PART 2

Developments in Flexible Pavement Design

Part 2
Foreword

Carpenter examines rutting data from the AASHO Road Test and discusses methods that can assist an agency in developing suitable procedures for using the 1986 AASHTO Design Guide without relying on the current insufficient modulus relationships for the asphalt concrete layer. Elliott examines the resilient modulus value used to represent the AASHO Road Test subgrade in the AASHTO flexible pavement design equation and finds that appropriate values for noncohesive soils need further study. Hossain et al. describe the 5-year performance of a porous pavement built to store storm water: the pavement is performing well and both the water infiltration rate and the storage capacity are still above the design values. Hajek et al. present the results of a field study that investigated the performance of five pavements incorporating open-graded drainage layers (OGDLs). They determined that drainage layers will perform only as part of a properly designed internal drainage system. Romero et al. present a description of the CEDEX Road Research Center test track in Spain and the test carried out there. Bonaquist describes several of the test programs conducted by FHWA using the Accelerated Loading Facility that demonstrate the mobility and flexibility of the equipment.

Load Equivalency Factors and Rutting Rates: The AASHO Road Test

Samuel H. Carpenter

Current needs in state department of transportation (DOT) pavement design and management programs require explicit information about the development of rutting in asphalt concrete mixtures. Many state DOTs are considering implementing the 1986 AASHTO *Pavement Design Guide*, and they require guidance in analyzing mix performance as a part of pavement design. Rutting data are examined from the AASHO Road Test sections built over cement-treated bases. The recorded rut depths are analyzed to derive relationships for the asphalt mixture used during the AASHO Road Test. Load equivalency factors are derived from the rutting data clearly showing that the AASHTO rigid pavement load equivalency factors more closely indicate the development of rutting under different axle weights and configurations. The fundamental properties describing rutting potential provide data useful in comparing rutting behavior of current mixes with that developed in the AASHO Road Test.

The AASHO Road Test, conducted from 1958 through 1960, produced the major pavement design procedure in use today in the United States. Load equivalency factors (LEFs) were derived from the test for use in describing relative damage produced by different wheel loads. The LEFs from the Road Test are based on the relative decrease in serviceability caused by an increase in axle load, or number of axles. These general LEFs have not been shown to be applicable for a specific distress element, such as rutting, and there is no guarantee that one specific distress is affected to the same degree as serviceability, which is primarily roughness related. If an individual distress is being investigated, its development under mixed traffic must be demonstrated using an LEF value derived specifically for that distress. Each distress will potentially have different LEF values.

There is a concerted effort to investigate load equivalency factors and extend the AASHO Road Test values using more technologically acceptable methods of determination, such as deflection, strain, or even stress matching. Uzan and Sidess (*1*) investigated the Road Test loops with deflection and stress-based relationships to extend the AASHTO LEFs to different axle configurations and derive LEFs as a function of total pavement condition, not only the initial condition, as is the case with the AASHTO LEFs. This development allows for a more reasonable determination of axle damage occurring at some time after the pavement has been built. The study by Hajek and Agarwal investigated several methods of calculating LEFs to investigate the axle weights for different wheel configurations that would produce the same damage as a standard single or tandem axle (*2*). They clearly showed an effect of wheel spacing on all procedures. These studies all investigated the general LEF as related to loss of serviceability, as was determined in the AASHO Road Test. Each investigation recommended that mechanistic studies be used to determine distress-specific LEF values. Kenis and Cobb used the VESYS-5 program to investigate the strain and deflection relationships for LEF values under different axle configurations (*3*). They clearly demonstrated a seasonal effect on the LEF values and showed that the season of failure can have an impact on the LEF for the pavement. These LEF comparisons, however, although based on mechanistically calculated response values, were developed for the entire pavement structure, and the rutting comparisons cannot be used in conjunction with a study of rutting in asphalt concrete. The Kenis study also used constant rutting model parameters for all load levels, which is questionable given recent laboratory studies (*4*).

This paper details an investigation of several sections of the AASHO Road Test that provide rutting information relative to the asphalt concrete mixture used at the AASHO Road Test. The AASHO information consists of rutting development as a function of axle repetitions, with several axle loads and configurations being included. This analysis provides sufficient information to establish material properties relevant to rutting in the AASHO asphalt concrete mix and to calculate LEFs specifically related to rutting development. The results indicate the degree of error when improper LEFs are used to evaluate field rutting performance of asphalt concrete mixtures, which could be quite large. The analysis provides a basis for comparisons with new mixes to establish performance levels relative to those of the AASHO Road Test. Although not specifically including parameters that may have changed since the AASHO Road Test, such as tire types and pressures, the results provide a beginning point based on true field performance to establish the basis for making comparisons.

AASHO ROAD TEST SECTIONS

Three of the six loops at the AASHO Road Test contained cement-treated base sections with asphalt concrete surfacing—Loops 4, 5, and 6. Each loop contained two sections, and each section contained four different base thicknesses, as follows:

- LOOP 4: 18-kip single axle in inner lane, 32-kip tandem axle in outer lane. Sections 557 and 563: 3-in. asphalt surface, base thicknesses of 9, 7, 5, and 3 in. in Subsections 1, 2, 3, and 4, respectively.

Department of Civil Engineering, University of Illinois at Urbana and Champaign, Urbana, Ill. 61801.

- LOOP 5: 22.4-kip single axle in inner lane, 40-kip tandem axle in outer lane. Sections 461 and 465: 3-in. asphalt surface, base thicknesses of 14.4, 11.1, 7.9, and 4.6 in. in Subsections 1, 2, 3, and 4, respectively.
- LOOP 6: 30-kip single axle in inner lane, 48-kip tandem axle in outer lane. Sections 281 and 289: 4-in. asphalt surface, base thicknesses of 16.1, 12.4, 8.6, and 4.9 in. in Subsections 1, 2, 3, and 4, respectively.

Rutting measurements on these sections provide data that can be attributed to the behavior of the asphalt concrete mixes rather than the stabilized base. This assumes that the cement-treated base does not fail and allow a general shear failure in the pavement structure. If rutting behavior can be established from these sections, any resulting behavioral descriptors should relate solely to the asphalt concrete mixture. These results would provide a baseline of AASHO material performance against which new materials can be compared.

As reported in Transportation Research Board Special Report 61E (*5*), the thinner bases exhibited failure. This was evident in the data, which will be presented shortly. For these reasons, Sections 3 and 4 were eliminated from the study.

ANALYSIS PROCEDURE FOR RUTTING MODELS

Models

The first requirement for this analysis is to use a model that can accept field and laboratory data and to develop similar material properties from the analysis. Although there are some highly complex theories, several phenomenological models describe general rutting behavior in asphalt concrete mixes and are suitable for laboratory and field studies. The following equation can be used to characterize either permanent strain or rut depth:

$$\varepsilon_p = AN^B \quad (1)$$

where

ε_p = permanent deformation, strain, or rut depth;
N = number of load repetitions; and
A,B = material properties.

As developed by Khedr (*6*), the rate of rutting can be expressed by

$$\varepsilon_p/N = AN^{B'} \quad (2)$$

where B' is equal to $B - 1$.

Section Data

The rutting rate model is most applicable to the study being conducted here because it allows a determination to be easily made relative to general pavement failure, or the onset of unstable mixture performance, and has been shown to function equally well in the laboratory and field for establishing material properties (*7, 4, 6*). Figure 1 contains the permanent strain rate [(rut depth/thickness)/N] plots for Section 557 (18-kip single axle) of the AASHO Road Test, with all subsections shown.

The failure of the base is clearly evident in Sections 3 and 4 when the data take an abrupt upturn at approximately 50,000 axle repetitions. The thick base Sections 1 and 2 carried the axle load to 1 million repetitions with no evidence of failure. The same trend is evident in Figure 2 for Loop 6, inner lane, a 30-kip single-axle section. These data support the findings of the Road Test that indicated base failure in the thin sections.

To allow general comparisons of different thicknesses, the rut depth measurements were converted to permanent strain by dividing by the asphalt thickness. For thicknesses in the 3- to 4-in. range, this is acceptable. Comparisons of thicker sections (6 in. of asphalt concrete or more) raise questions, because the thicker sections may not develop significant rutting in the lower depths and these lower depths should probably not be included in an analysis to compare mix performance. However, there is no analytical procedure today to allow this separation. The data for both subsections in a loop were combined and a regression analysis was performed on the resulting data set for that section or lane. The A and B' coefficients resulting from this analysis are given in Table 1.

The A and B' coefficients from this analysis are mix parameters that define the rutting behavior of the asphalt concrete mixture used in the AASHO Road Test. The values from each loop are representative of mix performance under the stress state induced by the different axle configurations, the climate of the 2-year test period, and loadings present on the different lanes and loops. Differences in the coefficients are attributable to the loading conditions on each loop or lane and not to mix differences, because great care was taken in the Road Test to ensure material uniformity.

The averaged A and B' values for each loop were then used to calculate the rut depth accumulation curves for each loop and axle configuration using Equation 2. The calculated rut depth accumulation curves for a 3-in.-thick layer are shown in Figure 3 for tandem axles and in Figure 4 for single axles.

DEVELOPMENT OF LEFs FOR RUTTING

To develop the LEFs, the rut depth accumulation curves for each axle type are required. An LEF is defined as the number of load repetitions of a standard axle [18-kip equivalent single-axle load (ESAL)] to produce a defined level of damage (rut depth) divided by the number of load repetitions of another axle load or configuration to produce that same level of damage.

In this analysis, rutting has been singled out as the sole variable to investigate for its relationship to axle loads. Damage levels considered as failure in a rutted pavement can vary between agencies, and for this evaluation three rut depths were selected for comparison: 0.3, 0.4, and 0.5 in. The load repetitions calculated for each axle load and configuration to produce the assigned level of rutting in a 3-in. pavement surface constructed with the AASHO Road Test asphalt concrete mixture are shown in Table 2.

With the 18-kip ESAL as the standard and the LEF calculated for each axle, the LEFs for rutting were obtained by

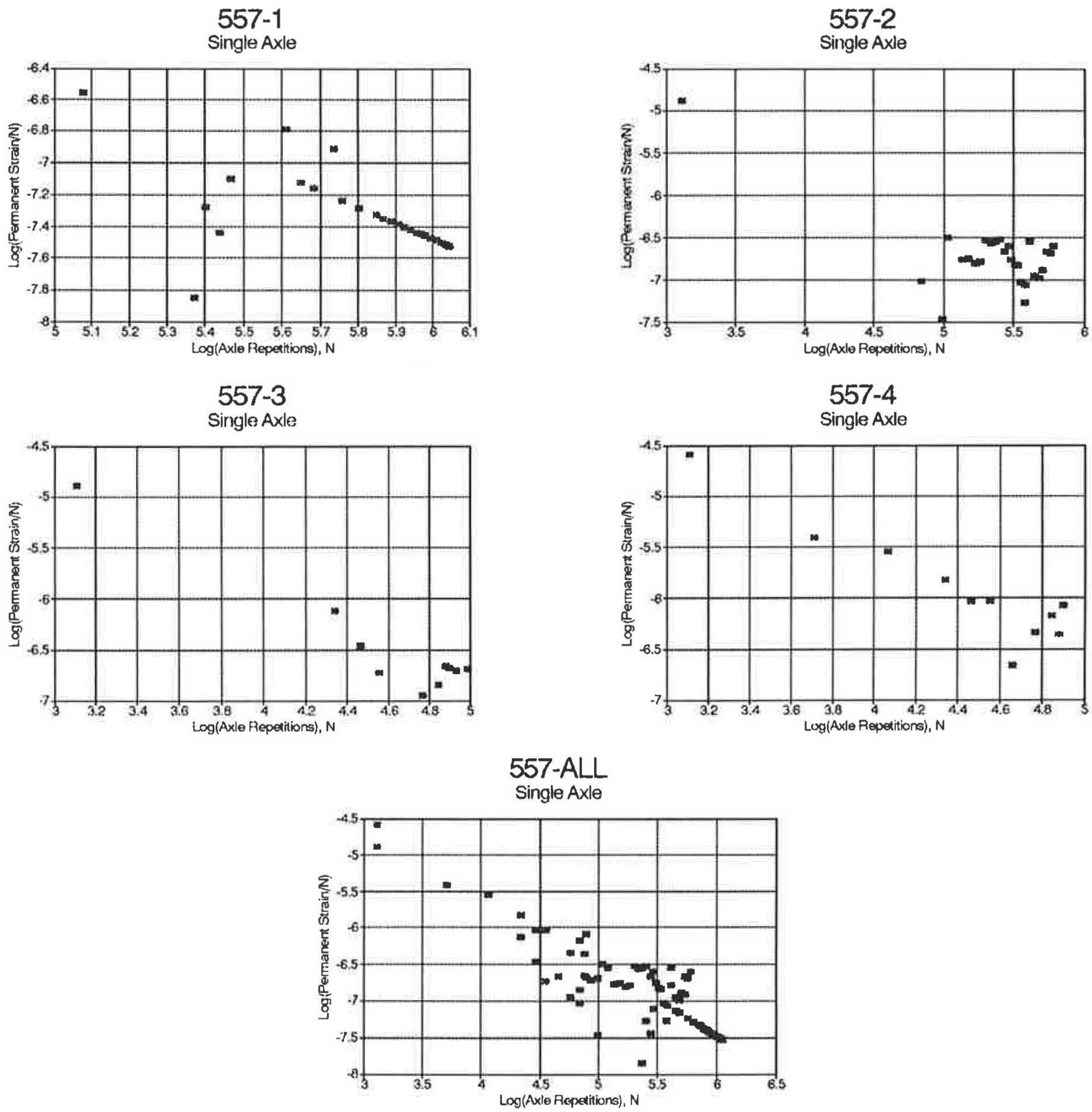

FIGURE 1 Rut data for AASHO Road Test, Loop 4, Section 557, inner lane.

dividing by the appropriate axle repetitions. These LEF values are given in Table 3.

A preliminary evaluation of the adequacy of these LEF values can be made by comparing them with the standard AASHTO LEF values. Figures 5 and 6 show the comparison of the rutting LEFs for the single-axle data for a flexible and a rigid pavement, respectively. This comparison indicates that single-axle rutting LEFs follow those for a very thick flexible pavement (P_t = 2.5) or for a relatively thin concrete pavement quite precisely for the 0.5-in. rut depth failure criteria. If smaller rut depths were chosen as the failure level, the LEF values would be smaller, necessitating use of LEF charts for thinner concrete or thicker flexible pavements.

The comparison of the rutting LEF values for the tandem axles indicates quite a different performance picture. Figures 7 and 8 compare the tandem-axle rutting LEF values for rigid and flexible pavements, respectively. The relationship for the rigid pavement, thin slab, is again very close to that of the AASHTO LEFs. The notable exception is the heavy 48-kip tandem axle. Given the excellent correlation for the lighter tandem-axle and single-axle loads of similar magnitude and the fact that these similar loads did not cause the pavement to fail, the indication is that tandem-axle loads at these levels produce significantly higher damage due to rutting than other distresses such as roughness. The LEF comparison in Figure 8 for flexible pavement indicates that the flexible AASHTO LEF values are seriously in error when applied to rutting, with the tandem LEF values for flexible pavements being very low as compared with the values determined from the field data.

The AASHO Road Test data analyzed here indicate that the LEF for rutting accumulation in an asphalt concrete mix

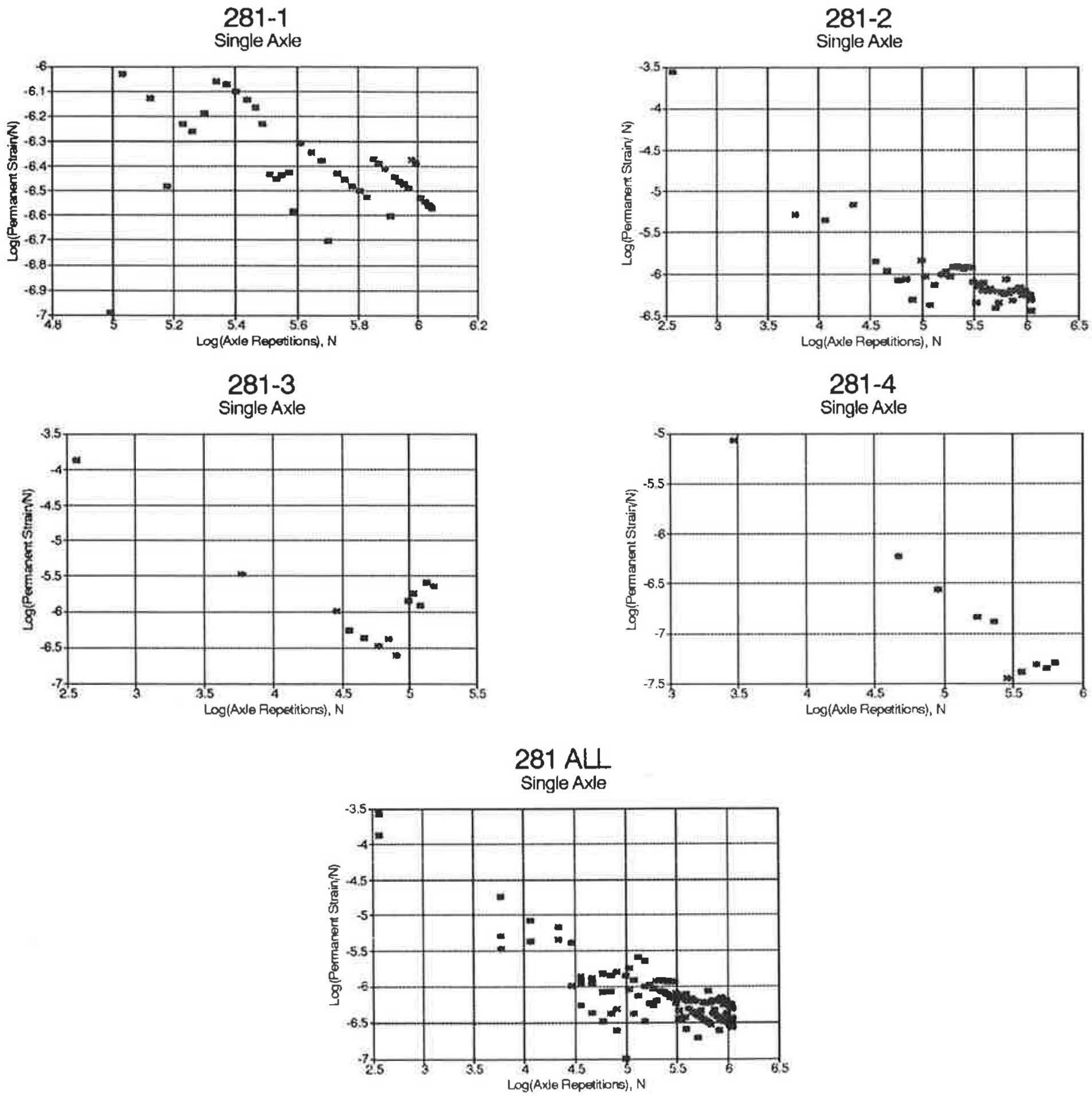

FIGURE 2 Rut data for AASHO Road Test, Loop 6, Section 281, inner lane.

TABLE 1 Regression Analysis of AASHO Road Test Rut Data

		SINGLE AXLE			TANDEM AXLE		
LOOP	SECTION	A	B′	R^2	A	B′	R^2
4	557	-2.6801	-.7800	.59	-2.4408	-.7909	.83
4	563	-3.5947	-.5908	.42	-3.0560	-.6714	.72
5	471	-3.2364	-.6792	.55	-3.1948	-.6675	.73
5	465	-4.0637	-.5098	.47	-3.7730	-.5527	.54
6	281	-3.6365	-.5732	.69	-2.7493	-.6110	.76
6	289	-2.7244	-.7607	.62	-2.8500	-.7039	.85

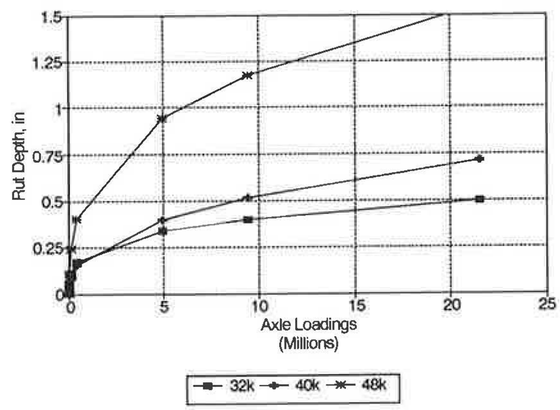

FIGURE 3 Rut accumulation curves for tandem-axle sections.

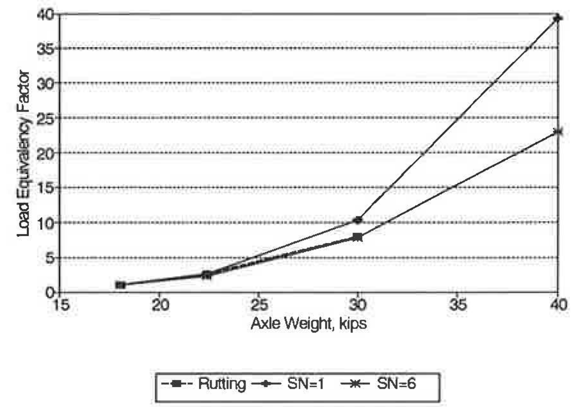

FIGURE 5 Single-axle LEFs, flexible pavement.

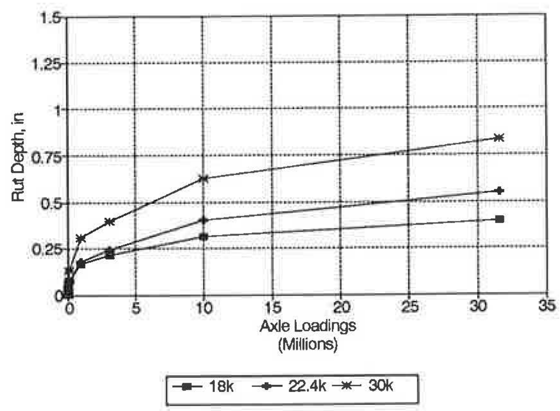

FIGURE 4 Rut accumulation curves for single-axle sections.

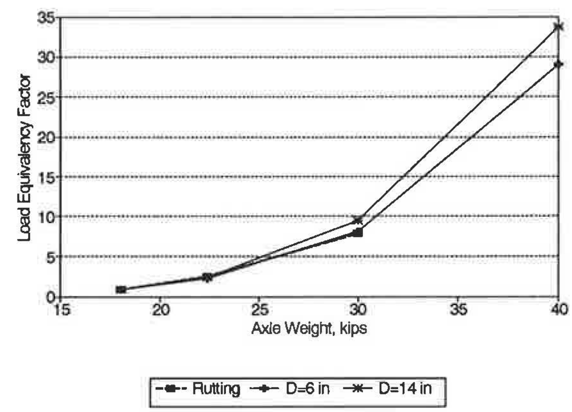

FIGURE 6 Single-axle LEFs, rigid pavement.

TABLE 2 Load Repetitions to Produce Specified Rut Depths

	LOAD REPETITIONS TO INDICATED RUT DEPTH		
AXLE TYPE	0.3 in	0.4 in	0.5 in
18 k single	6,165,950	15,310,875	30,902,954
22 k	3,548,134	7,079,458	12,105,981
30 k	954,992	2,089,296	3,890,451
32 k tandem	3,235,937	9,440,609	21,527,817
40 k	2,371,374	4,931,738	8,709,636
48 k	177,828	416,896	785,235

TABLE 3 LEFs for Rutting From AASHO Road Test

	LEF FOR SPECIFIED RUT DEPTH		
AXLE TYPE	0.3 IN	0.4 IN	0.5 IN
18 Kip single	1.0	1.0	1.0
22.4 Kip	1.74	2.16	2.55
30 Kip	6.46	7.33	7.95
32 Kip Tandem	1.91	1.62	1.44
40 Kip	2.6	3.10	3.55
48 Kip	34.67	36.7	19.09

most closely follows the level and trend established at the AASHO Road Test for the deterioration of a thin, rigid pavement. Only the single-axle LEF for rutting followed the trend of a very thick flexible pavement (SN = 6). This could be expected from a thick pavement that protects the base and subgrade from fatigue and develops little permanent deformation in the lower layers. For rutting development the tandem-axle effect on the asphalt concrete surface produces two somewhat distinct load pulses, and a tandem-axle LEF for rutting should be larger than an LEF for total damage—

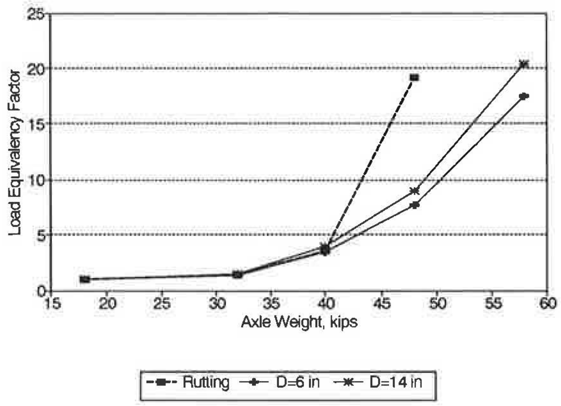

FIGURE 7 Rigid pavement LEFs, tandem axle.

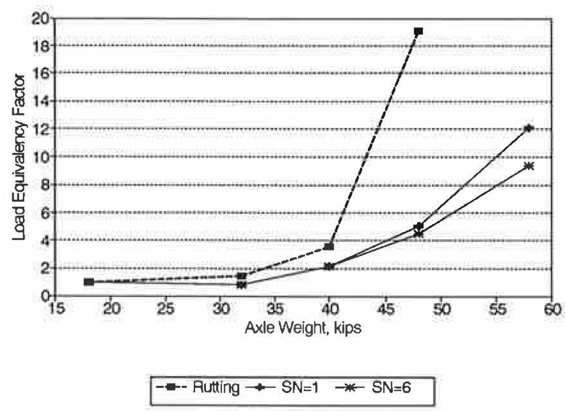

FIGURE 8 Flexible pavement LEFs, tandem axle.

much closer but not quite equal to twice the single-axle LEF value. This intuitive conclusion is substantiated by the field measurements analyzed and discussed here.

Data Anomaly

The 48-kip tandem-axle data produced LEF values that were significantly different from the consistent relationships established by the other sets of data. This is most clearly shown in Figure 7, in which the mixture has entered the unstable portion of its permanent deformation life, the tertiary mode of failure. The mix subjected to single-axle loads, even at 30 kips, did not become unstable after 1 million axle repetitions. The tandem axle, however, produces twice as many wheel loads per axle pass. This doubling of the repetitions clearly caused the bituminous mix to fail, placing it in the unstable deformation mode. This is clearly evident in the data plotted as shown in either Figure 1 or 2. There is a distinct flattening of the data above 1 million wheel repetitions (500,000 axle repetitions), indicating unstable mix behavior.

LEF Relationships

Single Axles

The two different trends in the LEF data developed in this study can clearly be seen in equations developed to relate LEF values to terminal rut depth and axle load. The relationship for the single axles is

$$\text{LEF} = 1.83 \times 10^{-5} (RD)^{0.3854} (\text{SWeight})^{3.89}$$

where

LEF = load equivalency factor,
RD = terminal rut depth selected for the criteria (in.), and
SWeight = axle weight (kips).

This relationship had an R^2 of 0.99 with a standard error of the estimate of 0.041 (on the log of the LEF). The exponent of the axle weight is very close to the standard exponent of 4 normally assigned to axle weight ratios on flexible pavements when PSI loss is examined. This relationship can be used to calculate LEF values for rutting comparisons with single axles of varying weights.

Tandem Axles

The relationship for tandem-axle loadings, excluding the heavy 48-kip weight, which indicated a failed asphalt mixture, is

$$\text{LEF} = 1.113 \times 10^{-4} (RD)^{0.0279} (\text{TWeight})^{2.778}$$

where the variables are as defined before and TWeight is the tandem-axle weight. This relationship had an R^2 of 0.87 and a standard error of the estimate of 0.075 (on the log of the LEF).

The relationship for tandem axles does not provide the accuracy of the single-axle equation and probably should not be used for calculating LEF values for tandem axles because it includes a failed mix at the high-axle-load data point. The relationship and data clearly indicate the decreased impact of increased axle loads for tandem axles as compared with increased loads for single axles.

FIELD COMPARISONS

As part of a layer coefficient study in Wisconsin (*7*), 31 flexible pavement sections were structurally evaluated. Fifteen of the 31 sections from which cores were taken were tested in the laboratory for permanent deformation. These pavement sections were relatively young, all less than 5 years of age. The 15 cores, representing virgin and recycled mixes, were carefully prepared for repetitive load testing. The A and B' parameters were determined on data taken from 5,000 load repetitions at a deviator stress level of 20 psi and a temperature of 70°F. These conditions roughly approximate the yearly conditions at the AASHO Road Test for an 18-kip single axle and allow a comparison to be made between the field mixes and the AASHO values. A more thorough examination would perform repeated load testing at several temperatures and stress levels, but such a testing program would not provide any better data for a better comparison with the AASHO mixture itself.

Using the A and B' coefficients calculated from the AASHO Road Test for the 18-kip loads in Loop 4, a probable range for these parameters can be established. The A and B' values

for the 18-kip ESAL loading on the AASHO mixture are

- Low range: $A = 1.58 \times 10^{-3}$; $B' = -0.77$.
- High range: $A = 1.00 \times 10^{-3}$; $B' = -0.69$.

The rut depth accumulation curves for a 3-in.-thick mixture were calculated for the recycled and virgin mixes. Figure 9 shows several of the virgin Wisconsin mixes with the AASHO curves superimposed. The curves were generated using rutting Equation 2 with the appropriate A and B' coefficients from the laboratory testing. These data indicate that the rutting potential of the mixes tested is generally comparable with that of the AASHO mixture, with some extremes. Each mix was compared with the AASHO mixture in terms of general rutting potential. Table 4 shows the relationship between the modulus for the Wisconsin mixes tested and the rutting potential compared with those for the AASHO mixture. On average, the stiffer mixes (486,000 psi modulus) had better rutting resistance (low rating, rut curves below the AASHO curves), and the mixes with rutting potential similar to that of the AASHO mix (curves between the AASHO low or high curves) had a modulus in the range of 426,000 psi (at 70°F), very close to the AASHTO standard mixture modulus of 450,000 psi at 68°F. The mixes with high rutting potential compared with the AASHO mix (rut curves well above the high AASHO curve) had lower modulus values (312,500 psi). This relationship is shown in Figure 10 for the various levels of rutting potential. Although there is a high degree of variability, with stiff mixtures rutting more than softer mixtures, within this data set a general statement can be made for increased rutting in a mix with less stiffness. This general statement is not a hard and fast rule that ties modulus and rutting potential together, however, because the amount of scatter in the data is relatively high.

The AASHTO structural design procedure mandates that a lower structural layer coefficient be assigned to a mix with lower stiffness than that of the AASHTO standard mix. The Wisconsin data and the data from other laboratory investigations would indicate that a less stiff mix would generate more rutting than the stiffer mix. Thus, the structural layer coefficient of a mixture should not be reduced on the basis of stiffness alone because the potential exists that a less stiff mixture may have more rutting potential and deteriorate more quickly. A more appropriate design approach is to recognize that use of a mix with less stiffness or higher rutting potential, or both, will decrease pavement life compared with the AASHO mix because of the more rapid development of rutting. With the AASHO mixture parameters and the current mix parameters developed from laboratory tests, this loss of life can be calculated and used to adjust the layer coefficient, producing a coefficient more representative of a lower-quality mix that shortens pavement life because of increased rutting. This approach provides a means of assessing the impact of the mix on pavement life, but the "adjusted" layer coefficient must never be used in an original thickness design process. Unless specific comparison tests are made on new mixes, no new layer coefficient should be assigned without some indication of field performance.

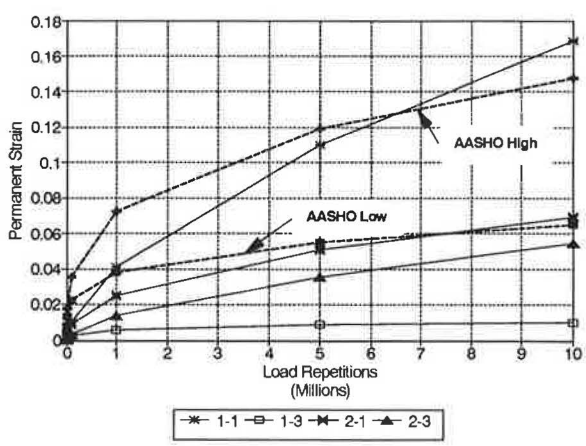

FIGURE 9 Rut potential comparisons for virgin mixes.

TABLE 4 Relationship Between Modulus and Rutting

Rutting Potential	Resilient Modulus, psi	Section ID
High	363,000	2-4
High	262,000	4-2
AASHO High	663,000	1-1
AASHO High	156,000	7-1
AASHO	242,000	5-3
AASHO Low	513,000	2-1
AASHO Low	555,000	2-3
AASHO Low	312,000	2-6
AASHO Low	657,000	1-6
Low	500,000*	2-5
Low	625,000	1-3
Low	100,000*	7-2
Low	516,000	4-3
Low	478,000	4-1
Low	700,000*	1-5

* Modulus estimated from indirect tensile strength relationship

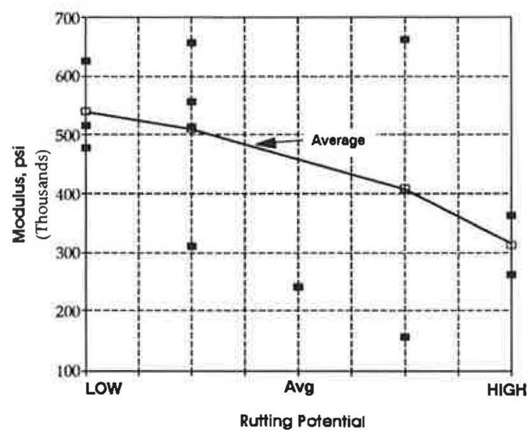

FIGURE 10 Modulus versus AASHO mixture rutting potential.

SIGNIFICANCE OF RESULTS

When the progression of rutting is studied, the vehicles in a traffic stream must be converted to ESALs for design-life comparisons. Common methods of evaluating mix performance today involve measuring the rutting on a well-designed flexible pavement or on a rigid pavement that has been overlaid. To compare the performance of the mixes, the rut depths are typically presented as a function of the accumulated ESALs. If the LEFs used to obtain the ESALs are those of the underlying pavement, whether flexible or rigid, significant error can result, even if the mixes themselves are performing identically. In this case the difference arises from an improper LEF value for the tandem axles in the traffic stream.

The misapplication of the LEF value can present a problem when rutting performance is compared between different flexible pavements that are developing rutting only in the asphalt concrete layer. A hypothetical situation could exist in which two pavements have traffic streams that are very different but the same number of ESALs could be calculated. With different traffic streams the ESALs calculated for rutting comparisons using flexible AASHTO LEFs are not correct. An increased number of tandem axles in one of the traffic streams could actually cause more rutting in a shorter time because of the higher LEF that should be used compared with the LEF for flexible pavement. Use of the flexible pavement LEFs results in severe underprediction of the number of ESALs, which provides a distorted relationship of traffic level and rut depth development. The pavement with more tandem axles incorrectly appears to develop rutting at an accelerated rate. If the correct LEF values had been used, a more consistent relationship would have been developed.

The improper use of the tandem-axle flexible pavement LEF would represent approximately a 45 percent discrepancy in the estimation of the 18-kip ESALs required to rut an asphalt concrete mix to a depth of 0.5 in. Given that a traffic stream can have 25 percent trucks, which are typically equipped with tandem axles and contribute more than 80 percent of the total ESALs in the traffic stream, the underprediction of flexible pavement ESALs could amount to 30 percent, providing a false service life for mixture comparisons.

When new asphalt mixes are tested in the laboratory to develop rutting coefficients, they are tested under a standard stress level or series of stress levels. The A and B' coefficients can be used in the rutting equation to calculate rutting for an increased number of loadings for comparison with the AASHO mixture and for field comparison of this mix with others. These new mixes should do much better than the AASHO mix, which became unstable after very few heavy tandem-axle loads. Studies on rutting should be directed toward establishing this limiting number of load repetitions for unstable performance, as well as the mix parameters applicable to the stable deformation phase. All mixes will eventually reach the limit and initiate unstable performance. Current technology ignores this.

ACKNOWLEDGMENTS

The data presented in this paper were developed as part of NCHRP Project 1-26 (*8*), conducted at the University of Illinois at Urbana-Champaign, and a report for the Wisconsin Department of Transportation conducted by ERES Consultants (*7*). The assistance of the authors of these studies is gratefully appreciated.

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