Rutting Rate Analyses of the AASHO Road Test Flexible Pavements

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Asphalt concrete (AC) fatigue cracking, AC low-temperature cracking, and pavement surface rutting are the flexible pavement distress modes normally considered in flexible pavement analysis and design. AC fatigue cracking and rutting in component pavement layers (AC surface, granular base and subbase layers, and subgrade) are related to structural responses (stress-strain-deflection). Pavement rutting is discussed. One practical and applied pavement rutting approach is to correlate structural responses (stress-strain-deflection) with field distress measurements. The forms of laboratory-based material/soil distress models are helpful in establishing the general parameters that best define the structural response–field distress measurement relationships. The NCHRP 1-26 Phase 1 Final Report indicated that the log permanent strain (ε_p)–log load repetitions (N) phenomenological model was an appropriate, versatile, and practical approach. Paving materials (AC and granular base/subbase) and subgrade soils generally follow the model. It is assumed that a phenomenological pavement surface rutting model would be of the same form. An analogue, a proposed pavement surface rutting rate (RR) model, is evaluated: RR = RD/N = $\mathrm{A}/\mathrm{N}^{B}$, where RR is the rutting rate, RD is the rut depth in inches, N is the number of repeated load applications, and A and B are terms developed from field calibration testing data. The RR model was validated by analyzing selected AASHO Road Test data and rutting performance information from Illinois Department of Transportation rehabilitated sections of the AASHO Road Test flexible pavement tangent sections. The analyses indicated that the RR concept is valid. Stable pavement rutting trends were related to ILLI-PAVE estimated pavement structural responses, particularly the subgrade stress ratio. Similar RR performance (the B values in the RR equation) was noted for the original AASHO sections, reconstructed sections built with salvaged AASHO materials, and new sections constructed with similar paving materials. The RR approach can be effectively used in a priori pavement analysis and design and pavement management system activities. For the typical "generic specification" flexible paving materials used by a highway agency, the B terms and relationships relating structural responses to A can be established from a flexible pavement performance data base.

Flexible pavement distress modes normally considered in flexible pavement analysis and design are fatigue cracking, rutting, and low-temperature cracking. Asphalt concrete (AC) fatigue cracking and rutting in component pavement layers are significant considerations related to structural responses (stress-strain-deflection). Pavement rutting is the focus of this paper.

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To limit pavement surface rutting to acceptable levels, careful attention must be directed to all of the various paving layers and the subgrade. The AC surface, the granular base and subbase layers, and the subgrade may contribute to the accumulation of pavement surface rutting. High-strength stabilized base materials, such as cement-treated aggregate and pozzolanic-stabilized base, do not significantly contribute to rut depth accumulation.

Mechanistic-based distress models for fatigue and rutting use stress-, strain-, or deflection-related parameters to estimate fatigue life or permanent deformation accumulation under repeated loading. The development of acceptable flexible pavement distress models includes the successful integration of structural modeling concepts and the material/soil testing procedures used in establishing laboratory-based fatigue or permanent deformation accumulation models. Field calibration (reconciling of actual distress development under field conditions with predicted distress development) and the establishment of shift factors are required.

An alternative approach is to directly correlate structural response outputs (stress/strain/deflection) determined from a selected standard structural analysis model with field distress measurements. The forms of laboratory-derived material/soil distress models are helpful in establishing the general parameters that best define the structural response–field distress measurement relationships.

In this paper, the application of the log permanent strain–log number of load repetitions phenomenological model and a pavement surface rutting rate (RR) model is evaluated. The primary data are from the AASHO Road Test data base.

PERMANENT DEFORMATION MODELS

Material permanent strain accumulation models (AC, granular materials, and cohesive soils) and pavement system rutting models and algorithms were considered in Phase 1 of NCHRP 1-26 (*1*). The log permanent strain–log load repetitions phenomenological model appeared to be an appropriate, versatile, and practical approach. The model is expressed as follows:

$$\log \varepsilon_p = a + b \log \mathrm{N} \tag{1}$$

or

$$\varepsilon_p = A\mathrm{N}^b \tag{2}$$

where

ε_p = permanent strain,
a and b = experimentally determined factors, and
A = antilog of a.

Ohio State University (OSU) researchers have proposed a permanent strain accumulation prediction model for use in a pavement design system developed for the Ohio Department of Transportation (*2*). The OSU permanent strain accumulation model is

$$\varepsilon_p/N = AN^m \quad (3)$$

where

ε_p = plastic strain at N load repetitions,
N = number of repeated load applications,
A = experimental constant dependent on material and state of stress conditions, and
m = experimental constant depending on material type.

If the b term from the log permanent strain–log N model is known, m is equal to $b - 1$.

Soils and Granular Materials

Various data considered elsewhere (*1*) indicate that for reasonable stress states (considerably below material failure strengths), the b term for soils and granular materials is generally within the range of 0.12 to 0.2 (*3–6*). The lower values are for the soils. The a term is variable and depends on material/soil type, repeated stress state, and factors influencing material shear strength. Stress state is generally expressed in such terms as repeated deviator stress ($\sigma_D = \sigma_1 - \sigma_3$), principal stress ratio (σ_1/σ_3), and deviator stress ratio (σ_D/σ_3). In these terms, σ_1 is the major principal stress and σ_3 is the minor principal stress.

The OSU study (*4*) indicated that A is "dependent on soil type and structure, moisture content, dry density, and dynamic stress level." Extensive University of Illinois data (*6*) confirm that A is influenced by many factors. The Illinois study indicated that for a given soil the parameter "log A" was significantly correlated with repeated deviator stress. Examination of the A data indicated that most of the soils also exhibit a "threshold stress level," which is defined as the stress level above which the permanent deformation of the soils under repeated loading is rapid and below which the rate of cumulative deformation from additional stress applications is very small. In most cases the threshold stress level is 50 to 60 percent of the ultimate strength of the soil.

The stress ratio (repeated stress/ultimate strength) approach has good potential. In relative terms, low A values are noted for reduced stress ratios, and large A values are noted for increased stress ratios. Since stress ratio is a valid indicator of rutting potential (as evidenced by the A term), the factors influencing the stress state and strength of in situ granular materials and soils are important considerations.

Asphalt Concrete

Khedr's AC permanent deformation model (*7*) (in the form of Equation 3) was based on repeated load compression tests. The study summarized data for a series of AC mixtures (three crushed limestone aggregates, 85/100 AC-20 asphalt cement) and a range of testing temperatures and stress levels.

Khedr's analyses showed that the m term ($m = b - 1$) does not show considerable variability as influenced by temperature and stress state. Although in Khedr's statistical analyses "m was found to be constant," the m values tended to decrease for higher temperatures (i.e., for decreased AC stiffness). Khedr's average b for the AC mixtures tested was 0.22. The A term was dependent on the repeated deviator stress and the AC mixture modulus. Log A decreased as a function of the log of the AC modulus/repeated deviator stress (i.e., 1/AC strain).

Leahy (*8*) and Leahy and Witczak (*9*) have recently reported on a comprehensive AC permanent deformation study. Two hundred fifty-one asphalt concrete specimens were tested under varying conditions. Temperature, deviator stress, asphalt type and content, aggregate type, and compactive effort were considered. The study confirmed the general applicability of the log permanent strain-log N phenomenological model (Equation 1).

They concluded that a and b were affected by test conditions and mixture properties. a was influenced to a greater extent than b. For the data base considered, the a term varied considerably (coefficient of variation of 97 percent), but the b term showed less variability (average was 0.44 with a coefficient of variation of 27 percent).

Some of Leahy's more specific relevant conclusions are as follows (*8*):

- The slope coefficient, b, was moderately influenced by temperature, asphalt content, and compaction/air voids. It was not affected by deviator stress or aggregate or asphalt type.
- The intercept coefficient, a, was heavily influenced by temperature, deviator stress, and asphalt type and moderately influenced by asphalt content and compaction/air voids. The aggregate had no effect on the intercept coefficient.

Recent Texas A&M studies by Mahboub and Little (*10–12*) include the development of proposed procedures for considering AC rutting in the mixture design process. AC mixture rutting potential is evaluted by laboratory creep testing, and a modified SHELL procedure is used to estimate rutting. The following expression is used to characterize AC permanent deformation:

$$\varepsilon_{vp} = at^b \quad (4)$$

where

ε_{vp} = viscoplastic strain,
t = time, and
a and b = regression constants.

The exponent b from creep testing is generally considered to be comparable with the b term in the log permanent strain–log N relation established from repeated load testing. Mahboub and Little (*10–12*) found from their data and various literature sources that the average b (six values based on creep testing data) was about 0.226, with a standard deviation of 0.031. They indicate that b can be "treated as a constant."

The average b value (0.44) for Leahy and Witczak's data base does not compare favorably with the 0.226 value from Mahboub and Little or the 0.22 value from Khedr. However, the test parameters in the Leahy study represent a much wider data set. For example, Leahy's data for AC Mixture 2 (4.8 percent AC-20, crushed aggregate) indicates that b may change significantly at extremes of temperature or stiffness.

PAVEMENT RUTTING RATE MODEL

The OSU researchers (*2*) indicated that "this relation [Equation 3] is also valid for describing rutting progress in all pavement layers—asphalt, granular base course, subbase materials and subgrade support soils." The references cited in this paper support the general validity of that statement.

If all of the paving materials (AC and granular base/subbase) and the subgrade soils generally follow the log ε_p–log N phenomenological model (Equation 1) and the OSU model (Equation 3), it is reasonable to assume that a phenomenological pavement surface rutting model would be of the same form. A pavement system rutting rate (RR) analogue can be obtained by substituting rut depth for the permanent strain term. The resulting equation is

$$RR = RD/N = \mathbf{A}/N^{B} \quad (5)$$

where

RR = rutting rate,
RD = rut depth (in.),
N = number of repeated load applications, and
A and B = terms developed from field calibration testing data.

To evaluate the validity of the concept, the RR model (Equation 5) was used to analyze selected AASHO Road Test data.

RUTTING RATE ANALYSES OF AASHO ROAD TEST DATA

AASHO Road Test rut depth data for the single-axle lanes of the conventional flexible pavement sections (AC/granular) of Loops 3 through 6 and the bituminous wedge sections in Loops 3, 5, and 6 were analyzed to

1. Establish the RR parameters (**A** and B),
2. Evaluate the validity of the RR model, and
3. Identify the pavement structural responses that most influence **A** and B.

Typical rut-depth development data are shown in Figure 1 for AASHO Section 591 (outer wheelpath) of Loop 4. Section 591 is 5-in. AC surface, 6-in crushed stone base, and 8-in. gravel subbase. Loop 4 single-axle loading was 18 kips. Figure 2 shows the log RR–log N relation.

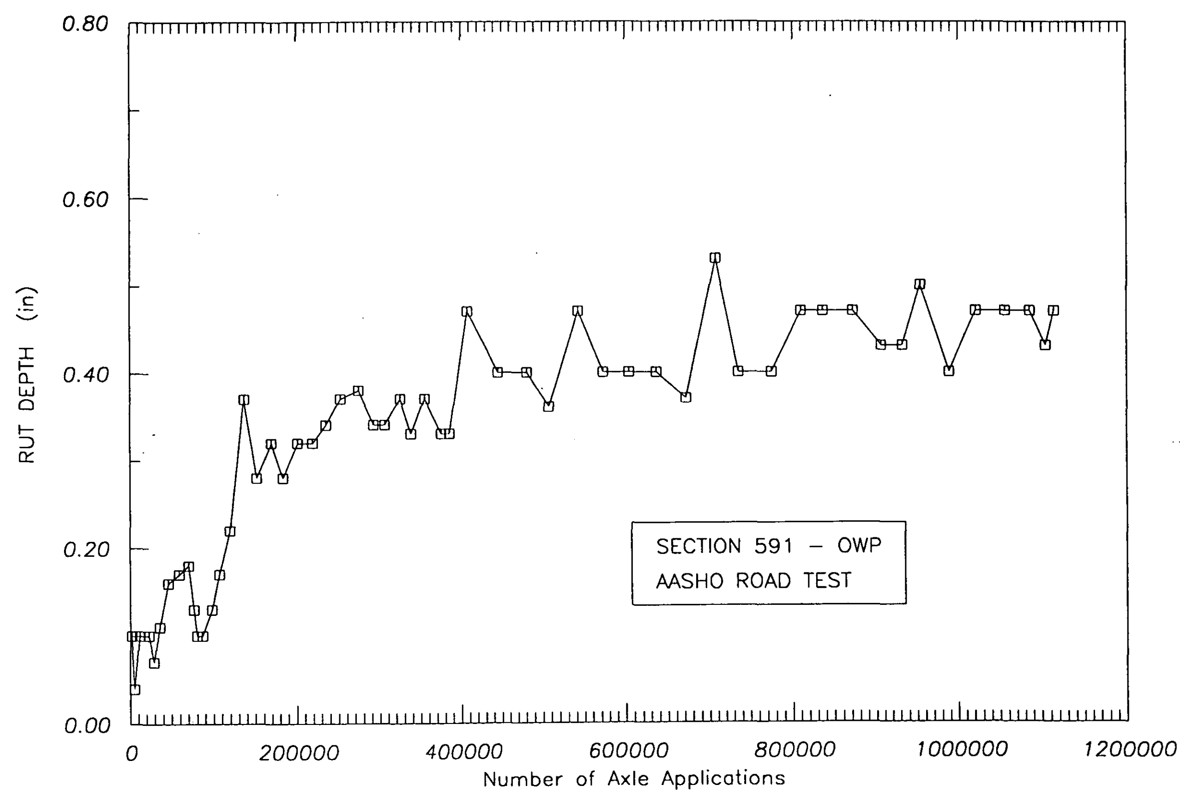

FIGURE 1 Rut depth versus N for Section 591.

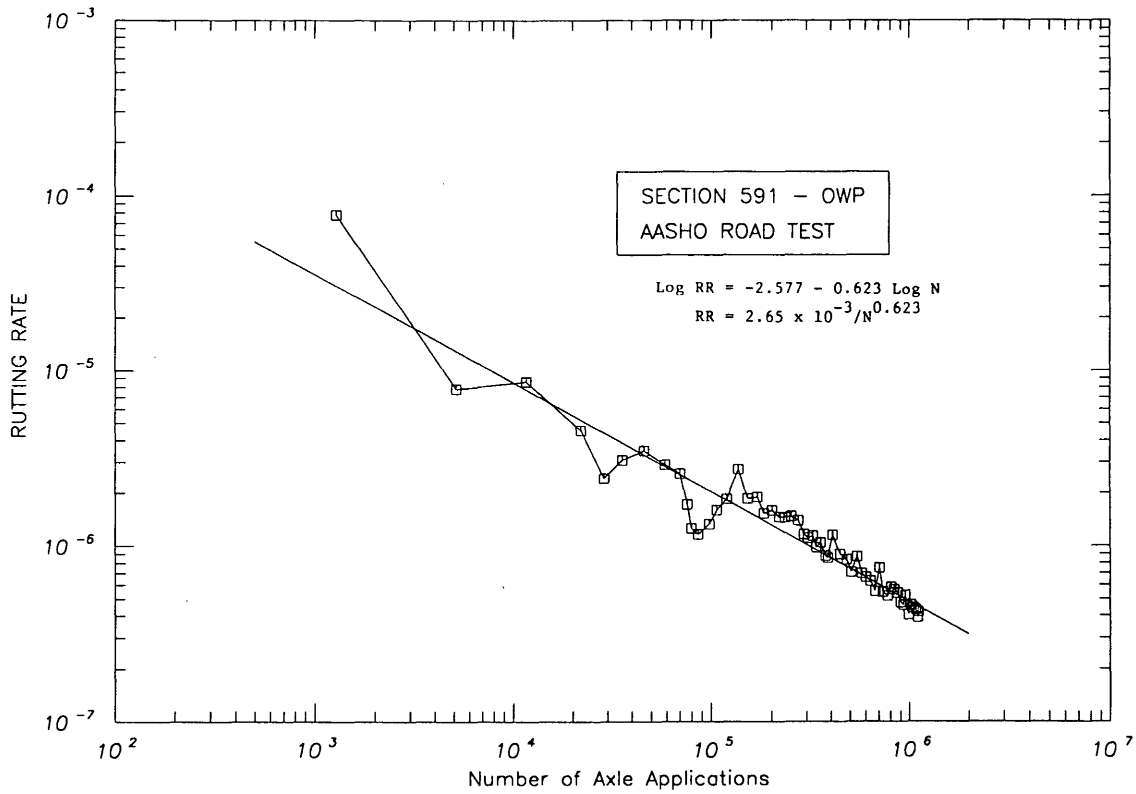

FIGURE 2 Log rutting rate versus log N for Section 591.

Table 1 is a summary (for all of the sections analyzed) indicating the veracity of the RR model. Statistically significant (α = 0.05) relations were obtained for 182 of the 192 cases (95 percent).

A strong relation (see Figure 3) was noted for the AC/granular sections on an arithmetic plot between B and **A**, regardless of axle loading. A B–log **A** plot and related regression equation are shown in Figure 4.

Figure 4 is for the entire data base summary including the bituminous wedge sections. The data in Figure 4 are for a range of single-axle loads (12 to 30 kips), pavement cross sections (surface, base, and subbase thicknesses), and pavement types (conventional flexible and full-depth type AC wedge sections).

TABLE 1 Rutting Rate Analysis Results

AASHO Loop	Axle Load (kips)	Number of Sections	Number of Significant Relations*
3	12.0	26	25
3-wedge	12.0	16	15
4	18.0	60	59
5	22.4	40	39
5-wedge	22.4	16	11
6	30.0	18	17
6-wedge	30.0	16	16
		192	182

*Statistically significant regression at α = 0.05.

The effects of axle load on the **A** parameters are shown in Figure 5 for similar AC/granular pavement sections. Note that for the 5-in. surface, 6-in. base, and 12-in. subbase section (the strongest section), **A** values do not increase with axle loading.

If the **A** term in the RR model can be related to pavement structural responses (stress, strain, and deflection), the B term can be estimated from the regression equation shown in Figure 4. Thus, a viable rutting algorithm can be developed for use in a priori design and pavement management system activities.

Thompson and Elliott (*13*) have developed algorithms based on ILLI-PAVE for estimating the 9-kip wheel loading structural responses of conventional flexible pavements. Extensive analyses of the Loop 4 AASHO Road Test data were conducted by Elliott and Thompson (*14*) in the development of mechanistic design concepts and procedures for the Illinois Department of Transportation. Representative seasonal values for AC moduli and subgrade moduli (E_{Ri}) were established, as indicated in the following table:

Season	*AC Modulus (ksi)*	*Subgrade E_{Ri} (ksi)*	*Estimated Unconfined Strength (psi)*
Spring	1,340	1.4	8
Summer	340	3.1	12
Fall	700	5.4	17

Pertinent structural reponses [surface deflection, subgrade deflection, subgrade strain, subgrade deviator stress, and subgrade stress ratio (SSR = deviator stress/unconfined strength)] were estimated for all of the Loop 4 sections for spring, summer, and fall conditions. Winter conditions were

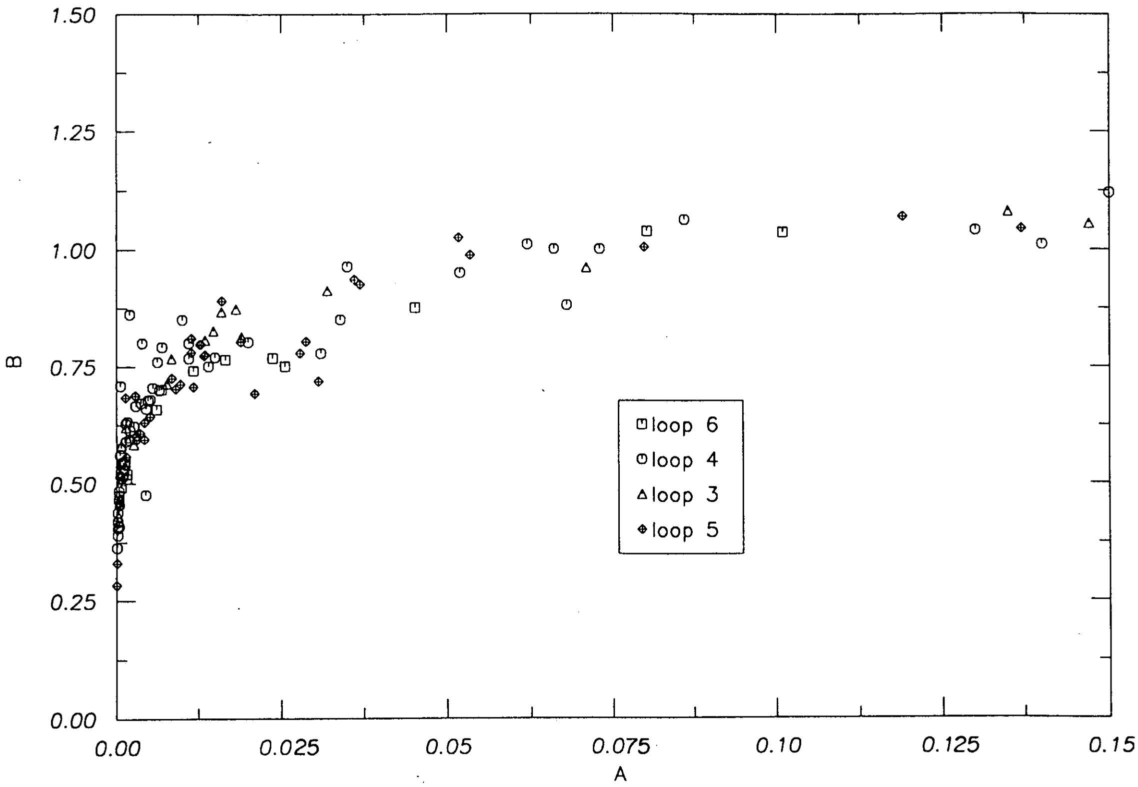

FIGURE 3 ***B*** **versus A for AASHO Loops 3 through 6.**

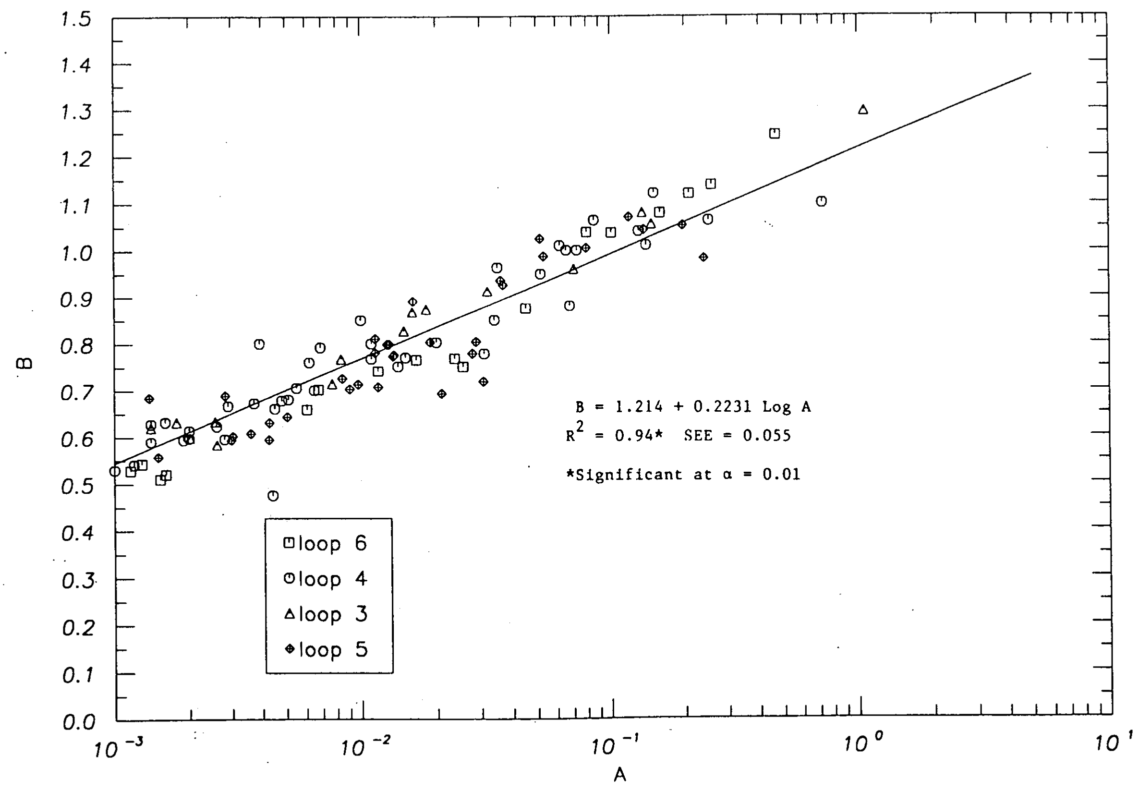

FIGURE 4 ***B*** **versus log A for AASHO Loops 3 through 6.**

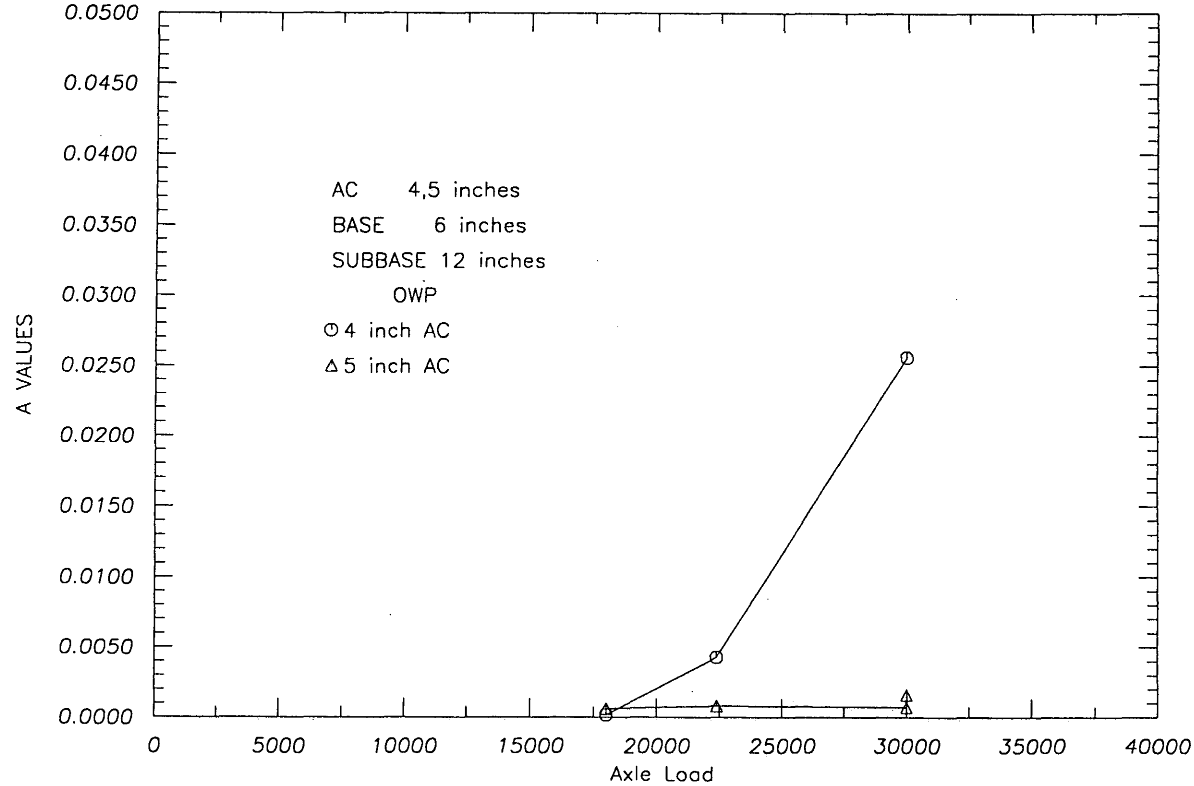

FIGURE 5 A versus axle load.

not considered. Rutting generally does not significantly increase during the winter period since, compared with other seasons, the AC stability is large and the modulus and shear strength of the frozen base/subbase materials and frozen subgrade are very high. It is generally conceded that the stress states calculated for the granular base and subbase layers are not particularly accurate. However, the response factors listed above are indicators of the stress state in the granular layers.

Selected plots of **A** versus subgrade stress ratio, surface deflection, and subgrade strain were examined. The plots (as shown in Figure 6 for the **A**–subgrade stress ratio relation for Loop 4) all indicate threshold type relations. For pavement structural responses less than a certain value, low **A**'s are noted. As the structural response values increase above the threshold value, erratic and inconsistent trends are noted, and the **A** relation is not well defined.

The data base was analyzed using the SPSS statistical package. Simple correlation results indicated that the spring structural responses are the most effective indicators of **A**.

Figure 7 indicates that low **A**'s are typical for spring subgrade stress ratios less than about 0.4. For the Loop 4 data base and subgrade stress ratios < 0.4, the average **A** is 1.08×10^{-3} (standard deviation of 1.29×10^{-3}) and the average B is 0.512 (standard deviation of 0.09).

Stepwise linear regression was used to establish relations between **A** and spring pavement structural reponses for those cases where the subgrade stress ratio was > 0.4. The subgrade stress ratio term was the first and only variable selected. Figures 8 and 9 show **A**–subgrade stress ratio relations and regression equations. Note the large standard errors of estimate associated with the regression equations. The equations are not good predictive equations even though they are statistically significant. Significant ($\alpha = 0.05$) regression equations were also obtained for **A**–surface deflection and **A**–subgrade strain relations, but their associated standard errors of estimate were equal to or greater than those for the **A**–subgrade stress ratio relations.

Figures 10 and 11 are plots (Loop 4 data) of number of load applications to a PSI of 1.5 versus **A**. For those sections that survived the total traffic (1.1×10^6 for Loop 4), the terminal PSI was greater than 1.5. Those sections with large **A**'s did not sustain more than about 100,000 load repetitions before reaching a PSI of 1.5. A plot for the combined data base (Loops 3 through 6) is shown in Figure 11. Similar trends are noted for all of the loops. It is apparent that high levels of early life rut depth development (quantified by large **A**'s) are indicative of reduced functional life as measured by PSI. Note that low **A**'s do not ensure long pavement life. A broad range (70,000 to 1.1×10^6) of load applications to failure was obtained with **A** values less than about 0.01. Other factors such as AC fatigue obviously contributed to the varied pavement performance achieved.

RUTTING RATE ANALYSES OF REHABILITATED AASHO ROAD TEST SECTIONS

The RR model was further evaluated by applying it to rutting data from various flexible pavement sections constructed by

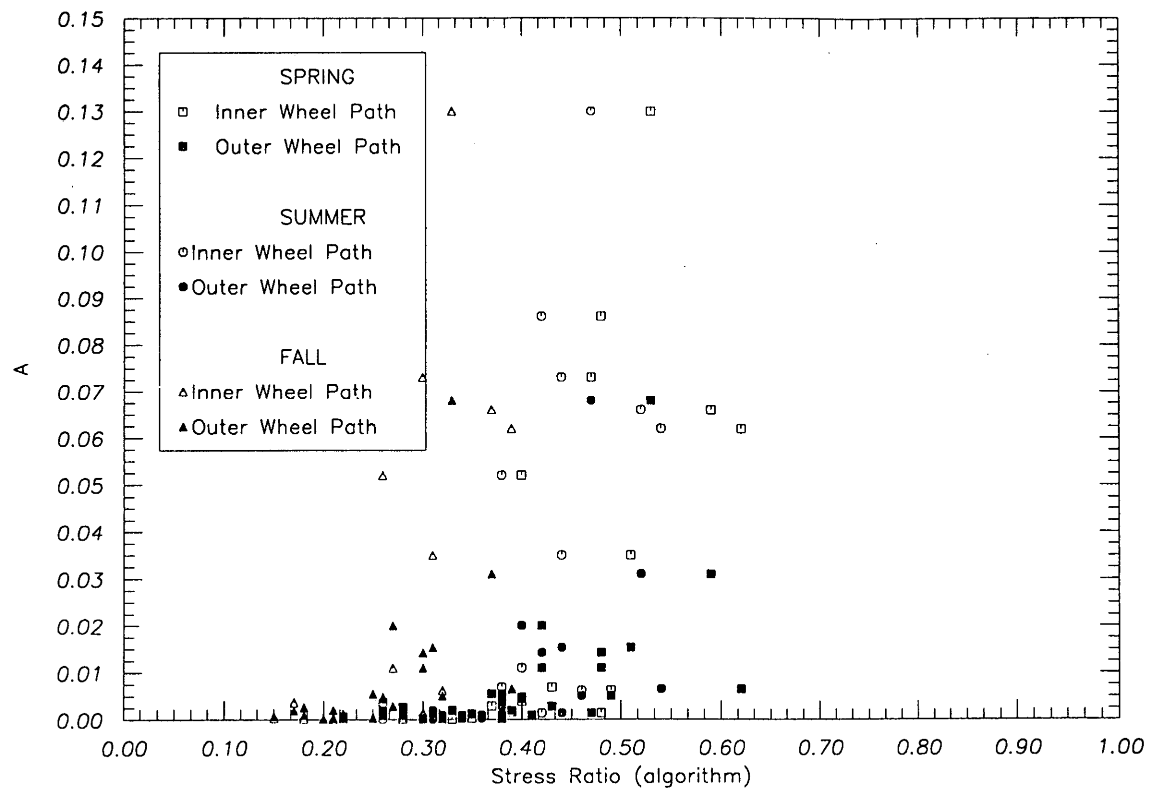

FIGURE 6 A versus subgrade stress ratio for Loop 4.

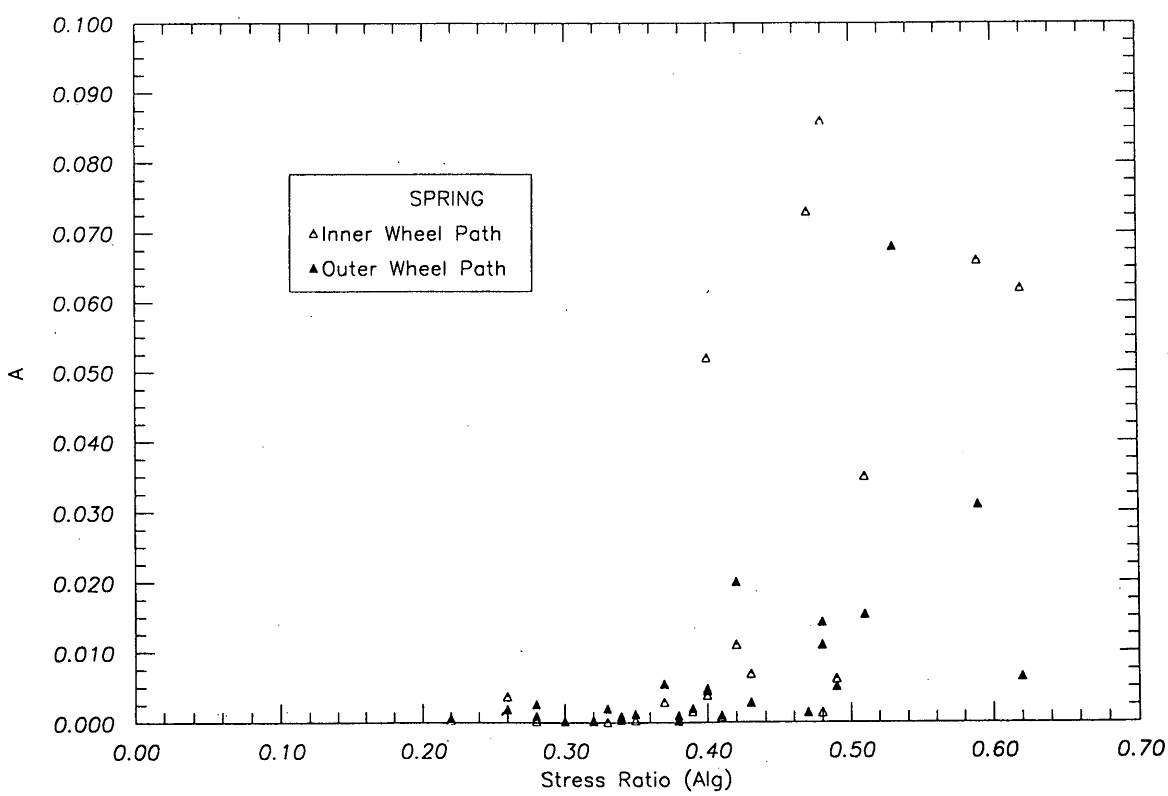

FIGURE 7 A versus spring subgrade stress ratio for Loop 4.

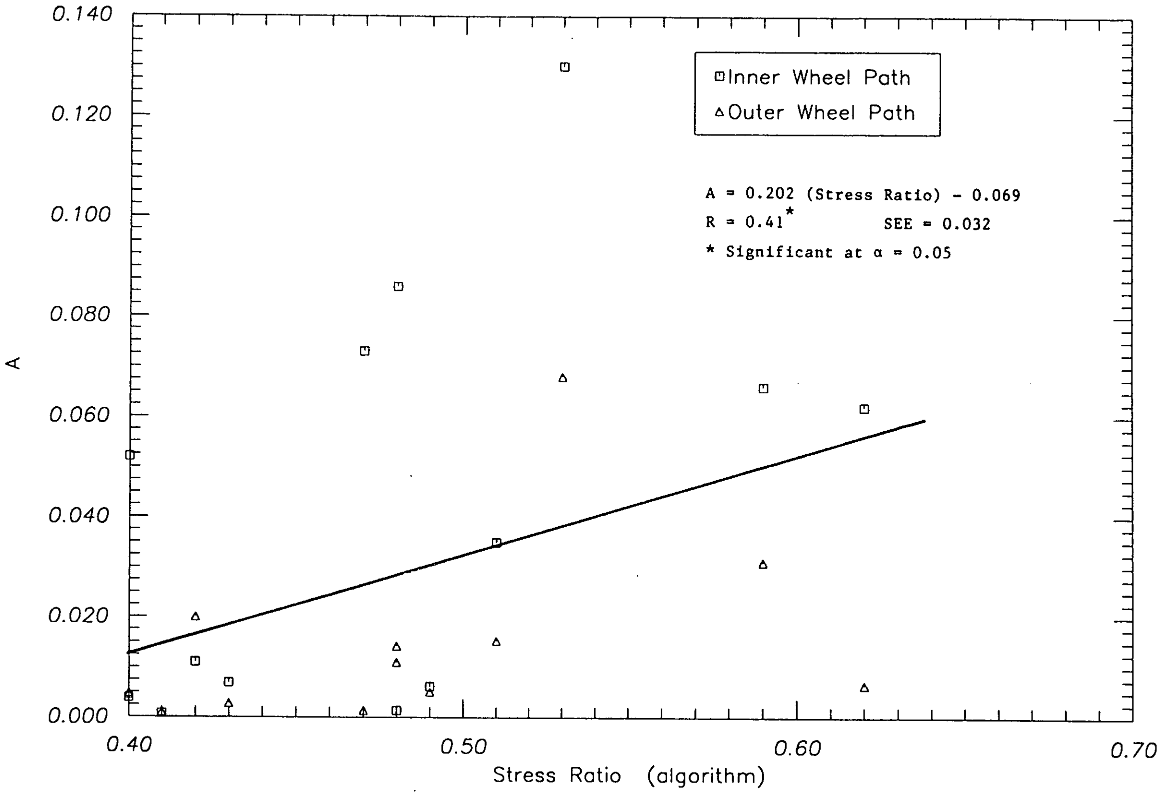

FIGURE 8 **A versus spring subgrade stress ratio for stress ratios > 0.4 (Loop 4 data).**

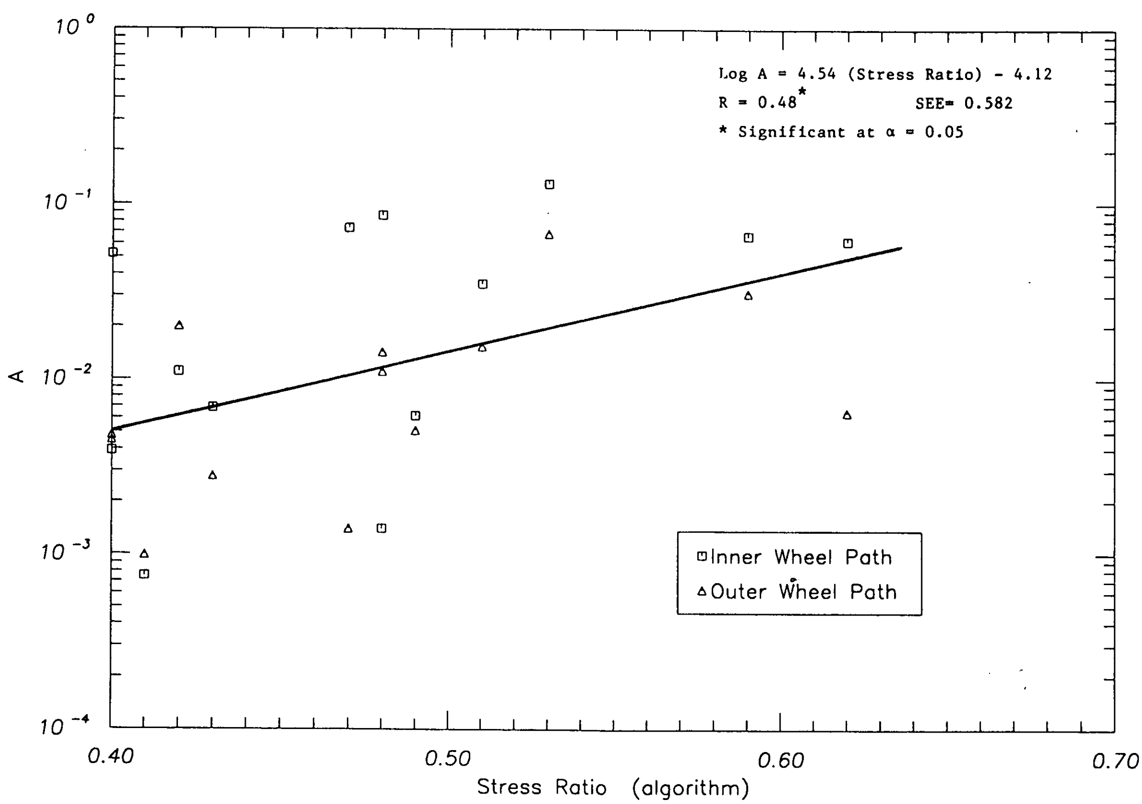

FIGURE 9 **Log A versus spring subgrade stress ratio for stress ratios > 0.4 (Loop 4 data).**

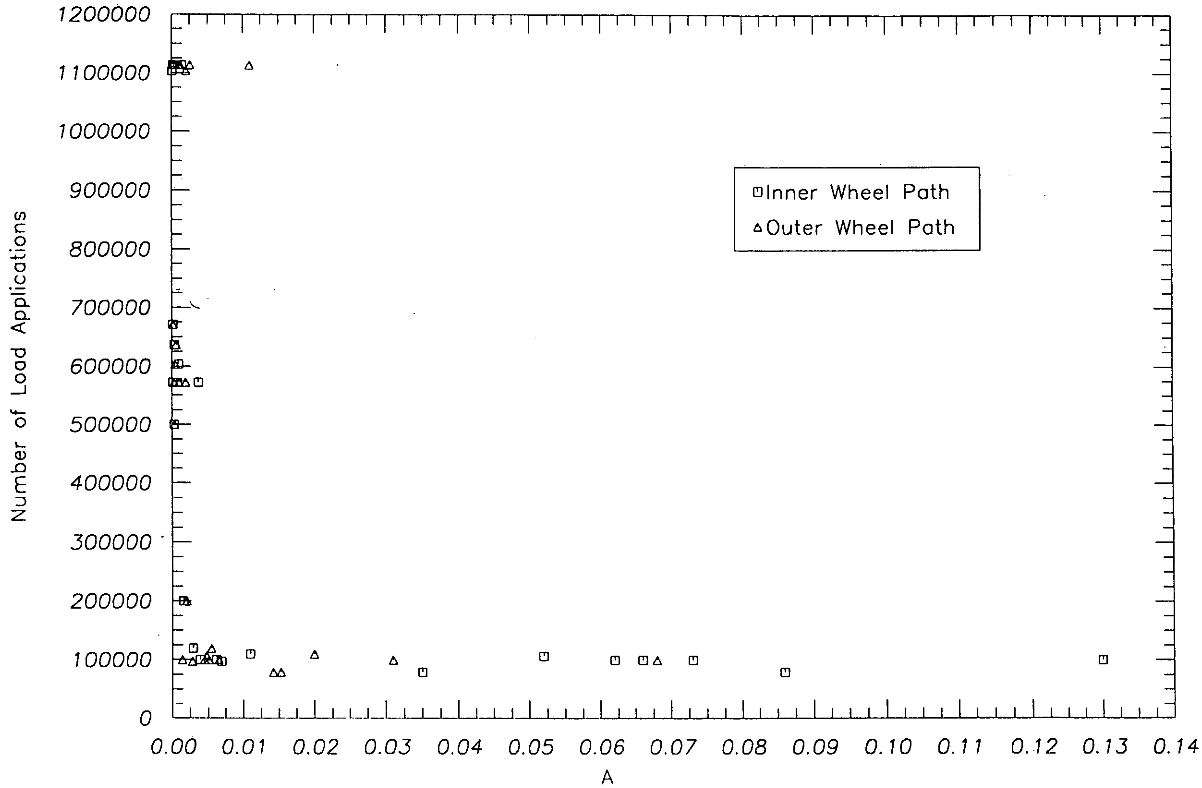

FIGURE 10 Number of load applications to failure (PSI = 1.5) versus A (Loop 4 data).

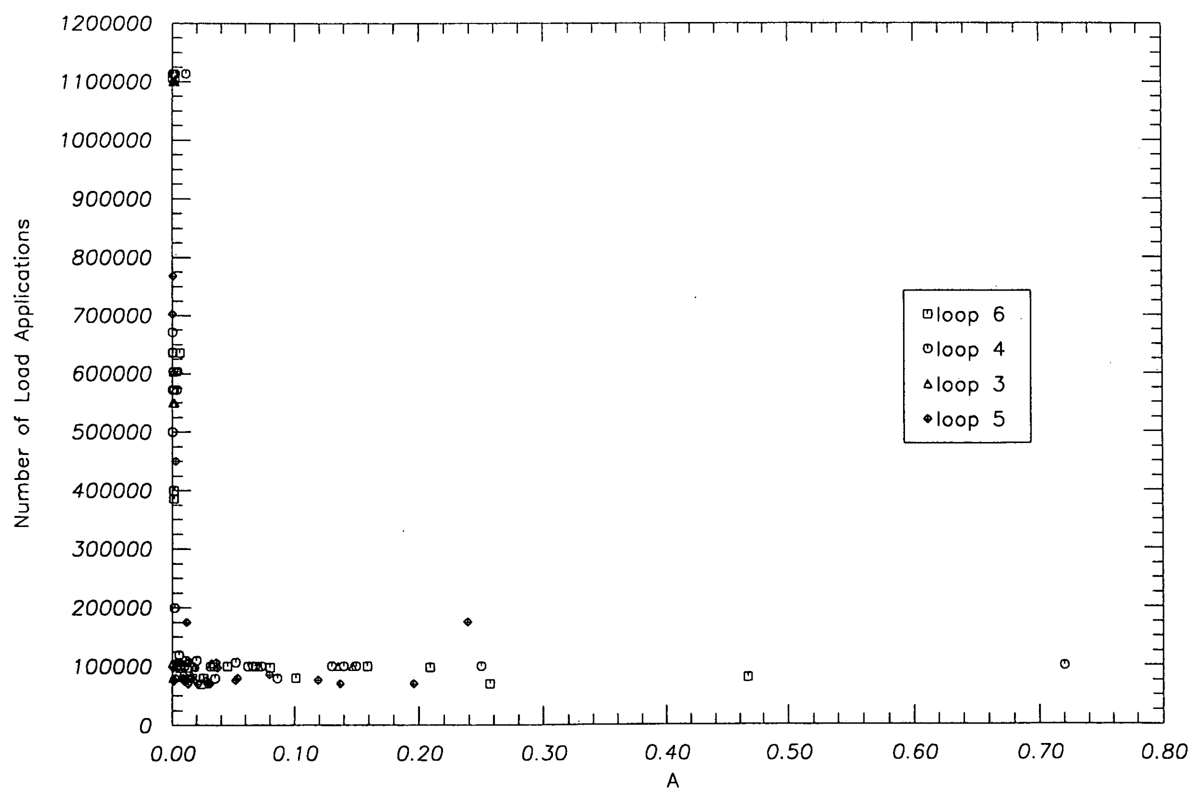

FIGURE 11 Number of load applications to failure (PSI = 1.5) versus A (entire data base).

the Illinois Department of Transportation as part of the AASHO Road Test rehabilitation program. Before incorporating the Road Test tangent sections into current I-80, considerable pavement rehabilitation and reconstruction were required (*15*).

Two new flexible pavement sections were built as duplicates of original flexible pavement designs (Sections 581 and 625) in Loop 4. Section 581 was 5-in. AC surface, 6-in. crushed stone base, and 12-in. sandy gravel subbase. Section 625 was 4-in. AC surface, 6-in. crushed stone base, and 12-in. sandy gravel subbase.

Salvaged crushed stone and sandy gravel subbase from the AASHO pavement sections were used in the reconstruction. The AC surface was a standard (for the 1960 era) Illinois Class I material. A new section of conventional flexible pavement was also constructed. The pavement section was 4.5 in. of Class I AC, 8.5 in. of dense-graded crushed stone base (Illinois Specification Grade 8), and 23 in. of dense-graded gravel subbase (Illinois Grade 7).

Annual pavement condition surveys were conducted by the Illinois Department of Transportation from 1962 to 1974, when the sections were overlaid to correct surface rutting conditions. Mixed traffic data were also collected. Mixed traffic was converted to 18-kip ESALs on the basis of AASHO equivalency factors for a terminal PSI of 2.5.

Rut depth development data for the reconstructed duplicate sections were analyzed using the RR model. Figure 12 shows the rut depth–ESAL relations for the various sections. The data are for the outer wheelpath (OWP). OWP rutting data for the original AASHO sections are also shown for comparison. Rutting rate–ESAL relations are shown in Figure 13. The RR model **A** and *B* parameters are shown in Figures 14 through 16 for the various sections (the regression relations are significant at $\alpha = 0.05$).

The excellent agreement of RR between the performance of the original and reconstructed sections is encouraging. The average *B* value was 0.504 (standard deviation = 0.027), and the average **A** was 4.44×10^{-4} (standard deviation = 3.4×10^{-4}). The **A** term showed more variability since the pavement section (and thus the pavement structural responses) are different. The original AASHO traffic (1.1×10^6 axle loads) was applied over a short period (September 1958 to March 1961) with 18-kip single axles, whereas the reconstructed sections received mixed traffic over a 12-year study period.

SUMMARY

Analyses of relevant portions (rut depth and number of load repetitions) of AASHO Data Base 7322 (*16*) and field performance data from the AASHO Test Site (I-80) rehabilitated and new flexible pavement sections (*15*) demonstrate that the rutting rate concept is valid. The Road Test data show that stable pavement rutting trends were related to estimated pavement structural responses, particularly the subgrade stress

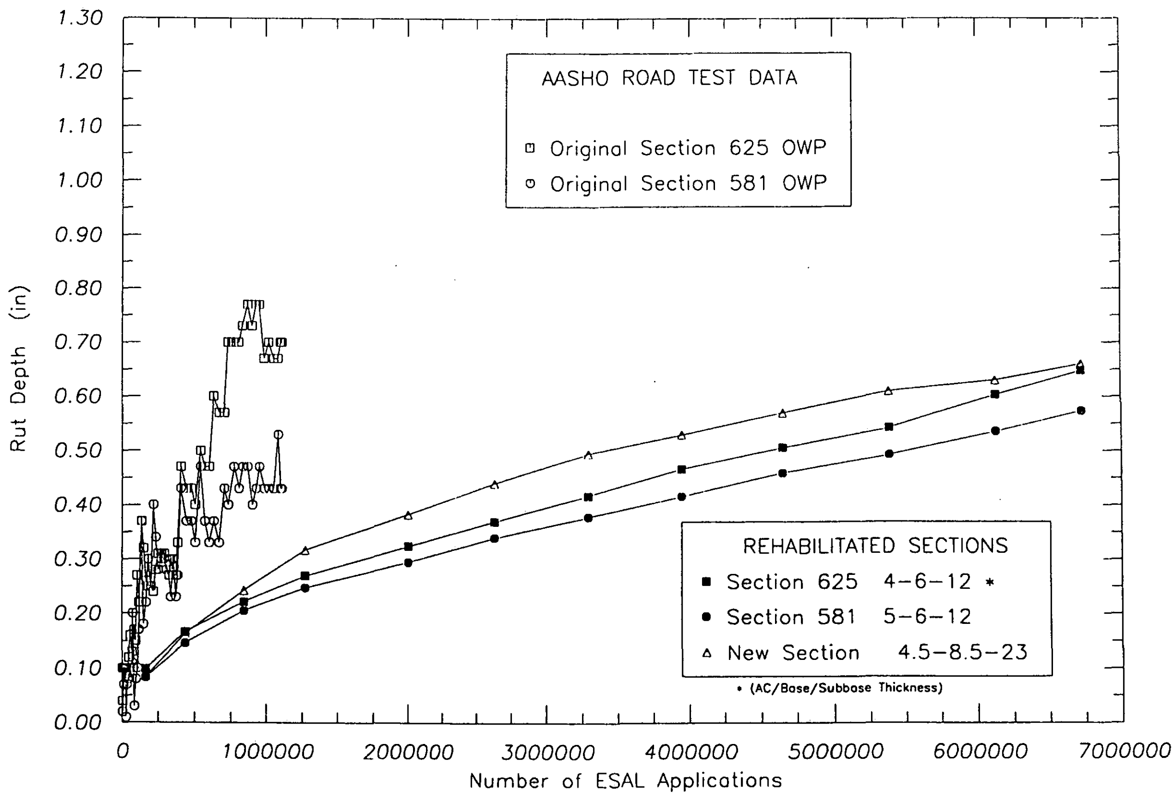

FIGURE 12 Rut depth versus 18-kip ESAL applications for rehabilitated AASHO Road Test.

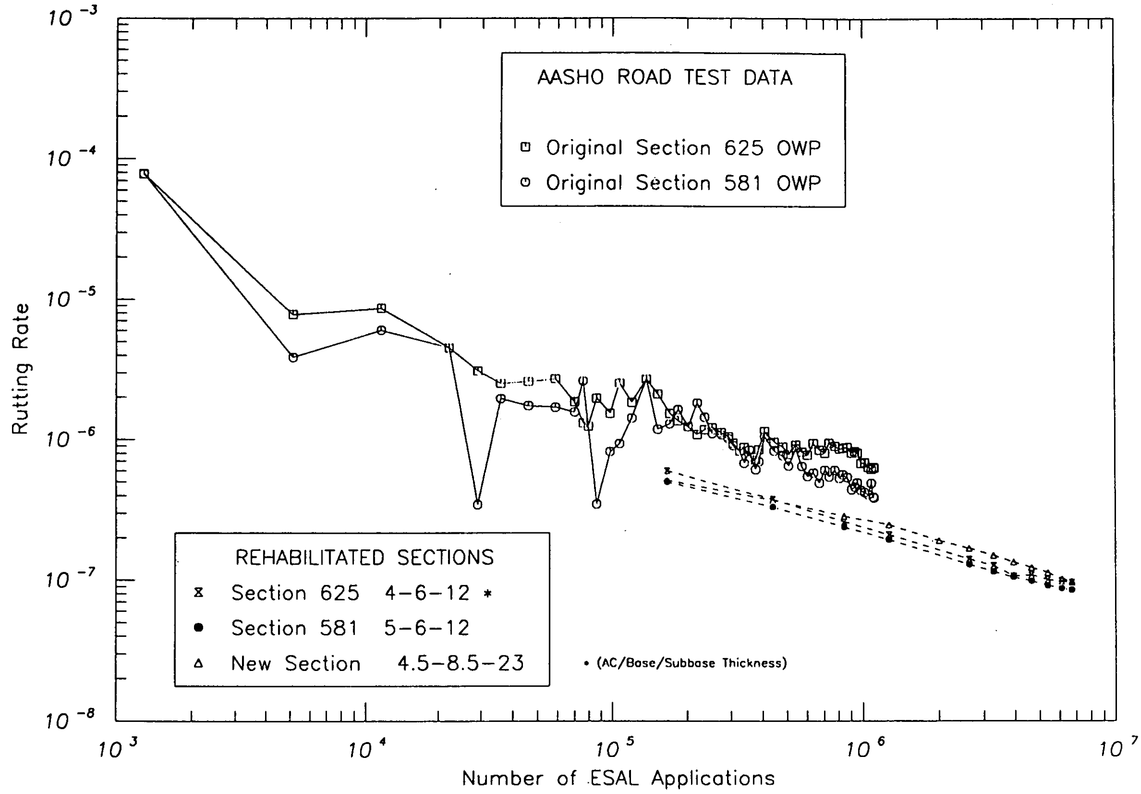

FIGURE 13 Rutting rate versus 18-kip ESAL applications for rehabilitated AASHO Road Test.

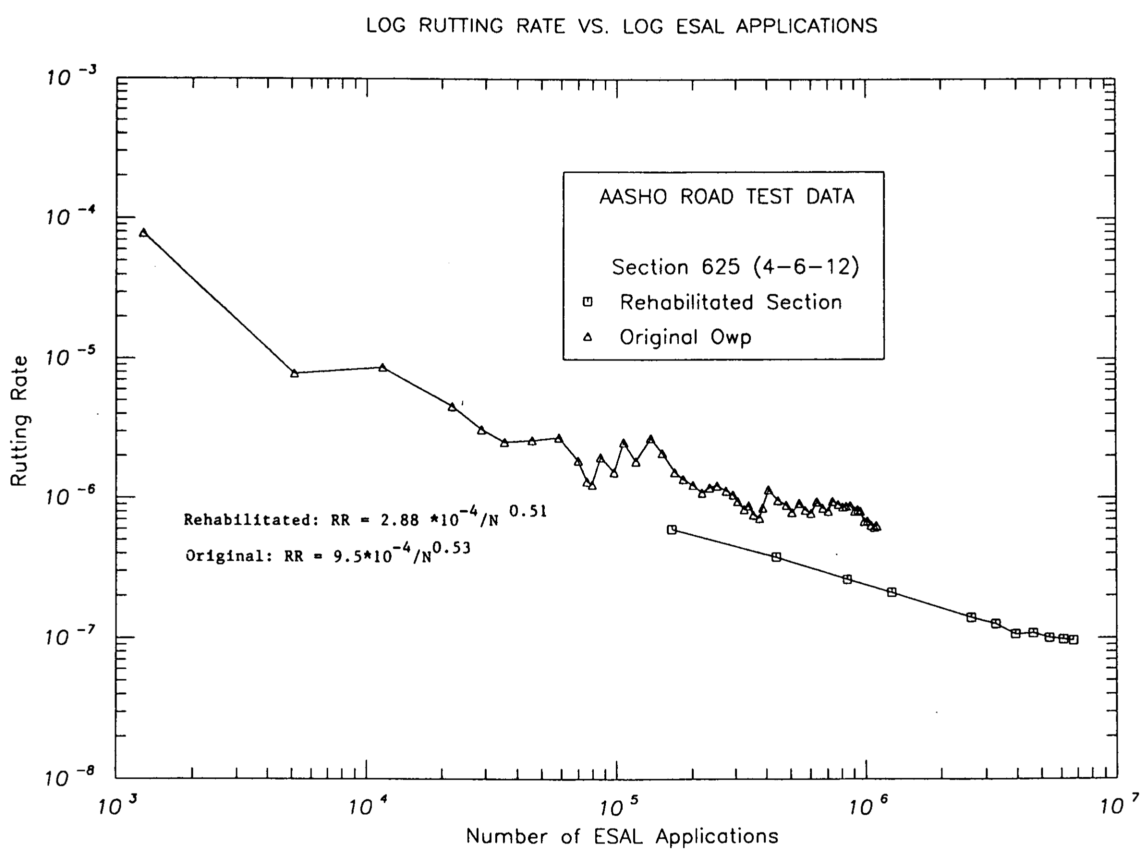

FIGURE 14 Rutting rate versus 18-kip ESAL applications for Section 625.

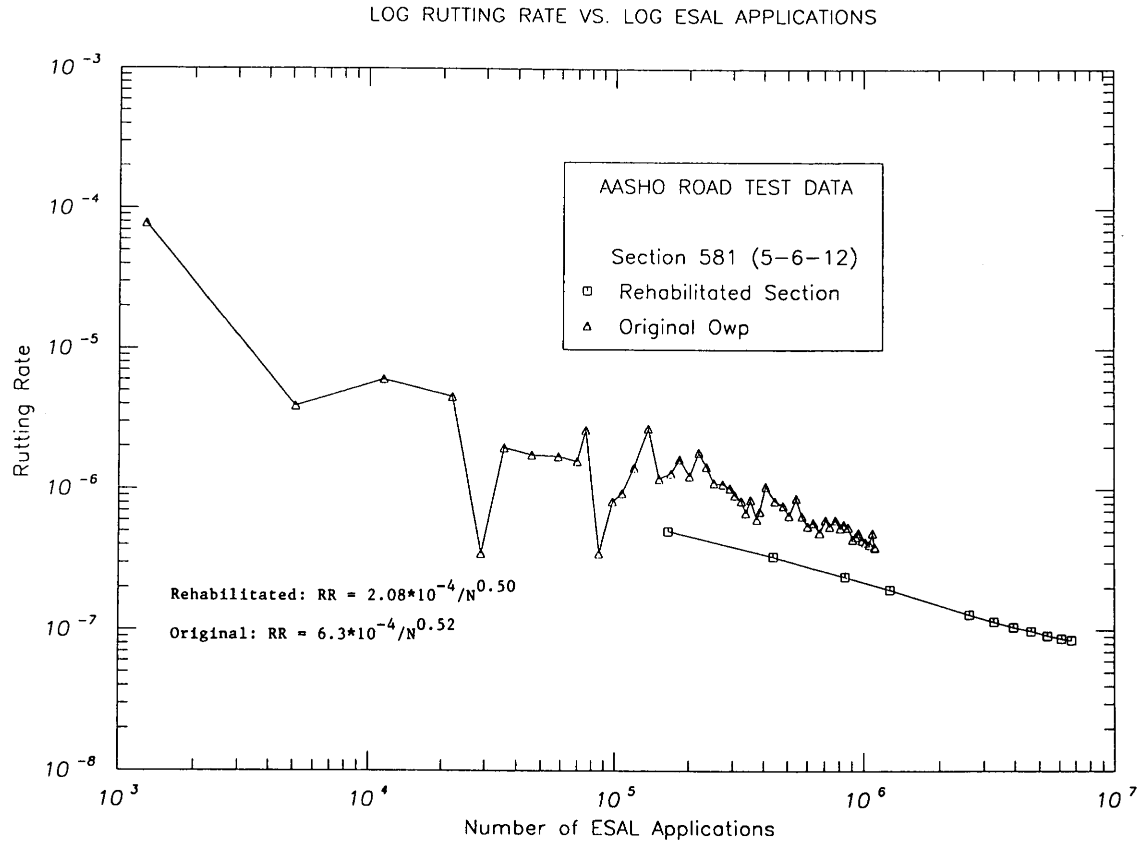

FIGURE 15 Rutting rate versus 18-kip ESAL applications for Section 581.

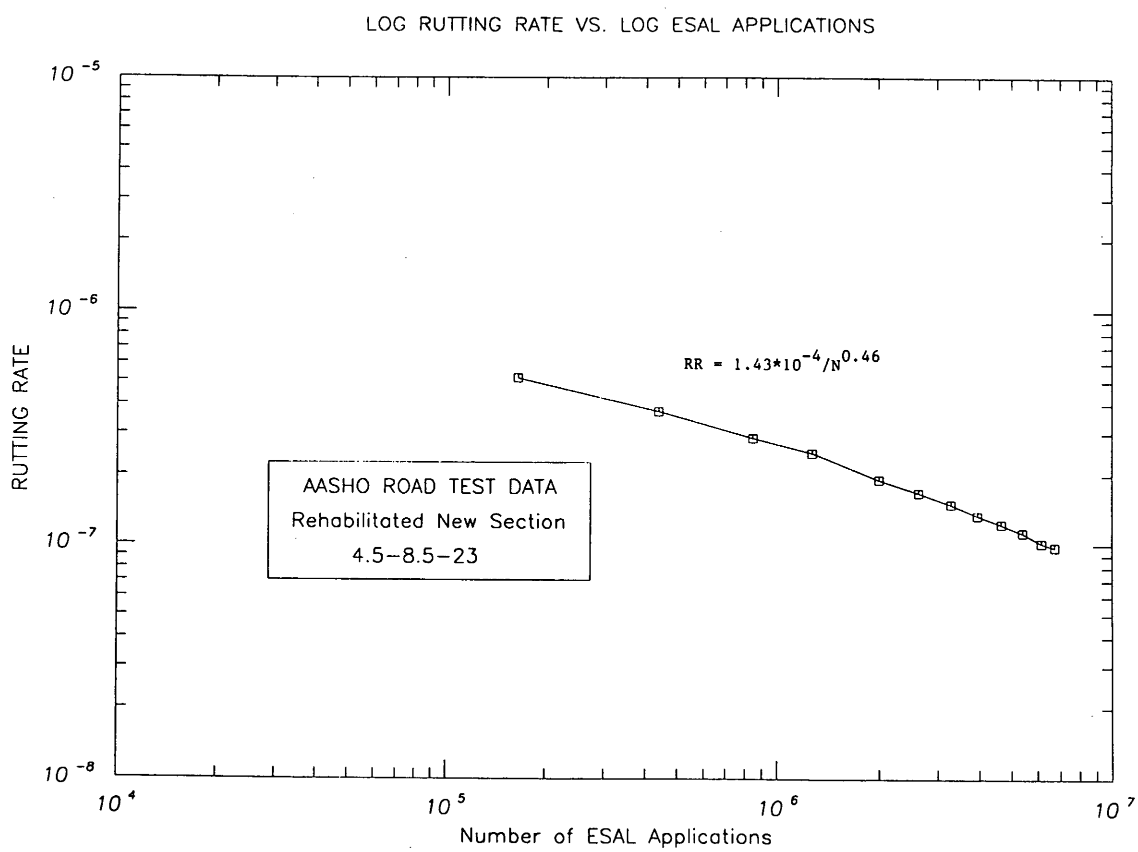

FIGURE 16 Rutting rate versus 18-kip ESAL applications for new section.

ratio. If the SSR was below a threshhold level, low **A**'s were noted. For SSRs > 0.4, a statistically significant trend (but rather inaccurate predictive equation) between SSR and **A** is noted (see Figure 9).

It is particularly encouraging to note the similarity between the rutting rate performance (the B values in the RR equation) of the original AASHO sections (AASHO Data Base 7322) and structurally similar sections constructed with AASHO materials (or very similar materials) included in the I-80 rehabilitation.

The RR approach can be effectively used in a priori pavement analysis and design and pavement management system activities. For the typical "generic specification" flexible paving materials used by a highway agency, the B terms and relationships relating structural responses to **A** can be established from a flexible pavement performance data base. In a pavement management system, the actual traffic and the development of pavement distresses are monitored. The monitoring data can be used to establish pavement distress/performance trends (i.e., rut depth-ESAL relations). The RR model is particularly helpful in analyzing the pavement rutting data for a specific pavement section and estimating future rutting for pavement management system use. As more rutting data are collected for the section, they can be used to update and refine the RR model and thus improve pavement management system predictions for the development of pavement rutting.

The concepts, principles, and analyses presented in this paper are for the specific materials and soils used in the AASHO Road Test. The approach is considered to be generally applicable to flexible pavement systems. The RR approach is a practical and easily used procedure.

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