the design period. Thus a design with "50 percent reliability" has a 50 percent chance of performing satisfactorily; conversely, the design has a 50 percent change of failing during the design period.

In NDT overlay design, a level of reliability can be applied to the required thickness at each individual NDT test point, to the overall average required thickness, or to both. However, the meaning of applying a reliability to the average required thickness from thicknesses already determined at a reliability level is unclear. An in-depth study is needed to determine a meaningful method of handling reliability in overlay design.

IMPLEMENTATION

ROADHOG was completed in May 1990 and turned over to AHTD for trial implementation. For approximately 1 year, the AHTD research staff evaluated ROADHOG by using it together with other overlay design approaches to develop thickness recommendations for the Roadway Design Division. After 1 year, ROADHOG was released to Roadway Design to be used as the primary, routine overlay design tool. In a recent meeting, design engineers using ROADHOG expressed satisfaction with the procedure. The only reservations expressed were relative to some very thin overlay thicknesses from a few projects. However, a review of these projects revealed that, whereas the pavements needed rehabilitation, this need was not due to structural inadequacy; and ROADHOG, like other NDT-based procedures, only addresses structural inadequacy.

As stated in previous sections, methods used for SN_{eff} and M_{ri} estimation are based on material properties representative of conditions encountered in Arkansas. To implement the ROADHOG procedure in other areas, care must be taken to ensure that the material properties used by ROADHOG are representative of local conditions. If local material properties vary significantly from those used in ROADHOG modules, additional analyses (similar to those used in developing the algorithms used by ROADHOG) should be performed with the local material properties.

CONCLUSION

ROADHOG has proven to be a practical, easy-to-use design procedure for determining the overlay thickness needed to correct structurally deficient flexible pavements in Arkansas. The procedure follows the general design approach contained in the 1986 *AASHTO Guide* but incorporates some improved features. SN_{eff} is determined by a method that is independent of the subgrade resilient modulus (M_r) and the depth to bedrock, and M_r is determined in a manner consistent with the AASHTO design equation and not requiring the modification needed by other backcalculation methods. The unit delineation method used in ROADHOG assists the designer in optimizing the design by identifying areas needing different overlay thicknesses.

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DISCUSSION

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The 1986 *AASHTO Guide* (*1*) incorporates a remaining life concept in overlay thickness design and expresses the overlay structural requirement in the following form (Equation 2 in the paper):

$$SN_{OL} = SN_O - F_{RL}(SN_{xeff}) \quad (5)$$

Elliott (*2*) demonstrated that the overlay thickness computations using AASHTO design curves for F_{RL} produced inconsistent results and recommended that "the AASHTO overlay design approach be revised to exclude remaining life considerations." However, subsequent work by Easa (*3*) and Fwa (*4*) illustrated that the AASHTO concept of remaining life is fundamentally correct and that consistent results are obtained using corrected F_{RL}. Unfortunately, the current paper continues to adopt the view expressed by Elliott (1989) and states that the inclusion of the concept of remaining life "was not found to be reasonable or practical." It is shown in this discussion that reverting to the use of the traditional overlay equation $SN_{OL} = SN_O - SN_{xeff}$ (Equation 2a in the paper, setting $F_{RL} = 1.0$), as recommended by Elliott (*2*) and the authors, is conceptually unsound.

SIGNIFICANCE OF REMAINING LIFE CONCEPT

The basic difference between the AASHTO overlay equation (Equation 5) and the traditional overlay equation lies in the fact that the traditional equation computes SN_{OL} required at the time of overlay construction, and no check is made to ensure that the overlay provided will be adequate during the entire design period. It can be shown (*1,4*) that, depending on the structural deterioration rate of an existing pavement after overlay application, the overlay requirement at a later stage of the service life of the pavement may exceed the value computed by the traditional overlay equation. Using different deterioration curves for old pavements after overlay, Easa (*3*) and Fwa (*4*) showed that the overlay thickness requirement varied with the remaining lives of the old pavements. Including the remaining life consideration in overlay design is therefore a refinement and improvement of the traditional overlay equation.

SIGNIFICANCE OF REMAINING LIFE FACTOR F_{RL}

The remaining life factor can be derived and shown to be a function of the structural capacities of existing and overlaid pavements and hence a function of the remaining lives of the pavements (*1,4*). Referring to Appendix CC of the 1986 *AASHTO Guide*, where an excellent description of the remaining life concept is presented, it is obvious that the correct F_{RL} value to be used in Equation 5 should be determined by considering the overlay requirements at all stages in the overlay design life. A detailed explanation of how this can be done is given elsewhere (*4*), where a procedure for selecting the governing F_{RL} value is described. The F_{RL} value so determined will lead to the choice of SN_{OL} from Equation 5 that provides an adequate overlay thickness for the entire period of the design service life. It is apparent that this important aspect of remaining life factor computation is not considered by Elliott (*2*) and the authors in their analyses of overlay design. Not realizing this significance of the concept has probably resulted in their call for exclusion of remaining life consideration from overlay design and their doubt of the statement that factor F_{RL} would "reflect a more realistic assessment of the weighted effective capacity during the overlay period."

BASIS OF AUTHORS' RECOMMENDATIONS

The authors state that "for all practical purposes, a value of 1.0 is the appropriate value for F_{RL}," and that the inclusion of the remaining life concept "within the structural deficiency design approach used in ROADHOG was not found to be reasonable or practical." The only basis for these recommendations was the work reported by Elliott (*2*). An examination of Elliott's paper shows that there is little justification for the strong recommendations. The recommendations were based solely on an analysis using a "simple scale transformation" that relates R_{Lyx} to R_{Ly} for a given R_{Lx} as follows:

$$\left\{\frac{R_{Lx}}{1}\right\} = \left\{\frac{R_{Lyx}}{R_{Ly}}\right\} \quad (6)$$

Substituting Equation 6 into the AASHTO equation for calculating F_{RL}, Elliott (*2*) concluded that the appropriate value for F_{RL} was 1.0. Three points can be raised regarding Elliott's analysis:

1. The F_{RL} value was computed for only one point (i.e., at the end of the service life), which is not a correct way of selecting a design F_{RL} value. For example, F_{RL} values greater than 1.0 were mentioned. This would not be the case if the proper procedure of selecting a design F_{RL} value according to the concept of remaining life is followed. At the time of overlay construction, F_{RL} would be 1.0 if evaluated then. This effectively eliminates one from choosing an F_{RL} value greater

than 1 when the overlay requirements at other times during overlay service life are checked.

2. No physical meaning or practical significance was given to justify why the relationship in Equation 6 was used. The "philosophy" given by Elliott (*2*) was "the concept of the man who each day walks halfway to his destination." This writer finds it difficult to relate the philosophy to overlay performance. It is, however, easy to show that Equation 6 has a highly controversial implication not stated by the authors or Elliott (*2*): for a given pavement with known R_{Lx}, the rate of change in R_{Lyx} is proportional to the rate of change in R_{Ly}. This underlying assumption of Equation 6 is severely restrictive in application, and it is not in agreement with common understanding of how old and new pavements deteriorate. Easa (*3*) and Fwa (*4*) have shown that there are many other more meaningful deterioration relationships that would produce consistent overlay designs according to the AASHTO remaining life design concept, and that the values of F_{RL} varied from about 0.5 to 1.0 for the cases they considered.

3. It is physically meaningful to derive the pavement performance relationship in terms of pavement conditions or structural capacity. Equations involving multiplication and division of remaining life fractions R_L of different pavements are difficult to interpret physically. This is because R_L is a nonlinear function of pavement structural condition, and it is a fraction of load repetitions N_f, which are different for different pavements. Fwa (*4*) has shown that putting different R_L values in an equation without paying attention to the different base N_f values can lead to erroneous results. For example, the "simple" transformation of (R_{Lx}, R_{Lyx}) to (1, R_{Ly}) as shown in Equation 6 is deceptively straightforward. However, expressed in terms of pavement structural condition or load repetition capacity, the "walking man philosophy" may not make any sense.

SUMMARY REMARKS

This discussion deals with the overlay design methodology of the paper. Explanation and findings of other studies have been presented to show that the AASHTO remaining life concept is technically sound and that the recommendations by the authors concerning the use of $F_{RL} = 1.0$ and the exclusion of the remaining life concept in overlay design are misleading and not justified.

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AUTHORS' CLOSURE

We recognize the validity of remaining life as a concept that needs to be considered in overlay design. However, its application as presented in the 1986 *AASHTO Guide* is flawed and adds complications to the design process that are not warranted. Because of this, the 1986 approach to remaining life was not included in ROADHOG. The concept adopted for ROADHOG is that SN_{eff} should represent the contribution of the pavement to the future performance after it is overlaid. If SN_{eff} is selected properly, the application of the F_{RL} term represents a double penalty for the effects of past traffic. Research is needed to determine whether the method of selecting SN_{eff} developed for ROADHOG selects the appropriate value.

We are familiar with the papers by Fwa and Easa. These papers acknowledge the flaw in the 1986 guide remaining life first observed by Elliott. Both papers attempt to remedy the flaw; however, the remedies further complicate a process that is already more complex than is warranted within the empirical AASHTO approach to pavement design. The AASHTO approach has served for many years as a useful design tool. However, it is a tool that has been extrapolated far beyond its original data base, often with little justification other than engineering judgment. Its application to overlay design represents further extrapolation. The addition of a complicated, sophisticated approach to remaining life simply is not justified.

In this respect, the decision to not include the F_{RL} term in ROADHOG was not solely because of its flaws. Even without the flaws there are reasons and sentiment for its removal. Other reasons are the removal of unwarranted complications as cited above and the elimination of confusion and lack of understanding generated by the remaining life factor when it was introduced in 1986.

The introduction of the F_{RL} term into overlay design created much confusion. Designers did not understand the term or its application. Even veteran pavement researchers had trouble accepting and understanding remaining life as it is presented in the 1986 guide. This is perhaps best demonstrated by the fact that the F_{RL} term was introduced in 1986 (and reviewed and questioned by knowledgeable pavement engineers before that), yet the flaws in the concept were not noted until 1989.

The development of the F_{RL} methodology and the modifications proposed by Fwa and Easa suggest a lack of understanding of the limitations of the AASHO Road Test performance equations that serve as the basis for the AASHTO pavement design procedures. These equations are best-fit regression equations developed to predict the performance of the pavement sections at the Road Test. Strictly speaking, they are only valid within the very limited context of the pavement types, axle loads, subgrade, environment, time, and so forth of the AASHO Road Test. To use them to develop a sophisticated concept of remaining life for overlay design represents a gross extrapolation, far beyond the original data base or intent of the equations. Such use suggests that the Road Test equations are fundamental behavioral relationships. They are not. To use these empirical equations in this manner is an interesting academic exercise, but it is not valid.

There is also a danger in incorporating procedures developed in such a manner into routine engineering practice, especially when such procedures are complicated and sophisticated in appearance. The incorporation and sophistication suggest a legitimacy that does not exist. Once accepted into practice, the procedures can become "etched in stone" and very difficult to change or correct when more advanced technology becomes available.

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