Effective Structural Number Algorithm Enhancements to ROADHOG

KEVIN D. HALL AND QUINTIN B. WATKINS

ROADHOG is a deflection-based flexible pavement overlay design procedure used by the Arkansas Highway and Transportation Department. It uses a structural deficiency approach to overlay design modeled after the guidelines given in the 1986 *AASHTO Guide for Design of Pavement Structures.* The effective structural capacity of the existing pavement (SN_{eff}) is calculated as a function of the difference in the maximum pavement deflection and a deflection at some radial distance from the point of loading. This deflection difference is termed *delta-D.* As originally developed ROADHOG is limited to the structural thickness design of asphalt concrete (AC) overlays for existing conventional flexible pavements (AC surface, granular base, subgrade). Research has enhanced ROADHOG by adding capabilities to determine the SN_{eff} for full-depth asphalt (FDA) pavements and surface-treated pavements (STPs). These enhancements allow the use of ROADHOG for any flexible pavement. The SN_{eff} algorithm for FDA pavements uses a *delta-D* approach similar to the algorithm currently used in ROADHOG for conventional flexible payments. SN_{eff} is determined for STPs by using a deflection ratio, *delta-D/D0,* in which *D*0 is the maximum pavement deflection under load. The algorithms are developed by using a comprehensive deflection basin data base generated by the finite-element pavement model ILLI-PAVE, varying surface and base course thickness and stiffness and subgrade stiffness. In both the FDA and STP algorithms the subgrade stiffness is not considered explicitly for estimating SN_{eff}. SN_{eff} estimates for surface-treated pavements also do not explicitly include the granular layer thickness of the STP. Comparisons of the new SN_{eff} algorithms with the current procedures in ROADHOG indicate that the new algorithms give more consistent and accurate estimates of the effective structural number of the existing pavement.

ROADHOG is a deflection-based structural overlay design procedure for flexible pavements developed in 1989 at the University of Arkansas for the Arkansas Highway and Transportation Department (AHTD) (*1*). AHTD designs new pavements by using AASHTO procedures, as detailed in the 1993 *AASHTO Guide for Design of Pavement Structures* (*2*). ROADHOG was developed to be compatible with AHTD new pavement design practices; thus, the structural pavement design concepts in ROADHOG are compatible with AASHTO flexible pavement design. A detailed description of the ROADHOG procedure is given by Hall and Elliott (*3*).

As originally developed the ROADHOG procedure is limited to asphalt concrete (AC) overlays of existing conventional flexible pavements (AC surface, granular base, subgrade). Recently, research was initiated to upgrade and enhance the capabilities of ROADHOG. One such enhancement is the inclusion of additional flexible pavement types as existing pavements. This paper describes the development of algorithms to determine the effective structural capacity (SN_{eff} for flexible pavements) of full-depth asphalt (FDA) pavements and surface-treated pavements (STPs).

Department of Civil Engineering, University of Arkansas, Fayetteville, 4159 Bell Engineering Center, Fayetteville, Ark. 72701.

ROADHOG OVERLAY DESIGN METHODOLOGY

ROADHOG uses a structural deficiency approach to overlay design, similar to that described in the AASHTO guide (*2*). By this approach the structural capacity required of the overlay is calculated as the difference between the structural capacity required to carry future traffic loadings and the effective structural capacity of the existing pavement. For AASHTO flexible pavement design, structural capacity is expressed in terms of a structural number (*SN*). The structural number of the overlay can be expressed in equation form, shown as Equation 1.

$$SN_{ol} = SN_f - SN_{eff} \tag{1}$$

where

SN_{ol} = structural number of overlay,
SN_f = structural number required to carry future traffic, and
SN_{eff} = effective structural number of existing pavement.

SN_f is calculated in a manner similar to that of a new pavement design. The methodology for estimating SN_{eff} in ROADHOG was originally developed by Kong (*4*). A brief synopsis of the SN_{eff} procedure contained in ROADHOG follows.

Figure 1 is an idealized representation of pavement response to an applied load, such as that applied by a falling weight deflectometer to represent a wheel load. At some distance from the applied load (*t*) the pavement surface deflection is almost entirely due to deformation within the subgrade. Directly beneath the load pavement surface deflection is due to deformations within all paving layers. Kong (*4*) suggested that the difference between two deflections, the deflection beneath the load (all layers contributing) and a deflection outside the zone of pavement influence (only subgrade contributing), could be used as a measure of pavement stiffness. If SN_{eff}

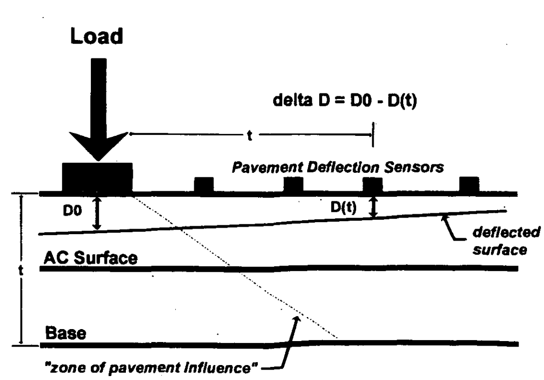

FIGURE 1 Conceptual basis for ROADHOG (*4*).

is a function of pavement stiffness (as assumed by AASHTO), then this deflection difference becomes a measure of SN_{eff}. Kong (*4*) related the SN_{eff} of a number of conventional flexible pavement configurations to a deflection difference termed *delta-D*. He estimated SN_{eff} by component analysis, in which the *SN* of a pavement is the sum of individual layer thicknesses multiplied by appropriate AASHTO layer coefficients (*2*), as shown in Equation 2.

$$SN = a_1d_1 + a_2d_2 \qquad (2)$$

where

SN = structural number,
a_n = AASHTO layer coefficient of layer n, and
d_n = thickness of layer n.

Kong (*4*) calculated *delta-D* by using the maximum surface deflection under the load and the surface deflection at a distance away from the load equal to the pavement thickness. Figure 2 shows the relationship between SN_{eff} and *delta-D* for various pavement thicknesses. The *delta-D*-SN_{eff} relationship is primarily a function of total pavement thickness; Kong found the effect of subgrade stiffness to be negligible (*3*).

FDA PAVEMENT ALGORITHMS

The algorithms used to estimate SN_{eff} for FDA pavements are developed in a format similar to those used for conventional flexible pavements in ROADHOG. Three tasks are performed to establish the algorithms: (a) generate a pavement deflection data base, (b) relate SN_{eff} to *delta-D* for each pavement in the data base, and (c) compare results for FDA pavements with the conventional flexible pavement algorithms currently in ROADHOG. The third task is performed to ensure that existing algorithms are insufficient, requiring that specific SN_{eff} algorithms be established for FDA pavements.

FDA Pavement Deflection Data Base

Pavement surface deflections are generated by using the ILLI-PAVE finite-element pavement model (*5*). FDA pavements are modeled as two-layer systems (AC surface, subgrade). The parameters that are varied to establish the data base are given in Table 1. Other material properties are selected after work performed by Elliott and Thompson (*6*) and Gomez-Achecar and Thompson (*7*).

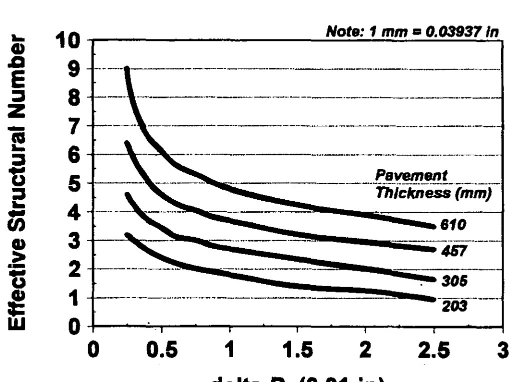

FIGURE 2 Original SN_{eff}/*delta-D* relationships (*4*).

TABLE 1 Parameters Varied To Establish FDA Pavement Data Base

Pavement Layer Property		
Asphalt Concrete		Subgrade
Thickness (mm)	Resilient Modulus (MPa)	Resilient Modulus (MPa)
152	1035	21
203	3450	52
254	10005	83
305		

NOTE: 1 mm = 0.03937 in.
1 Mpa = 0.145 ksi

FDA SN_{eff}/*delta-D* Relationship

The relationship between SN_{eff} and *delta-D* for FDA pavements is shown in Figure 3. The lines shown in Figure 3 result from regression equations fit to the *delta-D*/SN_{eff} data. The degrees of fit as suggested by the regression coefficient r^2 are 0.972, 0.984, 0.987, and 0.991 for FDA pavement thicknesses of 152 mm (6 in.), 203 mm (8 in.), 254 mm (10 in.), and 305 mm (12 in), respectively. Part of the unexplained variation in SN_{eff} (the difference between the reported r^2 value and a perfect fit of 1.0) may be attributed to the effects of AC temperature and subgrade stiffness.

Comparison with Current ROADHOG Algorithm

Figure 4 shows the SN_{eff}/*delta-D* relationship for a 254-mm (10-in.) FDA pavement calculated by using both the new FDA algorithm and the existing ROADHOG algorithm. The general trend shown in Figure 4 for the 254-mm (10-in.) FDA pavement is also observed in similar plots prepared for 152-mm (6-in.), 203-mm (8-in.), and 305-mm (12-in.) FDA pavements. The new FDA algorithms show a *delta-D*/SN_{eff} relationship that is markedly different from that relationship shown by the existing ROADHOG algorithms. This result is not unexpected. The *SN*s used to develop both *delta-D*/SN_{eff} relationships are calculated by a component analysis approach, in which the *SN* of the pavement is the sum of thicknesses (d_i) and layer coefficients (a_i) of the individual layers (*2*). For a given pave-

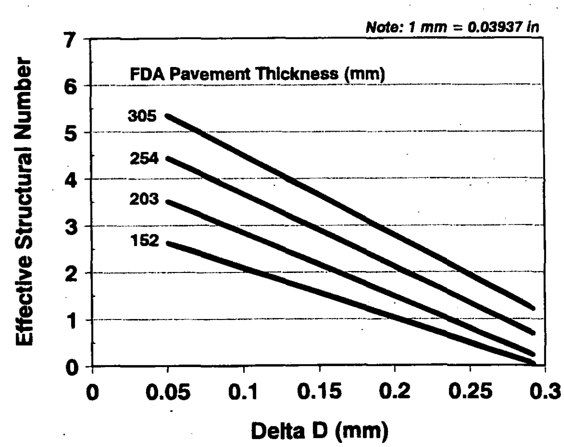

FIGURE 3 Full-depth asphalt SN_{eff}/*delta-D* relationship.

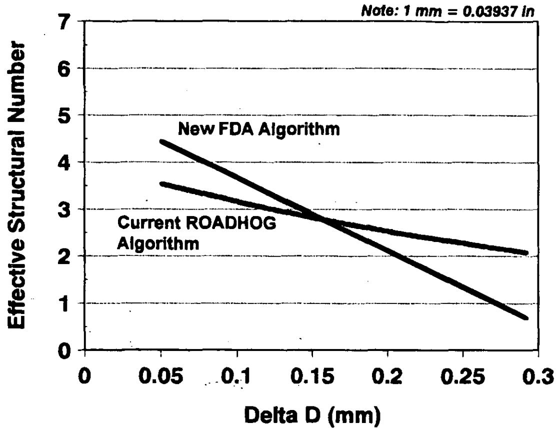

FIGURE 4 Comparison of full-depth asphalt SN_{eff} algorithms, 254-mm pavement.

ment thickness the *SN* of an FDA pavement will be calculated by using a single layer coefficient for AC; for a conventional flexible pavement, some portion of the SN will be calculated by using a layer coefficient for a granular base.

The new SN_{eff} algorithm for FDA pavements should better represent the effective structural capacity of the existing pavement for a given value of *delta-D*. The difference in SN_{eff} values between the two algorithms given in Figure 4 could result in differences in overlay thicknesses of more than 50 mm (2-in.), using a typical AC layer coefficient of 0.44. Continued use of the existing algorithms in ROADHOG could result in conservative overlay thicknesses for FDA pavements with lower *delta-D* values and inadequate overlay thicknesses for FDA pavements with higher *delta-D* values.

STP ALGORITHMS

The algorithms used to estimate SN_{eff} for STPs are developed in a format similar to those used for conventional flexible pavements in ROADHOG. Four tasks are performed to establish the algorithms: (a) generate a pavement deflection data base, (b) determine the extent to which the existing ROADHOG SN_{eff} algorithm accurately and consistently estimates the SN_{eff} of surface-treated pavements in the data base, (c) relate SN_{eff} to the deflection basin for each pavement in the data base, and (d) compare new algorithm results with the conventional flexible pavement algorithms currently in ROADHOG.

STP Deflection Data Base

Pavement surface deflections are generated by using the ILLI-PAVE finite-element pavement model (*5*). STPs are modeled as two-layer systems (granular base, subgrade). No structural contribution is assigned to the surface treatment itself. The parameters that are varied to establish the data base are given in Table 2. Other material properties are selected after work performed by Elliott and Thompson (*6*).

Existing ROADHOG Algorithm

In its current form ROADHOG estimates the SN_{eff} of a pavement on the basis of total pavement thickness and *delta-D*. Figure 5 shows the relationship between *delta-D* and SN_{eff} (as determined by

TABLE 2 Parameters Varied To Establish STP Data Base

Pavement Layer Property		
Granular Layer		Subgrade
Thickness (mm)	Resilient Modulus (MPa)	Resilient Modulus (MPa)
152	207	21
203	276	52
254		83
305		

NOTE: 1 mm = 0.03937 in.
1 Mpa = 0.145 ksi

ROADHOG) for STPs. The curves shown in Figure 5 represent various pavement thicknesses; the points representing 152-mm (6-in.) and 203 mm (8-in.) STPs combine to form one curve. The curves indicate that the existing ROADHOG algorithm produces inconsistent results. For the same pavement thickness [greater than 203 mm (8-in.)] identical SN_{eff} values can be produced by using different values of *delta-D*. In addition, the curves show a relationship in which *SN* increases with an increasing *delta-D*, which is not reasonable.

Figure 6 shows the SN_{eff} determined by ROADHOG plotted against the *SN* of the STP calculated by component analysis (in this application the component analysis-based *SN* represents a known structural number). It is seen in Figure 6 that, relative to the component analysis-based *SN*, the existing algorithm in ROADHOG generally overestimates the *SN* of STPs.

It is demonstrated that the existing SN_{eff} algorithm in ROADHOG neither accurately nor consistently estimates the *SN* for STPs.

STP SN_{eff}/*delta-D* Relationship

To be consistent with current ROADHOG design philosophy it is desired that a relationship between pavement stiffness (e.g., *delta-D*) and SN_{eff} that is reasonably independent of the subgrade resilient modulus be established (*1,3*). Unfortunately, traditional SN_{eff}/*delta-D* curves prepared from STP data show strong trends relative to the subgrade modulus value used to generate the data base. Various combinations of deflection basin data were examined to establish a relationship with SN_{eff} that would minimize the effect of subgrade modulus. The best available relationship uses *delta-D* values that are modified by dividing *delta-D* by the maximum deflection *D*0.

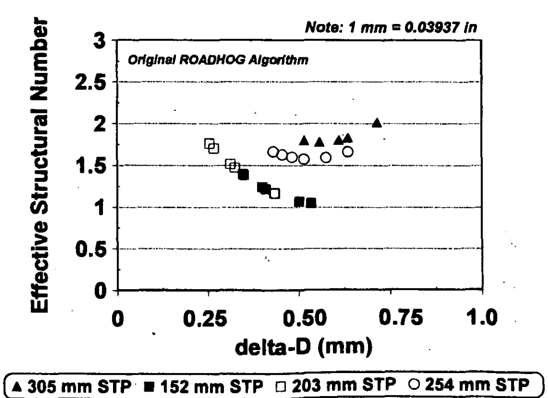

FIGURE 5 *delta-D*/SN_{eff} relationship for STP using current ROADHOG algorithm.

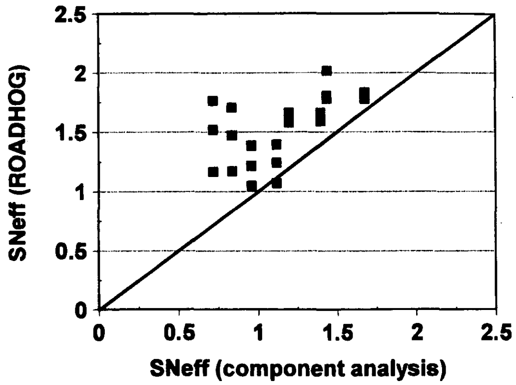

FIGURE 6 Comparison of SN_{eff} values for STPs estimated by using component analysis and current ROADHOG algorithm.

The resulting relationship between SN_{eff} and the (*delta-D/D0*) ratio for STP pavements is shown in Figure 7. In Figure 7 the thickness of the granular layer and the subgrade stiffness are not explicitly used to estimate SN_{eff}. Groupings of the data in Figure 7 are evident; these groupings represent variations in subgrade stiffness and granular layer thickness.

Comparison with Current ROADHOG Algorithm

Both the existing SN_{eff} algorithm used in ROADHOG and the regression line shown in Figure 7 relate pavement deflections to an *SN*; *SN*s used to establish the respective algorithms are calculated by using component analysis of known pavement structures. Figure 8 is a comparison of the relative abilities of the new SN_{eff}/(*delta-D/D0*) relationship and the existing ROADHOG algorithm to estimate the *SN*s of the known pavement configurations used in the study. The existing SN_{eff} algorithm in ROADHOG overestimates the structural number of STPs relative to the new deflection ratio algorithm. In addition, the ROADHOG algorithm is less consistent for STP data, as evidenced by a lower regression coefficient when fitted to a straight line ($r^2 = 0.41$ for ROADHOG versus $r^2 = 0.83$ for the new algorithm).

SUMMARY AND CONCLUSIONS

Algorithms are developed to estimate the SN_{eff} of FDA pavements and STPs on the basis of measured surface deflections. The SN_{eff} algorithms for FDA pavements are a function of the deflection difference *delta-D* as currently defined in the ROADHOG overlay design procedure. In addition, the specific SN_{eff} equation SN_{eff} used for FDA pavements depends on the thickness of the AC. For STPs SN_{eff} is a function of a deflection ratio, *delta-D/D0*, where *delta-D* is as currently defined in the ROADHOG procedure and *D0* is the maximum pavement deflection under load. The SN_{eff} equation for STPs does not explicitly consider granular layer thickness. Neither algorithm, FDA pavements nor STP, explicitly considers the subgrade resilient modulus in SN_{eff} estimation.

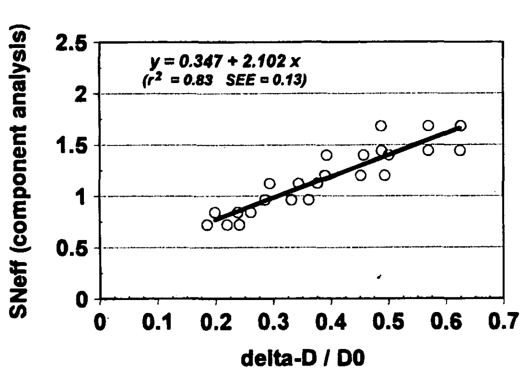

FIGURE 7 Proposed SN_{eff} algorithm for STPs.

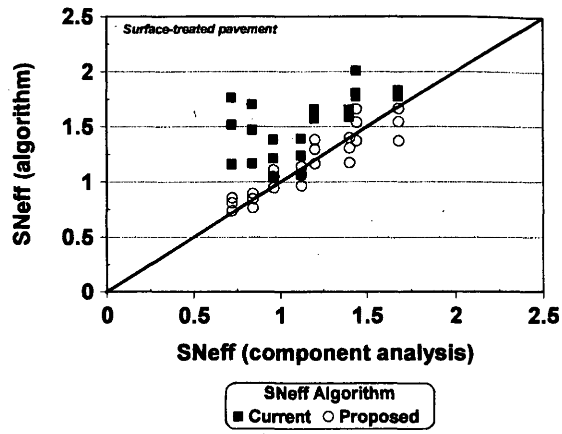

FIGURE 8 Comparison of current and proposed SN_{eff} algorithms for STPs with component analysis-based SN_{eff} values.

Comparisons of SN_{eff} values obtained by using the new algorithms with the values obtained by using current ROADHOG procedures show that the new algorithms provide better estimates of the *SN*s of modeled pavements. These results are not totally unexpected. The SN_{eff}/*delta-D* relationship in ROADHOG is based on conventional flexible pavement configurations. Relationships developed with different pavement configurations should model those configurations better than a generic relationship.

A number of items concerning these analyses must be noted. (a) Both the FDA pavements and STPs are modeled as single-layer, single-material pavements. Multiple layers above the subgrade may change the *SN* relationships shown. (b) The material properties used in the analyses are typical of those found in Arkansas. Significant deviation from the properties used in the pavement models may change the *SN* relationships that were developed. (c) Although AASHTO *SN*s and a structural deficiency approach similar to that recommended in the 1993 AASHTO guide were used in these analyses, FDA pavements and STPs were not included in the testing matrix that resulted in the original AASHTO flexible pavement design/performance equation. The *SN* concept is philosophically sound for use with FDA pavements STPs. However, these analyses do represent an extrapolation beyond the original AASHTO data base.

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