Use of Three-Dimensional, Dynamic, Nonlinear Analysis To Develop Load Equivalency Factors for Composite Pavements

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Asphalt overlays are frequently used to improve the serviceability of a deteriorated concrete pavement. The asphalt overlay has a significant influence on the concrete pavement's behavior and response to loads. Most highway agencies approximate the behavior of composite pavements to that of asphalt or concrete pavements. In fact the 1993 AASHTO design guide suggests that concrete pavement load equivalency factors (LEFs) be used to assess the effects of traffic on composite pavements. This is an approximation and has not been validated with field measurements or realistic analytical procedures. From a structural point of view an asphalt overlay of a concrete pavement should have a significant effect on the response of the composite pavement. A logical approach for the development of composite pavement LEFs is presented. These LEFs were developed for a study of permissible overloads and are based on total deformation, elastic and plastic, at the pavement surface. A three-dimensional dynamic finite-element mesh (3D-DFEM) method of analysis was used to analyze the composite pavements. The 3D-DFEM was verified in two steps for asphalt and concrete pavements: first for static, linear elastic analysis and then for dynamic, nonlinear analysis. Moving loads and realistic material models were used in the analysis.

Estimating the amount and characteristics of truck traffic is a vital step in pavement analysis, design, and evaluation. Most highway pavement design and evaluation procedures use the concept of load equivalency factors (LEFs) to convert a mixed traffic stream of different axle loads and configurations into a design traffic number. This number represents all of the axle loads expected to use the pavement during the design period converted into an equivalent number of 18-kip (8167-kg) single-axle loads (SAL) (*1*).

The most commonly used LEFs are those published by AASHTO (*2*). These LEFs are based on the AASHO Road Test (*3*) results and the concept of pavement serviceability. In the AASHO Road Test, asphalt and concrete pavement sections were constructed and tested with single and tandem axle loads. The present serviceability index (PSI), which is a function of slope variance (roughness), cracking and patching for concrete pavement, plus rutting for asphalt pavement, was used as a measure of pavement performance. Empirical relationships were developed to correlate PSI to the number of load repetitions for asphalt and concrete pavements. No composite pavement sections of asphalt overlaying concrete were included in the AASHO Road Test, and therefore no LEFs were developed for composite pavements. The 1993 AASHTO design guide (*1*) recommends the use of concrete pavement LEFs for composite pavements, ignoring the asphalt overlay thickness. In this case the effect of traffic on composite pavements is assumed to be similar to that of traffic on concrete pavements.

Other empirical LEFs, such as CanRoad LEFs (*4*), do not address composite pavements. Analytically based LEFs are based on multilayer elastic analysis. The model for this analysis assumes that pavements extend to infinity in the lateral and longitudinal directions and that the subgrade has infinite depth. Assumptions are also made in multilayer analysis that pavement materials are linear elastic and truckloads are static. Previous analysis (*5*) showed a lack of agreement between these types of LEFs and the AASHTO LEFs.

A study funded by the Indiana Department of Transportation (INDOT) and FHWA was conducted at Purdue University to develop a procedure for permitting overloaded trucks in Indiana. In that study the Indiana highway network was categorized into three classes: Interstate and U.S. highways and state roads (SRs). A typical pavement cross section was selected to represent each category in the analysis. Selection of these representative cross sections was made on the basis of the information available in the Road Life data base (*6,7*). The Road Life data base contains information about pavement structures and subgrade materials for more than 50 percent of the total lane miles of highways managed by INDOT. It was found that more than 60 percent of Indiana highways are jointed reinforced concrete pavements (JRCPs) overlaid at least once with asphalt concrete. Four typical pavement cross sections were selected to represent the different highway categories for the overload permit study. Composite cross sections that represented 70 and 77 percent of the total lane miles of Interstate and U.S. highways, respectively, were selected. Two cross sections were selected for the SR category: a composite pavement section representing 55 percent of the total SR lane miles and an asphalt cross section representing 40 percent of the total SR lane miles (*8*). Figure 1 shows typical cross sections of the composite pavements included in the overload permit study. Lean clay (CL) was found to be the predominant soil in Indiana; therefore, a CL subgrade was assumed for the typical sections.

A sample of overload permit applications was reviewed to determine the truck configurations being permitted. This sample revealed that permits were requested for trucks with up to nine axles in one group as well as trucks with axle loads of up to 72 kips (32 668 kg) (*9*). The AASHTO Road Test included only single and tandem axle loads up to 40 kips (18 149 kg) and 48 kips (21

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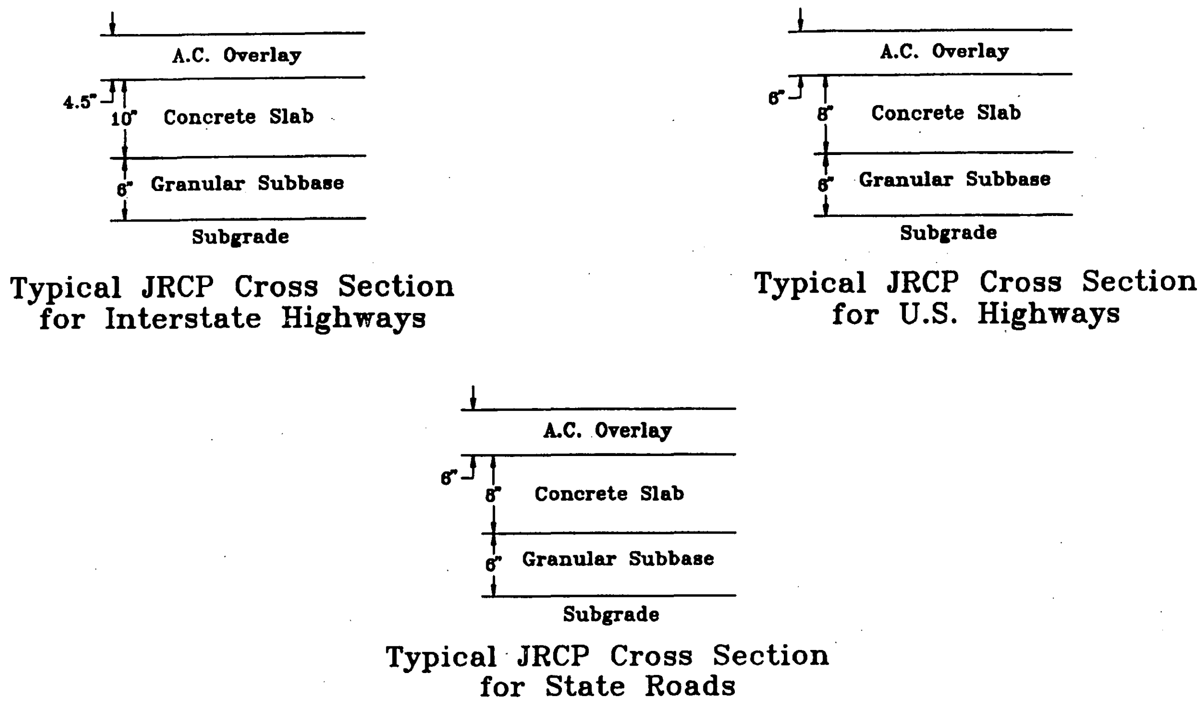


FIGURE 1 Typical composite pavement cross sections. (1 in. = 2.54 cm).

779 kg), respectively. LEFs based on AASHO Road Test results are valid only for these axles and load ranges. Simple extrapolation of regression relations beyond the range of factors for which data have been collected is risky without realistic material and structural models. This appears to be a deficiency of the AASHTO *Guide for Design of Pavement Structures* (*1,10*), in which LEFs are presented for single and tandem axle loads higher than those in the Road Test as well as for tridem axles, which were not used in the Road Test at all. These extrapolations were made by using the original serviceability-based regression equations for performance (*1*).

In this paper LEFs for composite pavements are presented. These LEFs are developed for a study examining permissible overloads and are based on total deformation, elastic and plastic, at the pavement surface [total surface deflection (TSD)]. A three-dimensional dynamic finite-element mesh (3D-DFEM) method was used to analyze the composite pavements (*11*). This 3D-DFEM has the capability of simulating truckloads moving at different speeds. Also, it can model paving materials as elastic, elastic-plastic, plastic, and viscoelastic materials. The 3D-DFEM predicts both the elastic and plastic pavement responses for one or more load applications. The 3D-DFEM was verified in two steps for asphalt and concrete pavements: first for static, linear elastic analysis and then for dynamic, nonlinear analysis (*12,13*). Verification studies for both pavement types showed excellent results.

3D-DFEM ANALYSIS

Model Geometry

The typical composite pavement cross sections for Interstate and U.S. highways and SRs, shown in Figure 1, were modeled in this analysis as two 12-ft lanes plus 8-ft shoulders on either side. The pavement structural model consisted of three layers: asphalt surface, concrete slab, and granular subbase on top of a CL subgrade. Shoulders were modeled to be untied concrete shoulders with the same structure as the traffic lanes. 3D-DFEM with variable openings was created to model the pavement structures. The mesh with variable size openings was used to reduce the computer memory requirements and computational time. A smaller mesh spacing was used to provide detailed response predictions where needed. Pavement structures were modeled as a set of layers. Figure 2 shows one of the 3D-DFEMs used in the analysis. In this example the subgrade thickness was represented by three elements, the concrete slab thickness was represented by two elements, and the granular subbase and the asphalt overlay thicknesses were represented by single elements. Longitudinal and transverse joints were modeled by using gap elements with an initial opening of 3/8 in. (9.53 mm). Depending on the deformed shape of the slabs after loading, the slabs might come into contact and develop friction. Dowel bars were modeled and located in the midthickness of the slab. The bond stress of one-half of the dowel bar was set to zero. Reflected cracks in the asphalt overlay were modeled by using interface elements. Details of the finite-element features used in this analysis are reported by Zaghloul and White (*12,13*). Loads were sequentially applied at surface nodes. The time rate of loading from one node to the next simulated vehicle speeds. From previous studies (*5,14*) vehicle speed was found to have a significant effect on pavement response. Therefore, a speed similar to the average speed of the AASHO Road Test, 35 mph (*15*), was used in developing the LEFs.

Material Models

In the analysis pavement materials were divided into four groups: asphalt concrete, portland cement concrete, granular materials, and

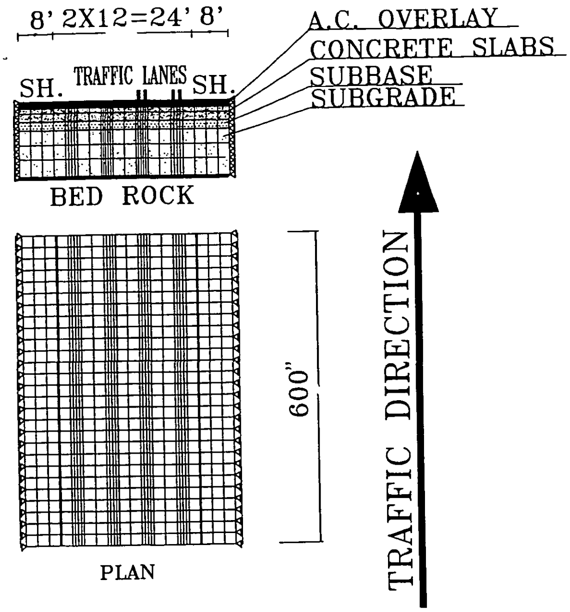


FIGURE 2 Example of a 3D-DFEM used in analysis (1 in. = 2.54 cm and 1 kip = 453.7 kg).

cohesive soils. Details of these material models were reported by Zaghloul in 1993.

Asphalt concrete was modeled as a viscoelastic material. The response of this type of material to loading is time and temperature dependent (*16*). These characteristics were represented by instantaneous and long-term shear moduli (*17*). The instantaneous shear modulus was selected at a loading time of 0.1 sec, and the long-term shear modulus was selected at a loading time of 1.0 sec. These loading times represented speeds of 40 and 1.5 mph, respectively. The temperature effect was considered through the shear modulus values. Figures 3(*a*) shows the effect of loading time and temperature on asphalt mixture stiffness.

Granular materials, base, subbase, and subgrade in some cases were modeled by using the Drucker-Prager model (*17,20*). This is an elastic-plastic model in which granular materials are assumed to behave elastically for low stress levels. When the stress level reaches a certain yield stress, the material will subsequently behave as an elastic-plastic material. Figure 3(*b*) shows the assumed stress-strain curve for a granular material.

The Cam-Clay model (*17,21,22*) was used to model clays. This model uses a strain rate decomposition in which the rate of deformation of the clay is decomposed additively into an elastic and a plastic part. Figure 3(*c*) shows the assumed soil response in pure compression.

Portland cement concrete behavior was divided into three stages: elastic, plastic, and after failure. Figure 3(*d*) shows the stress-strain curve used to model portland cement concrete. If the concrete slab is subjected to a stress level less than its yield stress, it will behave as an elastic material. When the stress level exceeds the yield stress of the concrete, behavior is elastic-plastic until the stress reaches the failure limit. At that point the after-failure stage starts (*17*).

Other material and layer characteristics required in the analysis include modulus of elasticity, Poisson's ratio, damping coefficient, and bulk density. Table 1 shows the typical material properties used in the analysis.

As a general assumption, concrete slabs are assumed to be repaired before construction of the overlay, which is a common technique in Indiana. Longitudinal and transverse joints were modeled in the concrete slab, as were the corresponding reflected cracks in the asphalt overlay. These cracks were extended through the shoulders.

VERIFICATION ANALYSIS

Several studies were conducted to verify the 3D-DFEM predictions.

Static Analysis Verification Studies

Asphalt Pavement

Predictions were compared for a multilayer analysis by using the computer program Bitumen Structures Analysis in Roads (BISAR) (*23*), and the 3D-DFEM assuming linear elastic material properties and static loads. There was good agreement between the two model predictions of deflection at different depths and offset distances from the loaded area (R^2 = 0.96). The factors included in that study were thickness of the asphalt layer, thickness of the granular layers, and subgrade modulus of elasticity (*12*).

Concrete Pavement

A comparison was also made of predictions of concrete pavement response by using Westergaard's equations and the 3D-DFEM assuming linear elastic material properties and static loads. These results also showed good agreement (R^2 = 0.977). The factors included in that study were thickness of the concrete slab, subgrade type, and load position (*13*).

Dynamic Analysis Verification Studies

Asphalt Pavement

Verification of dynamic response was made by comparing field-measured pavement deflections from loads moving at different speeds and the 3D-DFEM predictions for similar conditions (pavement structure, load magnitude and configuration, and speed). The predictions were in good agreement with the measurements (R^2 = 0.999). Figure 4(*a*) shows the result of the comparison (*5*).

Concrete Pavement

Verification of dynamic response was also made for concrete pavements by comparing field-measured pavement deflections from moving loads and the 3D-DFEM predictions for similar conditions (pavement structure, load magnitude and configuration, and speed). There was also excellent agreement between the pre-

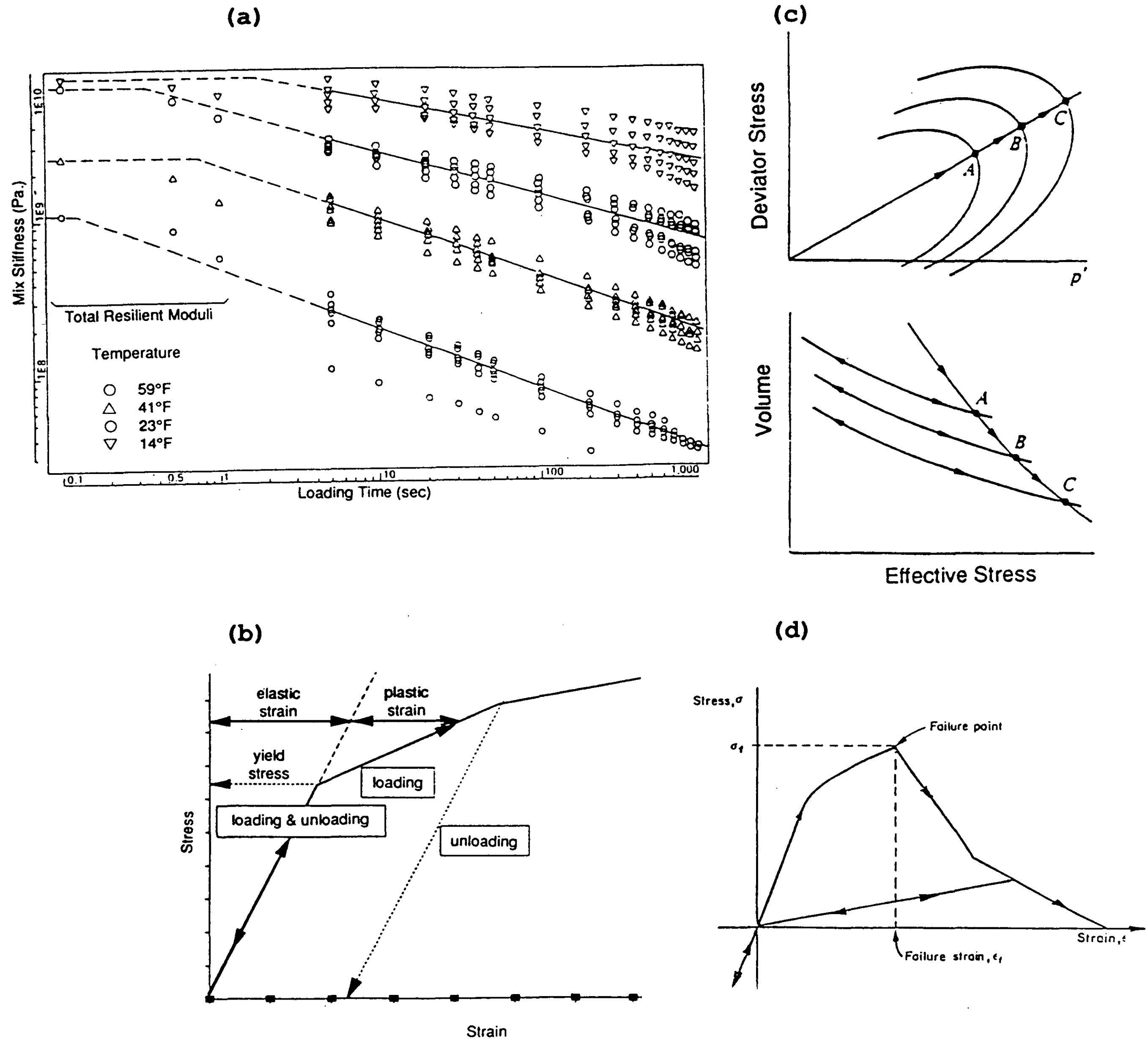


FIGURE 3 Material models used in analysis: (*a*) asphalt mixtures (*18*); (*b*) granular materials (*11*); (*c*) clays (*19*); (*d*) concrete (*11*).

dictions and the measurements (R^2 = 0.996). Figure 4(*b*) shows the result of this comparison (*14*).

Analysis of Falling-Weight Deflectometer Tests

A study was also conducted to verify the dynamic analysis capabilities of the 3D-DFEM by using a falling-weight deflectometer (FWD) data set for a full-depth asphalt section in Indiana. Excellent results were obtained from that study. The predicted peak deflections were found to match the measured ones. Also, the deflection history curves (deflection with time) at different offset distances were found to be in good agreement with the measured ones. The absolute sum of errors between the measured and predicted deflections was 6 percent. Figure 4(*c*) shows the measured and predicted deflection basins (*24*).

LEF Verification Studies

Asphalt Pavement LEFs

Comparisons among the AASHTO LEFs, Purdue LEFs, and other LEFs for single and tandem axle configurations showed excellent agreement between the AASHTO and Purdue LEFs. Conditions similar to those of the AASHO Road Test (layer thicknesses, material properties, and speed) were assumed in the analysis for developing the Purdue LEFs. There was poor agreement between

TABLE 1 Typical Material Properties Used in Analysis

Material Name	Material Property	Typical Value
Asphalt Surface	Modulus of Elasticity - psi	400,000 (2.762 GPa)
	Poisson's Ratio	0.3
	G-Ratio	0.8
	Density - pcf	150 (2.403 gm/cm^3)
	Damping Coefficient (%)	5
Concrete Slabs	Modulus of Elasticity - psi	4,000,000 (27.62 GPa)
	Poisson's Ratio	0.15
	Initial Yield Stress - psi	2670 (18.4 MPa)
	Failure Plastic Strain	1.3E-03
	Density - pcf	150 (2.403 gm/cm^3)
	Damping Coefficient (%)	5
Granular Subbase	Modulus of Elasticity - psi	40,000
	Poisson's Ratio	0.3
	Initial Yield Stress - psi	19.29 (0.133 MPa)
	Initial Plastic Strain	0.0
	Angle of Friction - degree	33
	Density - pcf	135 (2.1625 gm/cm^3)
Material Name	Material Property	Typical Value
	Damping Coefficient (%)	5%
Lean Clay (CL) Subgrade	Shear Modulus - psi	2750 (18.964 MPa)
	Poisson's Ratio	0.3
	Logarithmic Hardening Modulus	0.174
	Initial Overconsolidation Parameter - psi	8.455 (58.306 KPa)
	Permeability - ft/sec	0.000021 (0.00064 cm/sec)
	Initial Void Ratio (%)	8
	Initial Stress psi	weight of the pavement layers
	Density - pcf	130 (2.0824 gm/cm^3)
	Damping Coefficient (%)	5

the AASHTO and the other LEFs. Results of these comparisons are shown in Figures 5(*a*) and 5(*b*).

Concrete Pavement LEFs

A comparison also shows excellent agreement between the AASHTO and Purdue LEFs for concrete pavements for single and tandem axle configurations. Conditions similar to those of the ASSHO Road Test (layer thicknesses, material properties, and speed) were assumed in the analysis for developing the Purdue

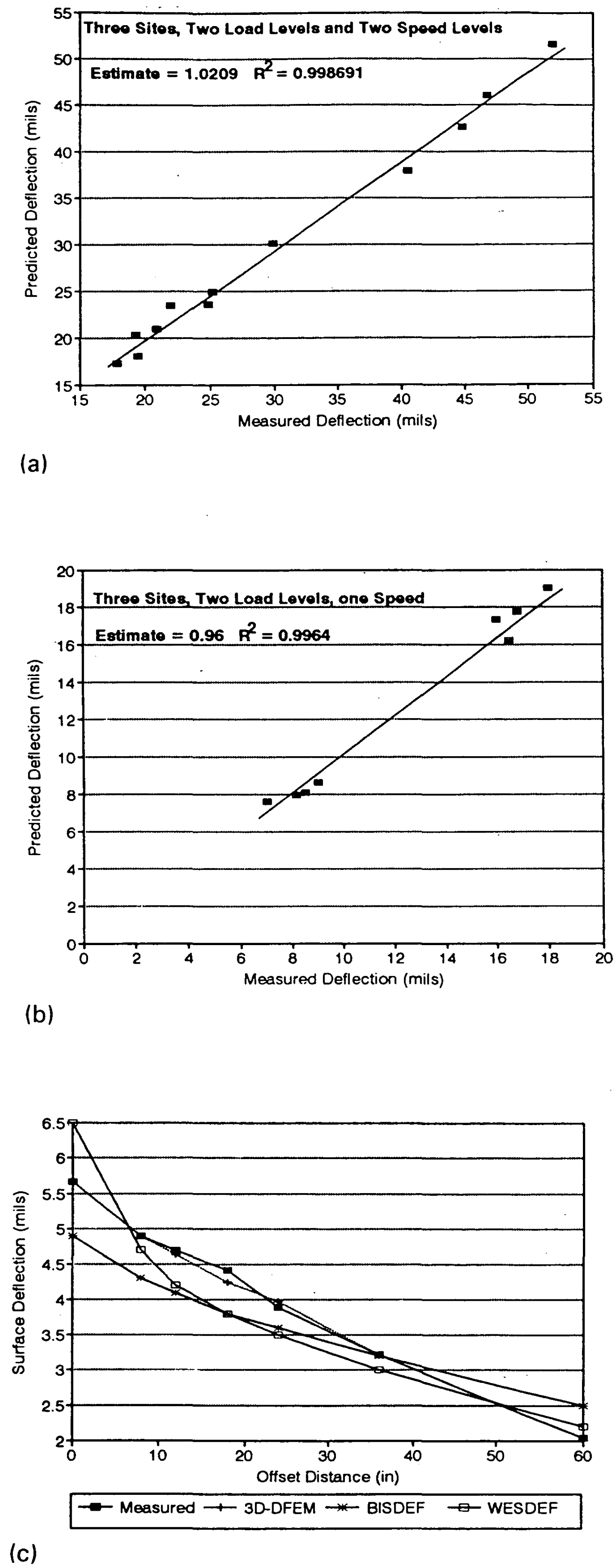
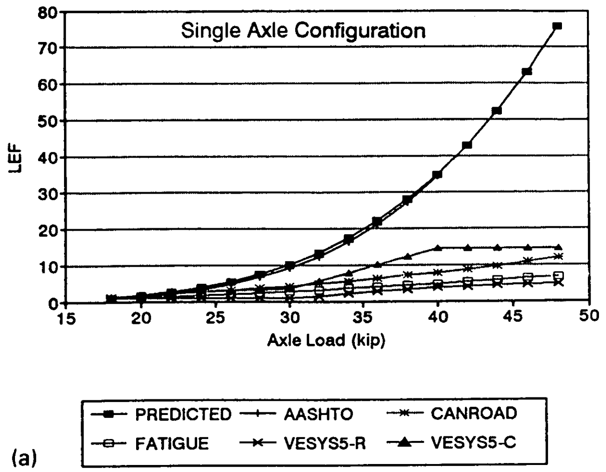
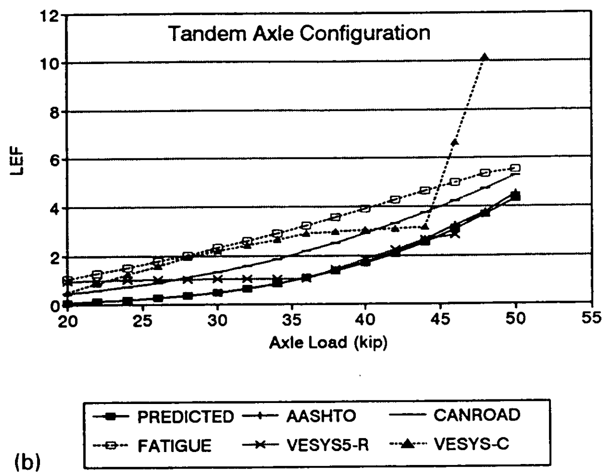


FIGURE 4 Dynamic analysis verification: (*a*) asphalt pavement, (*b*) concrete pavement, (*c*) FWD—asphalt pavement (1 in. = 2.54 cm and 1 kip = 453.7 kg).



(a)



(b)

FIGURE 5 Comparison between AASHTO LEFs and Purdue LEFs for asphalt pavements: (*a*) single axle configuration, (*b*) tandem axle configuration (1 in. = 2.54 cm and 1 kip = 453.7 kg).

LEFs. Results of the comparison are shown in Figures 6(*a*) and 6(*b*) (*14*).

PURDUE LEFs

The response, performance, and failure mechanisms of composite pavements are different from those of flexible or rigid pavements. When a very heavy load is applied and repeated on a flexible pavement, some permanent deformation develops in the different layers, including the surface layer. These permanent deformations accumulate at the pavement surface, resulting in a higher pavement roughness. When the roughness reaches a certain value the pavement is considered to be failed.

A similar heavy load applied and repeated on a concrete pavement causes no permanent deformation in the concrete slab itself. Some permanent deformation may be developed in asphalt-bound or unbound layers underneath the concrete slabs, resulting in a void. The development of this permanent deformation occurs if the yield stress of the materials beneath the concrete slab is exceeded. Generally, permanent deformation developed in the layers beneath a concrete slab does not accumulate at the pavement surface because of the concrete slab's rigidity. The total surface permanent deformation under no load in this case is almost zero because the concrete slab returns to its original position when the load is removed. The void under the slab will lead to a larger slab deflection when the load is repeated and to increased pavement roughness. This larger deflection leads to accelerated fatigue and failure (*13*).

The failure mechanism of composite pavements is a combination of those of flexible and rigid pavements. When a heavy load is applied and repeated on a composite pavement, some permanent deformation develops in the asphalt overlay. Permanent deformation may, depending on the stress levels, also develop in asphalt-bound or unbound layers beneath the concrete slab. Permanent surface deformation in this case reflects the permanent deformation of the asphalt overlay only, whereas the total loaded deflection (elastic and plastic) reflects the permanent deformation of the asphalt overlay as well as any permanent deformation in the layers beneath the concrete slab. The total deflection increases with the number of load applications resulting in increased pavement roughness. TSD is used as the basis of a rational equivalency criterion for composite pavements. Simply stated, the LEF of load j on cross section i (LEF_{ij}) is equal to the number of the 18-kip (8167-kg) SAL repetitions on cross section i required to develop the same TSD as one pass of the load j on the same cross section i.

Two statistical models were developed for composite pavement LEFs. The first model predicts the TSD from one pass of load j on cross section i, and then the predicted TSD is used as an input for the second model to estimate the number of 18-kip (8167-kg) SAL repetitions required to develop the same TSD in cross section i, which is the LEF_{ij}. Figure 7 shows the concept of the Purdue LEFs for composite pavements.

Design of Experiments

Two designs of experiments (DOEs) were implemented to develop the composite pavement LEFs. The following factors were included in the first DOE (DOE1):

1. Axle load (D) [three levels: 18, 24, and 36 kips (8167, 10 889, and 16 334 kg)/single axle in an axle group],
2. Number of axles in an axle group (N) (three levels: 1, 2, and 4),
3. Slab thickness (T_{con}) [Two levels: 6 in. (15.24 cm) and 12 in. (30.48 cm)], and
4. Overlay thickness (T_{asp}) [two levels: 4 in. (10.16 cm) and 8 in. (20.3 cm)].

Factor levels for slab and overlay thicknesses represent the range of thicknesses used in Indiana. Subgrade type was not found to be significant in the development of flexible pavement LEFs (*5*). The concrete slab's rigidity would further reinforce this result, and therefore subgrade type would not be expected to be significant for composite pavement LEFs. A subgrade was assumed for all cross sections. The 3D-DFEM analysis was conducted for a speed similar to that of the AASHO Road Test speed, 35 mph (*15*), to be consistent with previously developed flexible and rigid pavement LEFs (*5,14*).

A one-third partial factorial design was used for the above factors and levels. An analysis of different load–cross section com-

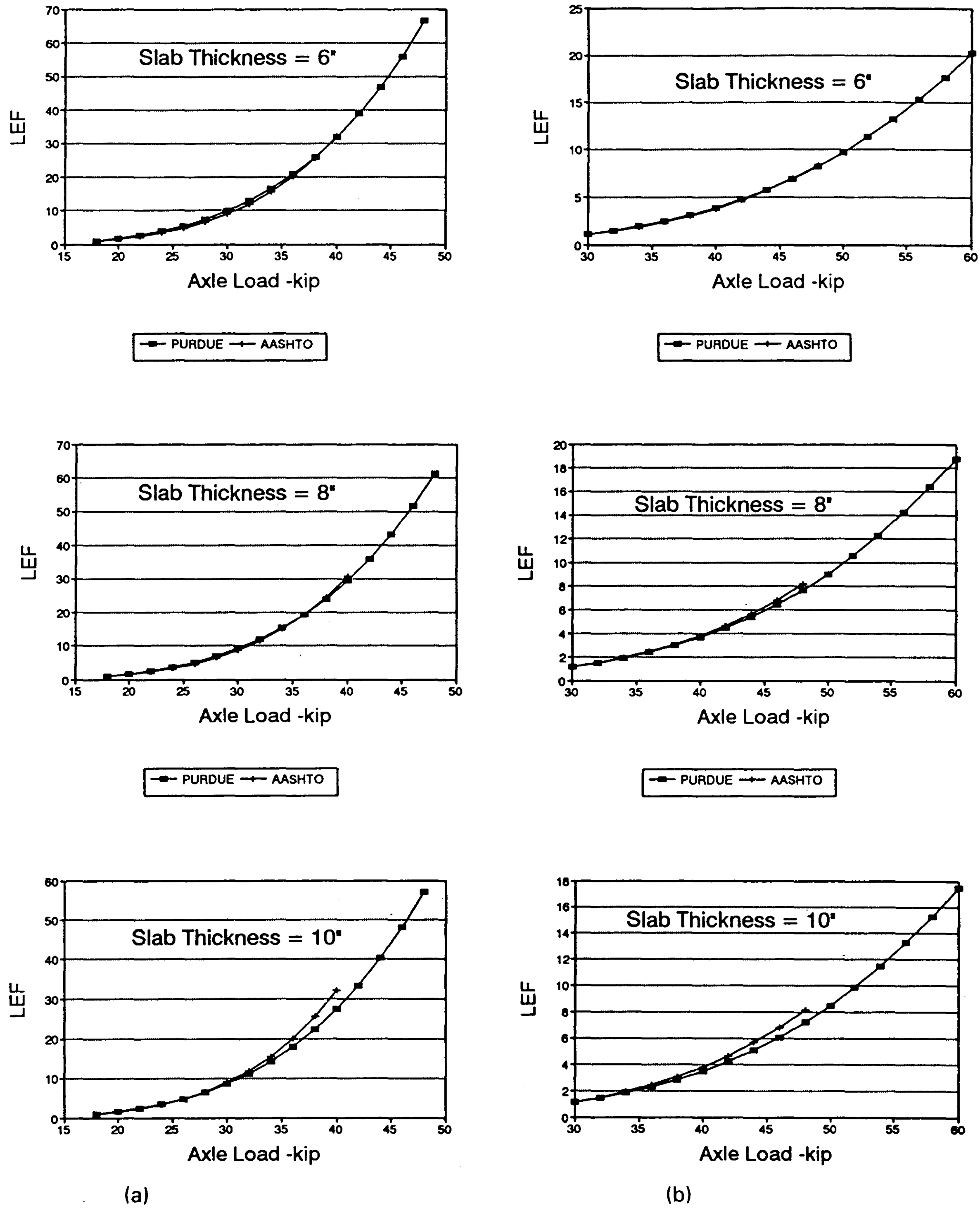


FIGURE 6 Comparison between AASHTO LEFs and Purdue LEFs for concrete pavements: (*a*) single axle configuration, (*b*) tandem axle configuration (1 in. = 2.54 cm and 1 kip = 453.7 kg).

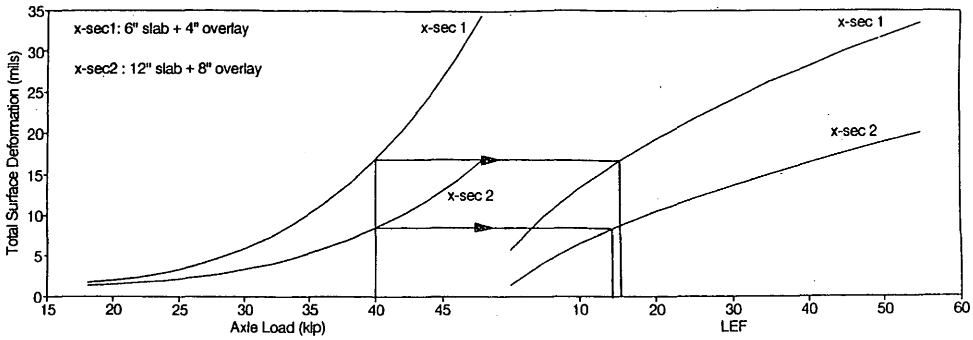


FIGURE 7 Purdue LEFs for composite pavements (SAL) (1 in. = 2.54 cm).

binations was made by using the 3D-DFEM. Analysis of variance (ANOVA) of the results was done to test the significance of the different factors. The significant main effects and two-way interactions were used to develop a regression model for predicting TSD for different loads and axle configurations on different cross sections. The form of the regression model is

$$\text{TSD} = 6.556E\text{-}6 \cdot D^4 + 1.0254 \cdot N - 2.28E\text{-}7 \cdot D^4 \cdot (T_{asp} + T_{con}) \qquad (R^2 = 98.72 \text{ percent})$$

where

D = axle load (kip/single axle in an axle group),
N = number of axles in an axle group, and
T_{asp} and T_{con} = asphalt overlay and slab thicknesses (in.), respectively.

A second DOE (DOE2) was implemented to consider the effect of the 18-kip (8167-kg) SAL repetitions. Three factors were included in DOE2: slab thickness (T_{con}), 6 in. (15.24 cm) and 12 in. (30.48 cm); asphalt overlay thickness (T_{asp}), 4 in. (10.16 cm) and 8 in. (20.32 cm); and number of 18-kip (8167-kg) SAL repetitions (C), 1 to 30 repetitions. A full factorial design was used to develop this model. Different overlay-slab thickness combinations were analyzed by using the 3D-DFEM. ANOVA of the results was done to test for the significance of the different factors included in DOE2. The significant main effects and two-way interactions were used to develop a regression model to predict TSD as a function of the 18-kip (8167-kg) SAL repetitions. The form of the progression model is

$$\text{TSD} = 4.653 + C(1.244 - 0.0502T_{con} - 0.0421T_{asp}) \qquad (R^2 = 97.78 \text{ percent})$$

where C is the number of 18-kip (8167-kg) SAL repetitions.

It should be noted that the first model predicts the TSD caused by one pass of any load configuration on any cross section, whereas the second model predicts the TSD caused by one or more passes of the 18-kip (8167-kg) SAL on any cross section. To extend the validity of these models additional cases were analyzed to cover wider ranges of factor levels, and the results were compared with the extrapolated predictions of the models. The extended factors included up to 40 repetitions of the 18-kip (8167-kg) SAL, an overlay thickness of 2 in. (5.08 cm), and a slab thickness of 16 in. (40.64 cm).

Example

A request for a permit is made for an overloaded truck having two single axles in addition to the steering axle. Each single axle will carry a load of 72 kips (32 668 kg) (*9*). The LEF of the 72-kip single axle is determined for the typical Indiana Interstate pavement cross section shown in Figure 1.

1. Total surface deformation of the 72-kip (32 668-kg) SAL j and the 18-kip (8167-kg) SAL on the Interstate typical section i:

$$\text{TSD}_{ij} = 6.556E\text{-}06 \cdot (72^4) + 1.025439 \cdot 1 - 2.28E\text{-}07 \cdot (4.5 + 10) \cdot (72^4) = 88.365 \text{ mils } (2.2445 \text{ mm})$$

$$\text{TSD}_{18} = 6.556E\text{-}06 \cdot (18^4) + 1.025439 \cdot 1 - 2.28E\text{-}07 \cdot (4.5 + 10) \cdot (18^4) = 1.3666 \text{ mils } (0.0347 \text{ mm})$$

2. Number of 18-kip (8167-kg) SALs required to develop the same damage from one pass of load j on cross section i (LEF_{ij}):

$$\text{LEF}_{ij} = \frac{(88.365 - 1.3666) - 4.653}{1.244 - 0.05025 \cdot 10 - 0.042081 \cdot 4.5} = 149.152$$

The AASHTO LEF for this axle load, ignoring the 4.5-in. (11.43-cm) asphalt overlay, cannot be determined! For comparison, the AASHTO LEF for a 40-kip (18 149-kg) SAL, ignoring the 4.5-in (11.43-cm) asphalt overlay, is 31.58.

Sensitivity Analysis

A comparison between the AASHTO LEFs for concrete pavement and Purdue LEFs for composite pavement for single axles in shown in Figure 8. In Figure 8 the maximum and minimum AASHTO LEFs for slab thicknesses in the range of 6 in. (15.24 cm) to 11 in. (27.94 cm) are presented. As can be seen from Figure 8 there is a minimal effect of slab thickness on the AASHTO LEFs (*1*). Four cases were considered for the composite pavement LEFs in this comparison:

1. Thin overlay [4 in. (10.16 cm)] on thin slab [6 in. (15.24 cm)],
2. Thin overlay [4 in. (10.16 cm)] on thick slab [12 in. (30.48 cm)].

3. Thick overlay [8 in. (20.32 cm)] on thin slab [6 in. (15.24 cm)], and
4. Thick overlay [8 in. (20.32 cm)] on thick slab [12 in. (30.48 cm)].

The cases of thin and thick asphalt overlays on thin concrete slabs have total thicknesses in the range represented in the AASHTO LEFs for concrete pavements. As can be seen from Figure 8 the LEFs for the thin and thick asphalt overlays on thin concrete slabs are lower than those of AASHTO. This indicates that the difference between the AASHTO LEFs for concrete pavements and Purdue LEFs for composite pavements is related to differences in layer thicknesses and the differences in the predicted response of composite pavements.

As expected, the thin overlay-thin slab combination showed the highest LEFs, whereas the thick overlay-thick slab combination showed the lowest LEFs. Also, the composite pavement LEFs were lower than the concrete pavement LEFs for the same concrete slab thickness. This was expected because the additional overlay thickness significantly increases the pavement structure stiffness. The effect of slab thickness on LEFs is shown in Figure 9(*a*), whereas the effect of overlay thickness is shown in Figure 9(*b*). As expected, as the slab or the overlay thicknesses increase, the LEFs decrease.

LEFs for tandem, tridem, and four-axle configurations are shown in Figure 10. This analysis was made for a 10-in. (25.4-cm) JRCP with a 4-in. (10.08-cm) asphalt concrete overlay. The sample of overload permit applications discussed above showed that the average axle spacing is 4 ft. Therefore, a 4-ft axle spacing was assumed for *n*-axle configurations.

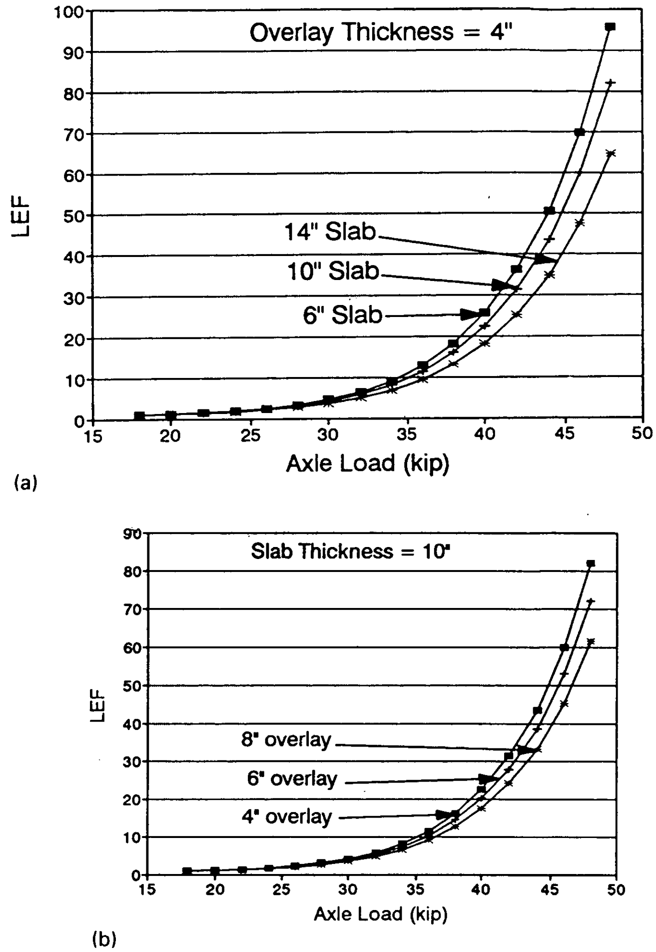


FIGURE 9 Effect of cross section parameters on Purdue LEFs: (*a*) slab thickness, (*b*) overlay thickness (1 in. = 2.54 cm and 1 kip = 453.7 kg).

Advantage of Purdue LEFs

No rational LEFs have been available for composite pavement analysis. The 1993 AASHTO design guide (*1*) recommends that the concrete pavement LEFs be used for composite pavements. In this case the significant contribution of the overlay is ignored.

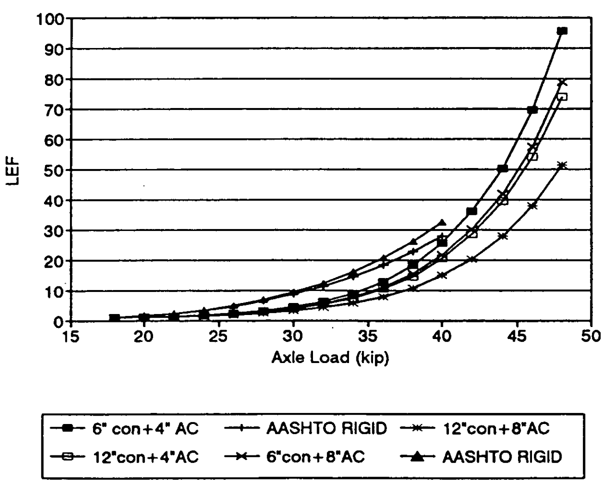


FIGURE 8 Comparison between AASHTO LEFs for concrete pavements and Purdue LEFs for composite pavements (single axle configuration) (1 in. = 2.54 cm and 1 kip = 453.7 kg).

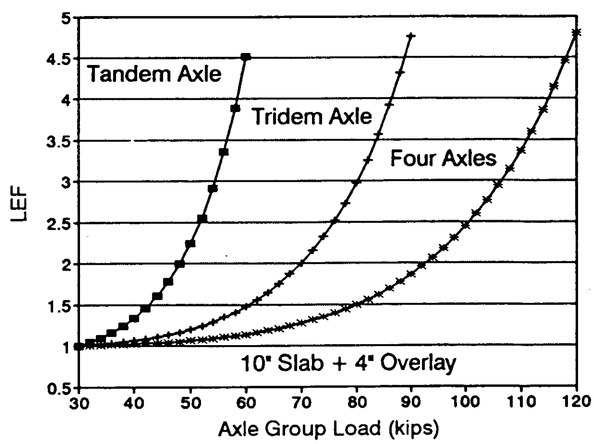


FIGURE 10 Effect of axle configuration on Purdue LEFs (1 in. = 2.54 cm and 1 kip = 453.7 kg).

Purdue LEFs can be considered serviceability-based LEFs and are developed by using TSD. TSD accounts for the permanent deformation developed in the asphalt overlay and unbound layers underneath the concrete slabs. The permanent deformation is related to potential accumulation of roughness, which is a large component of serviceability (*16*). Purdue LEFs have the following advantages:

1. Purdue LEFs are based on dynamic analysis in which moving loads are considered. Also, nonlinear material properties and models are included in the analysis.
2. The 3D-DFEM analysis used to develop these LEFs has been verified for static, linear elastic analysis and for dynamic, nonlinear analysis of both flexible and rigid pavements. Excellent results were obtained in the verification studies and in the comparison of AASHTO LEFs and Purdue LEFs for asphalt and concrete pavements.
3. Purdue LEFs consider the effect of load repetitions and not assume that the pavement response is a linear function of the number of load repetitions.
4. Purdue LEFs are based on an analytical model, which means that they can be easily updated or extended to cover wider ranges of variables, such as pavement thickness, material type, load level, and load configuration.

SUMMARY AND CONCLUSIONS

An asphalt overlay is frequently used to improve the serviceability of deteriorated concrete pavement. The asphalt overlay has a significant influence on the concrete pavement's behavior and response to loads. Most highway agencies approximate the behavior of composite pavements to that of asphalt or concrete pavements. The 1993 AASHTO design guide (*1*) suggests that concrete pavement LEFs be used to assess the effects of traffic on composite pavements. This is an approximation and has not been validated with field measurements or analytical procedures.

A study funded by INDOT and FHWA was conducted at Purdue University to develop a procedure for permitting overloaded trucks in Indiana. In that study the Indiana highway network was categorized into three classes: Interstate and U.S. highways and SRs. Typical pavement cross sections were selected to represent each highway class in the analysis. Four typical pavement cross sections were selected for the study. Three of these four cross sections are JRCPs with an asphalt overlay, composite pavement.

A LEF set was developed for composite pavements. The total surface deformation (elastic and permanent) was used as the equivalency criterion for these LEFs. The total surface deformation includes any permanent deformation developed in the asphalt overlay or the unbound layers underneath the concrete slab.

It was found that the composite pavement LEFs are lower than the AASHTO LEFs for concrete pavement. This is related to the additional stiffness caused by the asphalt overlay as well as to the differences in the responses of concrete and composite pavements.

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