Computerized Overload Permitting Procedure for Indiana

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Truck weight regulations are used to control the rate of damage accumulation for pavements and bridges. Permitting heavier loads can increase the rate at which pavement damage and bridge deterioration accumulate and the costs of maintainance. Truck weight limits have always been controversial. Each state has legal truck weight limits. In many cases, trucks carrying weights higher than legal limits need to use the highway system and a special overload permit is required. A study conducted at Purdue University and funded by the Indiana Department of Transportation and FHWA developed an enhanced procedure for permitting overloaded trucks in Indiana. The procedure evaluates damage effects of overloaded trucks for pavements and bridges. Both pavement and bridge analyses use statistical models developed especially for this study. The pavement statistical models are based on a three-dimensional, nonlinear dynamic finite-element analysis of rigid, flexible, and composite pavements. Repeated axle loads moving at different speeds are considered, and realistic material models, such as viscoelastic and elastic-plastic models, are used for pavement materials and subgrades. The bridge statistical models are based on analysis using the AASHTO Bridge Analysis and Rating System and selected samples of bridges and overloaded trucks. User-friendly computer software was developed to implement this enhanced procedure, which allows the user to run damage analysis for overloaded trucks at the network level (e.g., route-independent analysis) as well as at the project level for specific pavement or bridge structures. Three options are available at both project levels: to check for pavements only, to check for bridges only, or to check for both, the default option. At the project level, the user is permitted to enter all cross-section and load parameters. Typical default values are provided for material properties.

Indiana's legal truck weight limits are described in the *Oversize-Overweight Vehicular Permit Handbook* (*1*). Trucks exceeding these limits—overloaded trucks—are required to have an overload permit before using the Indiana highway network. The permit is granted for a fee if the overloaded truck does not exceed the following limits (*1*):

- Maximum gross weight, 108,000 lb;
- Maximum single axle weight, 28,000 lb;
- Maximum tandem axle weight, 24,000 lb;
- Maximum axle group weight, 51,000 lb;
- Maximum wheel weight, 800 lb per linear inch of tire measured between the flanges of the rim.

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Currently Indiana Department of Transportation (INDOT) regulations allow a truck exceeding the above limits to apply for an overload permit, which is evaluated for bridges and processed in two phases. In Phase 1, a simply supported beam and a two-equal-span, continuous beam are analyzed for the given permit vehicle for spans from 20 to 120 ft (6.1 to 36.8 m) in increments of 10 ft (3.05 m). The equivalent HS loading of the given overloaded truck is calculated by comparing the bending moments induced by the overloaded truck with those induced by the HS20 design truck in AASHTO's 1983 bridge maintenance standards. The overloaded truck will be permitted if its equivalent HS loading is less than HS30, (i.e., 1.5 times the HS20 design truck). When a truck matches a previously permitted truck, earlier results from Phase 1 are applied to make a quick evaluation. If the overloaded truck does not satisfy Phase 1 criteria, Phase 2, which involves a detailed load rating is implemented. The detailed load rating of Phase 2 requires specific information about the truck and bridges on the route for which the permit is requested. No evaluation for the damage effect of overloaded trucks on pavements currently is made.

PROBLEMS WITH CURRENT INDIANA TRUCK WEIGHT REGULATIONS

In Phase 1 of the current procedure, only beam-type bridges are considered. Hence, other types of bridges, such as trusses and arches, are not directly addressed. Girder cross-sectional properties are assumed uniform along the length of the span, and multispan bridges are represented, along with only two-span bridges. It is observed that long, overloaded trucks with multiple axles are controlled by the negative moment at the central support of the two-equal-span, continuous beam. From past experience with this procedure, INDOT has found that allowable loads for these long trucks are conservative. Nevertheless, the approximate nature of the procedure demands that the limits on its use be very restrictive.

The current procedure ignores pavements. Although pavement failures are not as potentially catastrophic as bridge failures, the cost of repairing or reconstructing pavements that have failed from heavy loads is significant.

PAVEMENT ANALYSIS

A three-dimensional, dynamic finite-element program (3D-DFEM) (*2*) was used in this study to analyze flexible, rigid, and composite pavement. A composite pavement is an asphalt-overlaid concrete pavement. The 3D-DFEM was verified for flexible and rigid pavement analysis. Two verification studies were conducted for each pavement type: static linear-elastic analysis and dynamic nonlinear analysis. Verification studies for both pavement types showed excellent agreement between field and predicted pavement response. Details of these analyses are reported by Zaghloul and White (*3,4*). No field measurements were available at the time of the study to conduct a similar verification study for composite pavements. However, considerable sensitivity studies were conducted to evaluate predicted composite pavement response.

Features of Finite-Element Model

Model Geometry

In this analysis, pavements were modeled as three-dimensional problems. For example, Figure 1 shows one of the three-dimensional finite-element meshes (FEMs) used to model flexible pavements. The FEM consists of two equally spaced meshes in the horizontal (*xy*) plane. A coarse mesh with 22.2-in. (56.39-cm) spacing was used in both the transverse (*x*) and longitudinal (*y*) directions. In the region of the load path, a finer mesh with 4.44-in. (11.28-cm) spacing was used in the *x* direction. Mesh dimensions in the vertical direction were selected to match the pavement layer thicknesses (i.e., surface, base, and subbase). The number of layers required to model the subgrade depends on the detail desired in predicting the vertical pavement response. In this example, the surface and base course were each modeled as a single

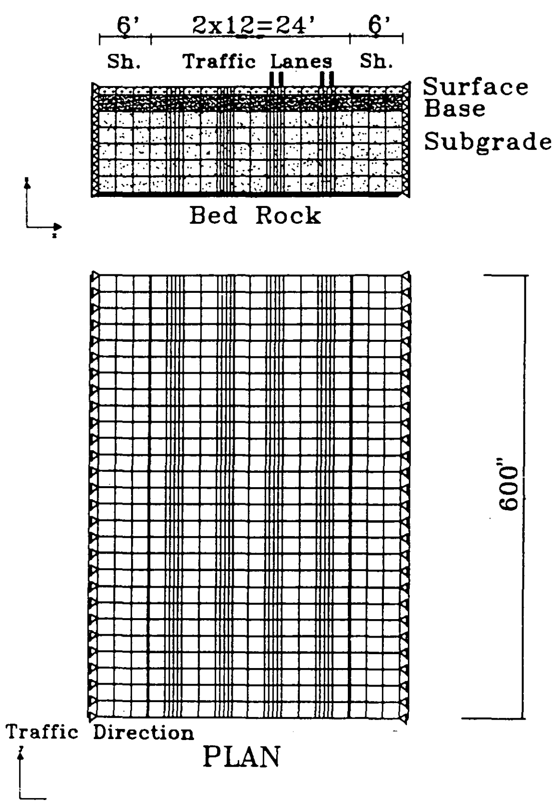


FIGURE 1 Example of the 3D-DFEM used in the analysis. (1 in. = 2.54 cm, 1 ft = 30.48 cm, and 1 kip = 453.7 kg).

layer, whereas the subgrade was modeled as a set of five layers. Adhesion between layers was considered a function of friction and normal pressure on the layers, according to the Mohr-Coulomb theory (*3*).

Boundary Conditions

Boundary conditions for the finite-element model have significant influence on predicted response. Reasonable boundary conditions were assumed for edges parallel and perpendicular to the traffic direction, bottom of the mesh (deep foundation), and joints (such as lane and shoulder joints for flexible pavements and longitudinal and transverse joints for concrete pavements) (*3,4*).

Material Properties

Pavement materials were divided into four groups: asphalt concrete; portland cement concrete; unbound granular base, subbase, and subgrade soils; and cohesive subgrade soils. Actual material behavior under repeated loads was considered for each group. Details of these material models are reported by Zaghloul (*3,4*).

Asphalt concrete was modeled as a viscoelastic material. This type of material is time and temperature dependent (*5*). The time-dependent properties are represented by the instaneous and long-term shear moduli (*6*). The instantaneous shear modulus was selected at a loading time of 0.1 sec, which is equivalent to a speed of 40 mph. The long-term shear modulus was selected at a loading time of 1.0 sec, which is equivalent to a speed of 1.5 mph. The temperature effect was considered through the shear modulus values. Figure 2(a) shows the effect of loading time and temperature on asphalt mixture stiffness.

Granular materials, base, subbase, and subgrade, in some cases, were modeled using the Drucker-Prager model (*6,7*). 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 start to behave as an elastic-plastic material. Figure 2(b) shows a typical stress-strain curve for a granular material.

The Cam-Clay model (*6,8,9*) was used to model cohesive soils. This model uses a strain rate decomposition in which the rate of deformation of the clay is decomposed addictively into an elastic and a plastic part. Figure 2(c) shows the assumed soil response in pure compression.

Three stages of portland cement concrete (PCC) were modeled: elastic, plastic, and after-failure stages. Figure 2(d) shows the stress-strain curve used to model PCC. If the PCC slab is subjected to a stress level less than its yield stress, it will behave elastically. When the stress level exceeds the yield stress of PCC, the behavior is elastic-plastic until the failure stress. At that point, the after-failure stage will start (*6*).

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

Finite-Element Model Verification

Before general application, the 3D-DFEM was verified in a two-step process for asphalt and concrete pavements. The two steps

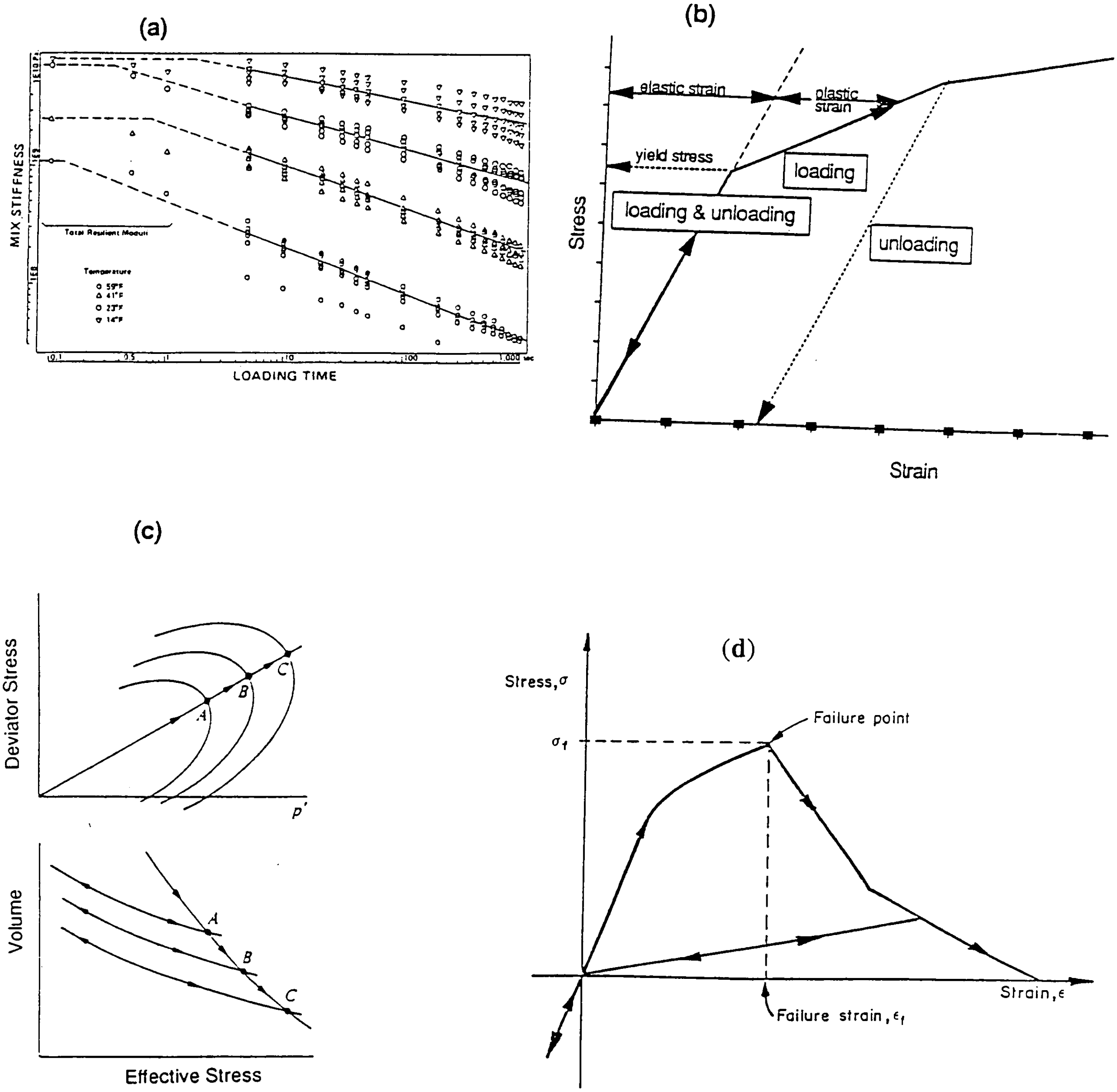


FIGURE 2 Material models used in the analysis; (a) asphalt mixtures, (b) granular materials, (c) clays, and (d) concrete. (1 in. = 2.54 cm, 1 ft = 30.48 cm, and 1 kip = 453.7 kg).

included evaluation of its capabilities to predict pavement response for both static and dynamic cases.

Static Analysis Verification

Design of experiments (DOEs) were developed for the elastic, static case. Subsequently, analyses of sections with factor combinations satisfying the design of experiment were conducted using a layered-elastic analysis for asphalt pavements and the Westergaard analysis for concrete pavements, and then compared with the 3D-DFEM analysis assuming elastic material properties for the various layers and static loading.

Three factors were included in the asphalt pavement DOE: surface layer thickness (T_s), base course thickness (T_b), and subgrade modulus of elasticity (E_{sg}). Two levels for each factor were included, low and high. Three factors were also included in the concrete pavement DOE: slab thickness (three levels), load position (three levels), and subgrade type (two levels). Linear correlation analyses were made between multilayer analysis predictions for asphalt pavements and Westergaard analysis predictions for concrete pavement as well as corresponding 3D-FEM predictions. High linear correlations were found for both asphalt and concrete pavements (R^2 = 96.4 percent and 97.8 percent, respectively).

Dynamic Analysis Verification

A study was also conducted to evaluate the time-dependent dynamic analysis feature of the 3D-DFEM. Because there is no stan-

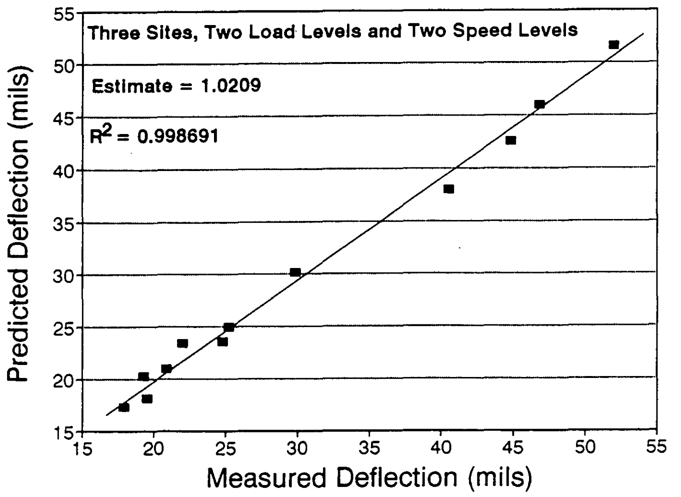
TABLE 1 Material Properties Used in the Analysis

Material Name	Material Property	Typical Value
Concrete Slabs	Modulus of Elasticity - psi(GPa)	4,000,000 (27.62)
	Poisson's Ratio	0.15
	Initial Yield Stress - psi (MPa)	2670 (18.4)
	Failure Plastic Strain	1.3E-03
	Density - pcf (gm/cm^3)	150 (2.403)
	Damping Coefficient (%)	5
Granular Subbase	Modulus of Elasticity - psi (GPa)	40,000 (0.276)
	Poisson's Ratio	0.3
	Initial Yield Stress - psi (MPa)	19.29 (0.133)
	Initial Plastic Strain	0.0
	Angle of Friction - degree	33
	Density - pcf (gm/cm^3)	135 (2.1625)
	Damping Coefficient (%)	5
Lean Clay (CL) Subgrade	Shear Modulus - psi (MPa)	2750 (18.964)
	Poisson's Ratio	0.3
	Logarithmic Hardening Modulus	0.174
Lean Clay (CL) Subgrade	Initial Overconsolidation Parameter - psi (KPa)	8.455 (58.306)
	Permeability - ft/sec (cm/sec)	0.000021 (0.00064)
	Initial Void Ratio (%)	8
	Initial Stress psi (MPa)	weight of the pavement layers
	Density - pcf (gm/cm^3)	130 (2.0824)
	Damping Coefficient (%)	5

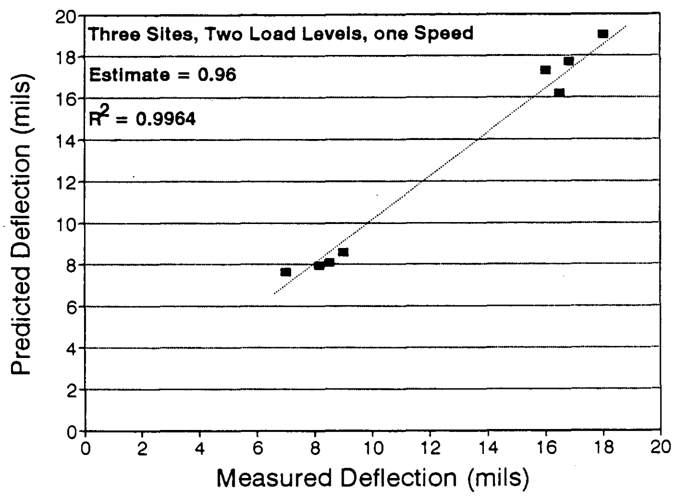
dard dynamic analysis method for the dynamic case, as there is for the static case, a decision was made to compare the predictions with measured response of pavements from moving loads. Figure 3 shows comparisons between field-measured and predicted pavement deflections of asphalt and concrete pavements. As can be seen, high linear correlations between the measured and predicted pavement deflections are found for both asphalt and concrete pavements, (R^2 = 99.9 percent and 99.6 percent, respectively). These high correlations imply that the 3D-DFEM can be used to predict the dynamic response of pavements subjected to moving loads (*3,4*).

Load Equivalency Factors

A sample of overload permit applications was reviewed to determine what truck configurations had been given permits. The sam-



a) Asphalt Pavement



b) Concrete Pavement

FIGURE 3 Dynamic analysis verification. (1 in. = 2.54 cm, 1 ft = 30.48 cm, and 1 kip = 453.7 kg).

ple revealed that permits were requested for trucks with up to nine axles in one group as well as for trucks with single axle loads of 72 kips (32 666 kg). Load equivalency factors (LEFs) were required to account for the variation in truck configurations. There are two types of LEFs: analytical-based LEFs and empirical-based LEFs. Current pavement analysis methods used to develop the analytical-based LEFs incorporate unrealistic assumptions, such as static loads and linear-elastic material properties, whereas empirical LEFs, such as the AASHTO LEFs, are based on data that are limited to single and tandem axle configurations with maximum axle loads of 30 and 48 kips (13 611 and 21 778 kg), respectively.

Because of these limitations, the 3D-DFEM was used to develop LEFs for the overload permitting study. Three LEF sets were developed for flexible, rigid, and composite pavements. Permanent deformation at the pavement surface, which accumulates from different layers, was used as the equivalency criterion for flexible pavement LEFs, whereas total surface deformation, elastic and plastic, was used for rigid and composite pavement LEFs. The LEFs developed incorporated the effect of load repetitions. Figure 4 shows comparisons between Purdue LEFs for conditions similar to those of the AASHO road test and the appropriate AASHTO LEFs (*10–12*). Figure 5 shows the relationship between LEFs and maximum surface deformation. It was found that the rate of increase in the maximum surface deformation with LEFs increases significantly when the LEF exceeds 35. Therefore, a LEF of 35 is used in the permitting procedure as an upper limit for any axle group on an overloaded truck.

Typical Pavement Cross Sections for Indiana

On the basis of an Indiana Highway Inventory Annual Report (*13*), there are approximately 91,500 mi of roads within the state of Indiana. INDOT is responsible for approximately 11,300 mi, or about 28,203 lane-mi. Local government units are responsible for the rest. The road life data base (*14,15*) has detailed information about the cross sections and subgrades for 14,766 lane-mi (more than 50 percent of the total lane miles). From the data available in the road life data base, the pavement structure distribution was obtained for different highway classes: Interstate U.S., and state roads. Typical pavement cross sections shown in Figure 6 were selected to represent different highway classes. These typical cross sections are used for evaluating the damage effect of overloaded trucks at the network level. Table 1 indicates typical values of the material properties used in the analysis.

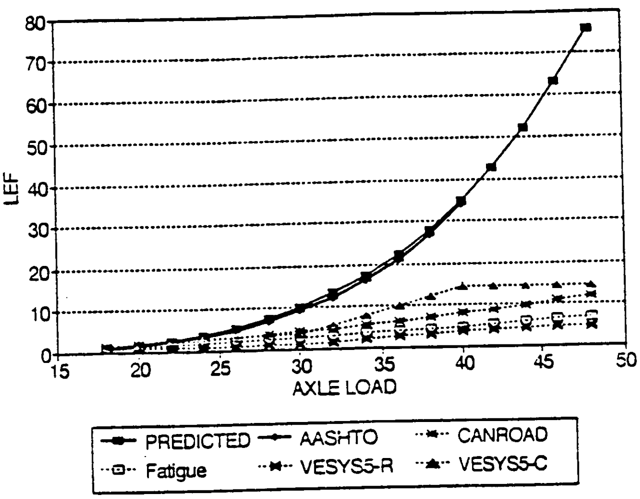
BRIDGE ANALYSIS

Sampling of Bridges and Overloaded Trucks

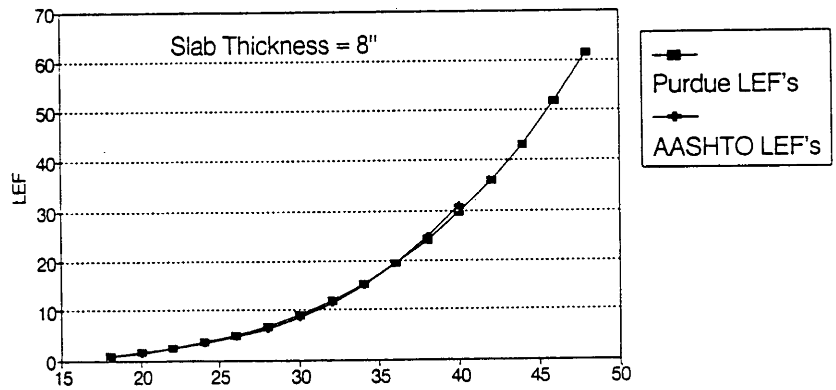
Preliminary information was obtained from INDOT for about 3,700 Indiana highway bridges classified into 19 different groups on the basis of structural form, material type, and type of construction. Within each group, the bridges are divided further into subgroups on the basis of the number of spans and overall length. Using a proportionate, stratified random sampling procedure, 148 bridges were selected.

On the basis of 550 permit requests received by INDOT during 1990 and 1991, 80 representative loading patterns were identified. Various significant truck parameters were identified: the number of axles (N), the distance between the front and the last axle, the wheel base (L), the number of equivalent axles (N_{eq}), the distance of the resulting load from the first axle ($\bar{x}$), and the standard deviation of the vehicle load distribution (x_σ). N_{eq} for any given truck is obtained by counting closely spaced axles [i.e., within 9 ft (2.74 m)] as a single equivalent axle.

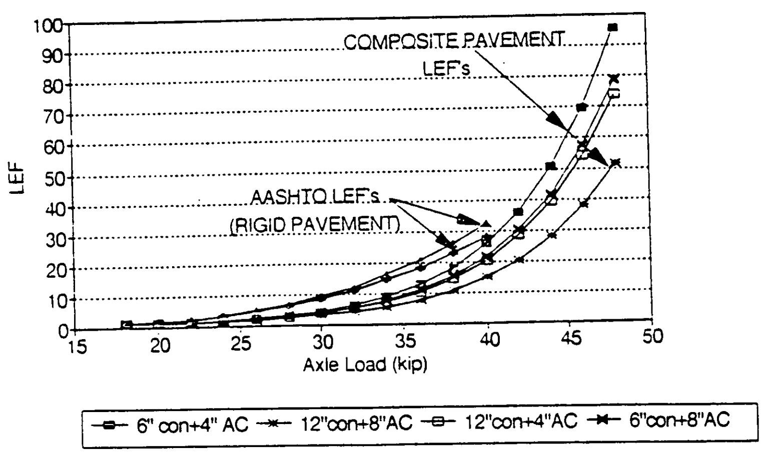
One objective of this study is to formulate a procedure for a route-independent evaluation of overload permit requests. Such a procedure can contain only truck parameters as input variables. Lack of proper representation of truck parameters in the truck sample could lead to serious restrictions on the scope of the results. Hence, it was important to obtain a truck sample that would uniformly cover the range of chief truck characteristics. A uniform sample of 22 trucks was selected. In addition to these trucks, an HS20 design vehicle with variable spacing and two recommended



a) Asphalt Pavement (Single Axle Configuration)



b) Concrete Pavement (Single Axle Configuration)



c) Composite Pavement (Single Axle Configuration)

FIGURE 4 Comparison between Purdue and AASHTO LEFs. (1 in. = 2.54 cm, 1 ft = 30.48 cm, and 1 kip = 453.7 kg).

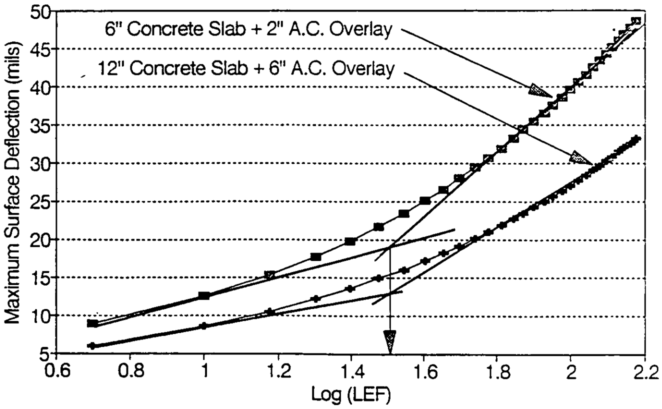


FIGURE 5 Effect of LEFs on maximum surface deflection. (1 in. = 2.54 cm, 1 ft = 30.48 cm, and 1 kip = 453.7 kg).

Indiana toll road loadings—to be used as alternative bridge loadings for bridge design in the future—were included in the sample.

Bridge Analysis and Rating

Detailed information for the 148 bridges selected was obtained from INDOT. The AASHTO Bridge Analysis and Rating System (BARS) was used in the analysis of bridge samples for the 25 selected trucks. The procedures in this program are based on elastic line girders and truss analysis. The rating of various structural components (i.e., girders, floor beams, stringers, and truss members) is performed using the working stress method at the operating stress levels defined in the 1983 AASHTO standard specifications for highway bridges. The operating stress level is 1.36 times the inventory stress level or design stress level, which corresponds to normal traffic. Stringers and girders lie parallel to the direction of traffic, whereas floor beams lie perpendicular to the traffic. Only flexural analysis is performed in this evaluation. The BARS program redistributes 10 percent of the negative moment over the supports to the positive moment area for compact section members of structural steel and composite steel and concrete. No redistribution of negative moments is used for either prestressed concrete or reinforced concrete bridges. The load distribution factors for a two-lane loading and the impact factor specified by the 1983 AASHTO bridge maintenance standards are used in the bridge analysis. The distribution factors are used in distributing the wheel load to the structural components (i.e., girders, stringers, and floor beams).

Data Base

Bridge components considered include stringers, girders, floor beams, and trusses. The BARS program gives the maximum allowable truck load for each of these bridge elements for a given truck. The information is recorded for all the elements. In this study the most critical of these values is used in the subsequent analysis as the maximum allowable load at the operating stress level for a given vehicle and bridge.

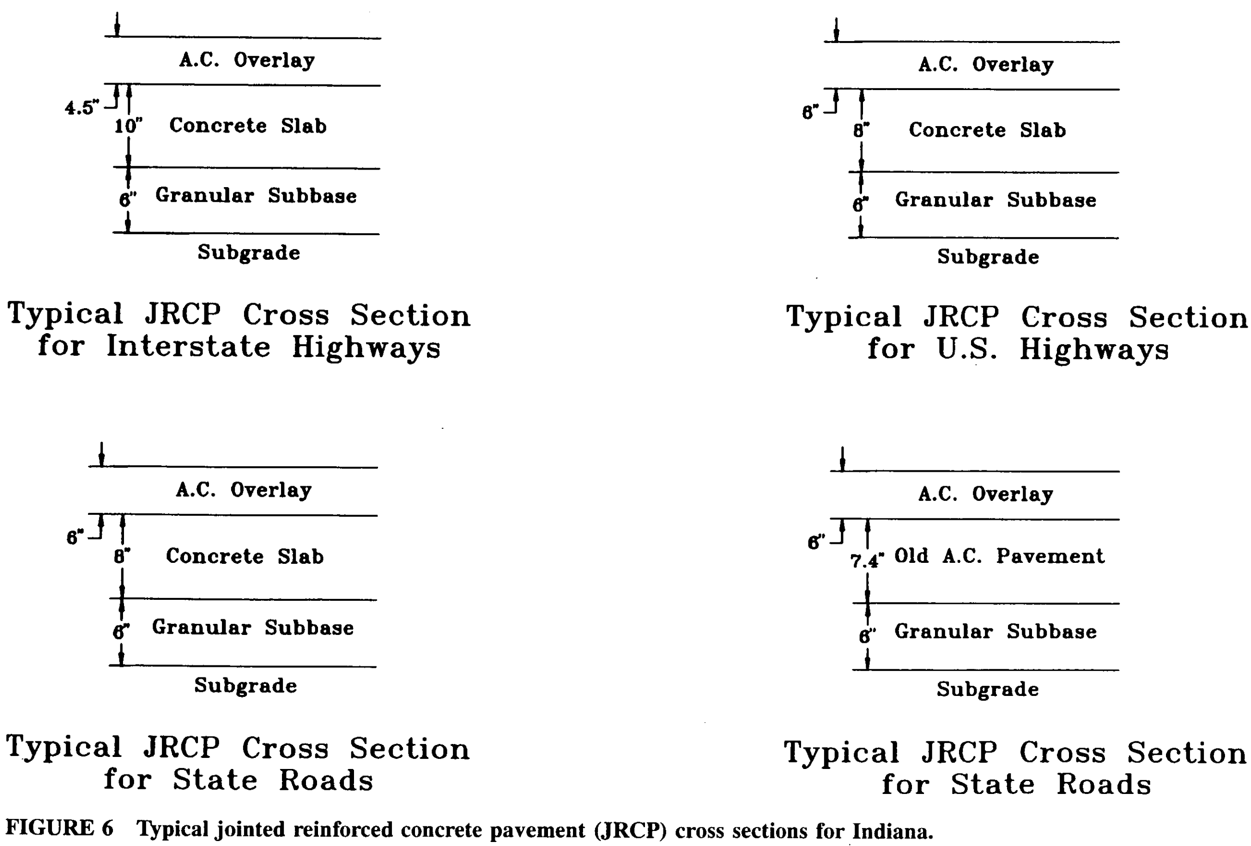


FIGURE 6 Typical jointed reinforced concrete pavement (JRCP) cross sections for Indiana.

Five different material types are also identified among the bridges. They are structural steel, reinforced concrete, composite steel and concrete, prestressed concrete, and composite prestressed concrete.

Statistical Procedure

In general, the allowable load may depend on a number of bridge and truck parameters. The purpose of this study was to identify the primary bridge and truck parameters that explain the variation in the dependent variable (i.e., the allowable load). On the basis of these parameters, different confidence limits were calculated.

A linear regression analysis was performed on various models that relates allowable load as the dependent variable to the bridge and truck parameters. It was assumed that the dependent variable is distributed normally. This assumption was verified at a later stage in the study. The correlation coefficient, r, was used in assessing the importance of each model. The regression models and values for constants at various reliability levels developed for the bridge analysis are shown below.

Route-Independent Model

$$\sqrt{W} = c_1 L + c_2 \quad (1)$$

where

W = maximum allowable load (tons),
L = wheel base (ft), and
c_1, c_2 = regression coefficients.

Route-Dependent Model

$$\sqrt{W} = c_1 \, (HS_{\text{truckcapacity}})L + c_2 \quad (2)$$

where the variables are those defined previously.

OVERLOAD PERMITTING PROCEDURE

Figures 7–10 show the flow chart of the overload permitting procedure. A user-friendly computer software was developed to implement this procedure. The procedure follows these steps:

1. Data entry, which includes

- Permit type (overweight, oversize, or mobile home);
- Vehicle information (overall length, width, and height; number of axles; gross load; axle loads and spacing; company name; and license; and
- Trip information (origin, destination, and route, if any).

The user is permitted to enter, review, and change the data.

2. Load parameters for bridge and pavement analyses are extracted from the vehicle information. Bridge analysis load parameters include wheel base, gross load, and number of equivalent axles. An equivalent axle is any group of axles that are placed within a distance of 9 ft (2.74 m). Pavement analysis load parameters include grouping the trucks into sets based on the distance between axles if less than 5 ft. (1.52 m) and calculating the axle group load, spacing, number of wheels, and number of axles for each axle group.

3. Selection of the level of analysis:

TABLE 2 Route-Independent Model

Factor	Reliability Level	Value
σ for individual predictions		1.031
Coefficient of Correlation (r)		0.830
c_1 / c_2	50%	0.0484 / 6.891
c_1 / c_2	85%	0.0484 / 5.822
c_1 / c_2	90%	0.0484 / 5.570
c_1 / c_2	95%	0.0484 / 5.195
c_1 / c_2	99%	0.0484 / 4.493

TABLE 3 Route-Dependent Model

Factor	Reliability Level	Value
σ for individual predictions		0.686
Coefficient of Correlation (r)		0.93
c_1 / c_2	50%	7.495E-4 / 6.795
c_1 / c_2	85%	7.495E-4 / 6.084
c_1 / c_2	90%	7.495E-4 / 5.916
c_1 / c_2	95%	7.495E-4 / 5.667
c_1 / c_2	99%	7.495E-4 / 5.2

- In network-level (default) analysis, typical pavement cross sections are used representing different highway classes. A route-independent formula is used for bridge analysis.
- In project-level: analysis, the user has to enter the pavement cross-section parameters and material properties. Default values are provided as a guide to the user. A route-dependent formula is used for bridge analysis.

4. Selection of type of analysis:

- Bridge analysis only,
- Pavement analysis only, or
- Bridge and pavement analysis (default).

If the user selects bridge and pavement analyses (the default), the bridge analysis is made first. The pavement analysis will be run

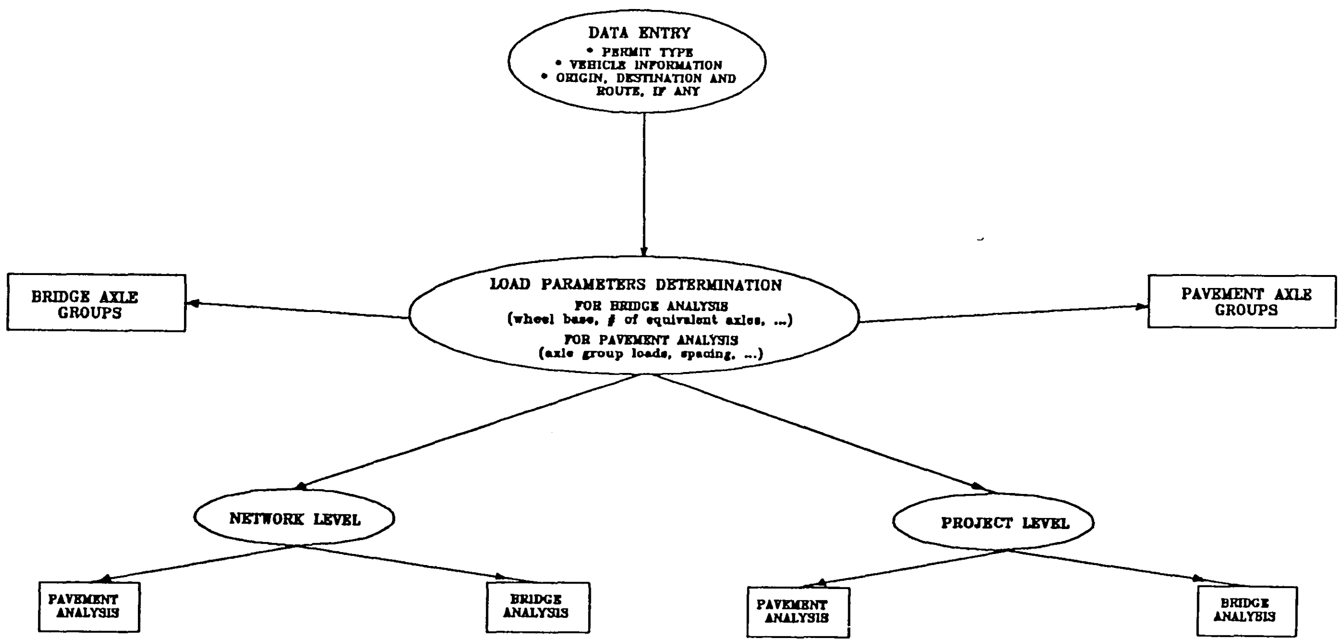


FIGURE 7 Flow chart of the overload permit procedure, Part 1.

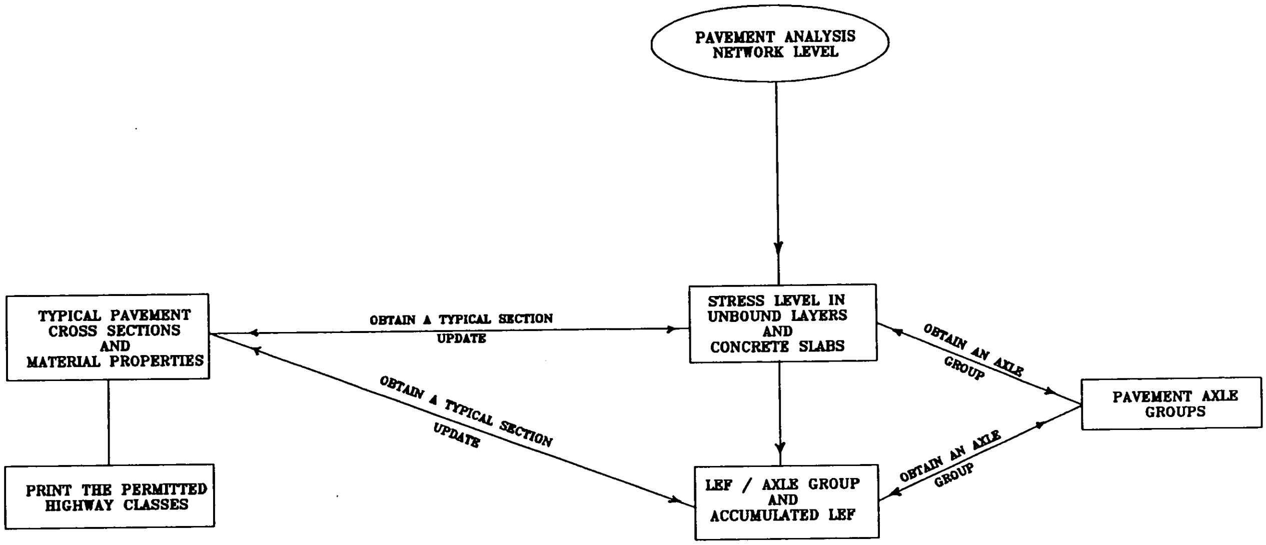


FIGURE 8 Flow chart of the overload permit procedure, Part 2.

regardless of the results of the bridge analysis. If the truck is not permitted, the reason why the truck is not permitted, bridge, pavement or both, will be shown in the permit.

Truck-damage effects on bridges and pavements are evaluated based on the user selections, as described in the next sections.

Network-Level Analysis

Bridge Analysis

The truck must have a minimum of six equivalent axles if the wheel base is more than 70 ft (21.34 m), or a minimum of three equivalent axles if the wheel base is more than 25 ft (7.62 m). The number of equivalent axles for any given truck is obtained by counting closely spaced axles [those within 9 ft (2.74 m)] as a single equivalent axle. Furthermore, the wheel base has to be in the range of 10 to 120 ft (3.05 to 36.6 m). If the truck satisfies the foregoing conditions, the route-independent model mentioned earlier (Equation 1) is used to evaluate the bridge damage. The results of this analysis are a function of truck parameters only.

Pavement Analysis

Typical pavement cross sections are used in this analysis to represent different highway classes (Interstate, U.S., and state roads). Trucks are represented as a set of axle groups. A sample of overload permit applications was reviewed, and it was found that the break point in axle spacing is 5 ft (1.52 m). Therefore, any two

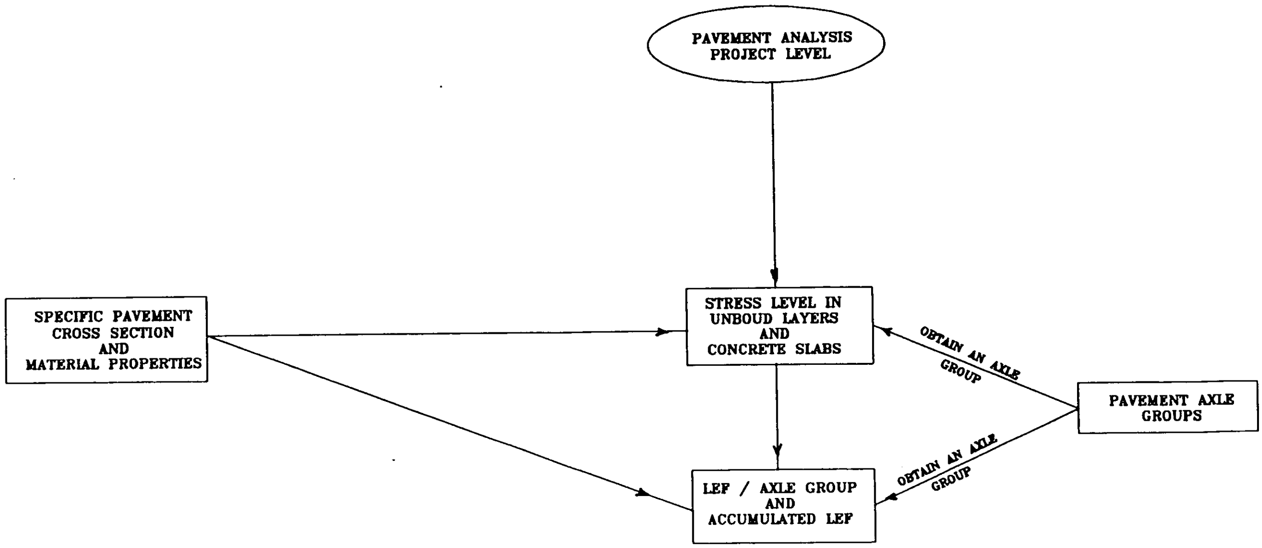


FIGURE 9 Flow chart of the overload permit procedure, Part 3.

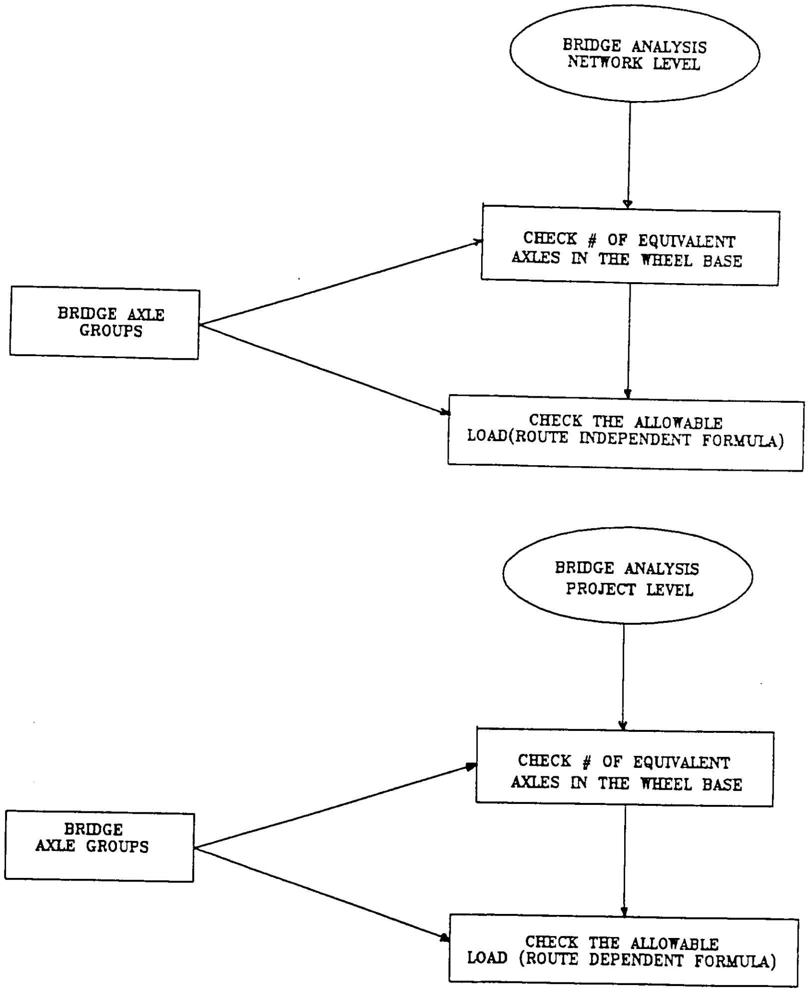


FIGURE 10 Flow chart of the overload permit procedure, Part 4.

successive axles with spacing equal to or less than 5 ft (1.52 m) are considered to be in one group. The pavement analysis involves (*a*) evaluating stress levels, and (*b*) determining LEFs.

Evaluation of Stress Levels When a pavement is subjected to a heavy load, some permanent deformation could develop in one or more of the pavement layers. Figure 11 shows the effect of heavy loads on asphalt and concrete pavements. As can be seen, when the pavements were subjected to an 18-kip (8 167-kg) single axle load (SAL), no permanent deformation developed in any of the unbound layers of the asphalt or the concrete pavements. When a heavy load was applied [a 58-kip (26 315-kg) SAL on the asphalt pavement and a 60-kip (27 222-kg) SAL on the concrete pavement], some permanent deformation developed in the unbound layers of both types of pavement. These permanent deformations developed because the unbound layers were subjected to stress levels higher than their yield stresses. Therefore, if stress levels in the unbound layers are kept below their yield stresses, no permanent deformation is expected and the pavement damage is minimal (*3,4*). Regarding concrete slabs, if the ratio of the stress to the modulus of rupture exceeds 0.5 (*5*), some fatigue damage develops.

The purpose of this evaluation is to estimate stress levels developed by the overloaded truck axle groups in the unbound layers and concrete slabs of the typical pavement sections. These stresses are compared with the corresponding yield stress of the unbound layers and the modulus of rupture of the concrete, respectively. Statistical models were developed to estimate stress levels in the unbound layers and the concrete slabs of the typical sections as a function of truck parameters. Previous analysis (*3,4*) determined that the effect of static loads is more severe for pavements than that of moving loads; therefore, static loads were used in the development of the statistical models. For each of the typical cross sections, if the yield stress in any of the unbound layers, including the subgrade, is exceeded or the concrete stress ratio (stress/modulus of rupture of the concrete) exceeds 0.5, the overloaded truck is not permitted to use this highway class. Further analysis will be made only for the typical cross sections that pass this check (satisfactory cross sections).

Determination of LEFs For each satisfactory cross section, the LEF of each axle group is determined using Purdue LEF sets (*10–12*). If the axle group LEF exceeds a certain limit (35 ESALs), the truck is not allowed to use this highway class. The

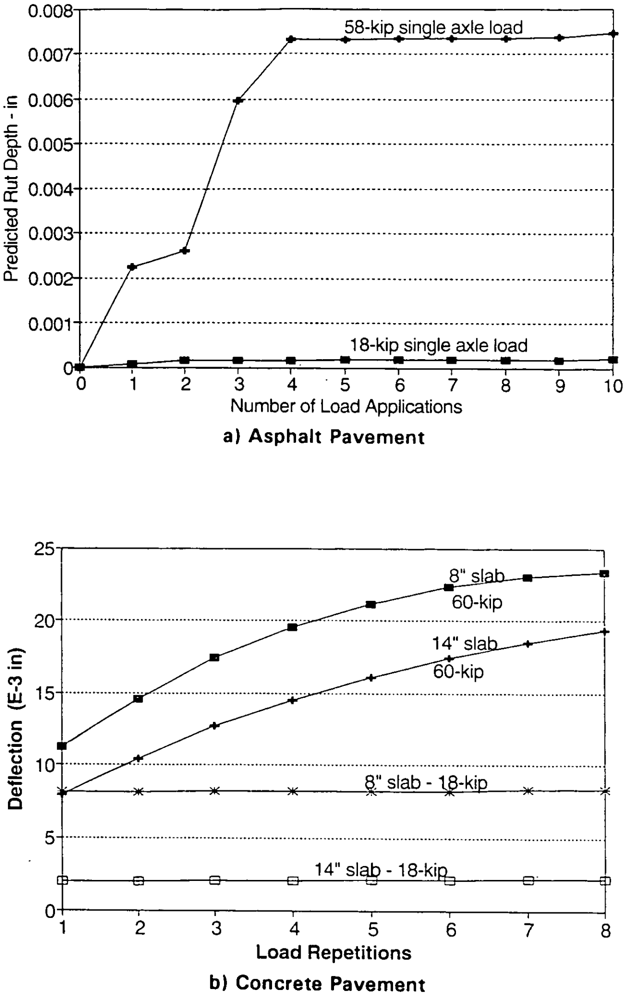


FIGURE 11 Effect of heavy loads on pavements (1 in. = 2.54 cm, 1 ft = 30.48 cm, and 1 kip = 453.7 kg).

35-ESAL limit is based on Figure 5. Also, the accumulated LEF for the truck is calculated by summing the LEFs of all axle groups. If the accumulated LEF exceeds a certain percentage of the average daily truck traffic of a certain highway class, the truck will not be permitted to use this highway class.

The truck is permitted to use highway classes that pass the previous checks. These highway classes are shown on the permit.

Project-Level Analysis

Bridge Analysis

In the bridge analysis, the allowable load at the operating stress level depends on both bridge and truck parameters. The bridge parameter is referred to as the HS truck capacity, which is defined as the maximum gross vehicle load that the bridge can carry within the operating stress level for a vehicle with the same configuration in terms of axles and axle-load distribution as the standard HS20 truck with variable axle spacing. In addition the truck has to satisfy both the minimum number of axles per wheel base and length of wheel base (*16*). The route-dependent model mentioned earlier (Equation 2) is used in this analysis.

Pavement Analysis

For the pavement analysis, the user has to provide information about the pavement cross section and material properties, including

- Pavement type (asphalt, concrete, or composite
- Layer thicknesses, and
- Material properties of each type of layer as follows:

–Asphalt surface layer—Modulus of elasticity, Poisson's ratio, damping coefficient, bulk density and G-ratio, expressed as

$$\left(1 - \frac{\text{long-term shear modulus}}{\text{instantaneous shear modulus}}\right)$$

–Granular layers—Modulus of elasticity, Poisson's ratio, initial yield stress, yield function, cohesion, angle of internal friction, damping coefficient, and bulk density.

–Cohesive layers—Modulus of elasticity, Poisson's ratio, initial yield surface, yield function, water content, cohesion, angle of internal friction, damping coefficient, and bulk density.

Typical default values for these properties are provided to the user. As for the network-level analysis, the overloaded truck has to pass the stress level and LEF checks in order to obtain a permit.

SUMMARY AND CONCLUSIONS

This study, conducted at Purdue University, was funded by INDOT and FHWA to develop an enhanced procedure for permitting overloaded trucks. In the procedure, damage effects of overloaded trucks are evaluated for pavements and bridges. The bridge analysis includes two steps:

1. The truck must satisfy a minimum of six equivalent axles if the wheel base is more than 70 ft (21.34 m), or a minimum of three equivalent axles if the wheel base is more than 25 ft (7.62 m). The number of equivalent axles for any given truck is obtained by counting closely spaced axles, those within 9 ft (2.74 m) as a single equivalent axle. Second, the wheel base has to be in the range of 10 to 120 ft (3.05 to 36.6 m).
2. The overloaded truck weight is checked versus the allowable weight calculated from statistical models based on analysis using BARS and selected samples of bridges and overloaded trucks.

A three-dimensional, nonlinear dynamic analysis of rigid, flexible, and composite pavements was used to develop statistical models to correlate pavement damage with load and cross-section parameters. Repeated axle loads moving at different speeds were considered, and realistic material models, such as viscoelastic and elastic-plastic models, were used for the pavement materials and subgrade. The pavement analysis can be conducted in two steps:

1. Check whether the stress level developed by the overloaded truck axle groups in the unbound layers of the pavement structure, including the subgrade, exceeds the layers' yield stresses, and whether the ratio of stress to modulus of rupture for the concrete

exceeds 0.5. The stress level in this step is estimated on the basis of static loads.

2. Calculate the LEF of each axle group of the overloaded truck using Purdue LEF sets and check whether this LEF exceeds a certain limit. Also, check that the accumulated LEF for the truck, which is the sum of the LEFs of the truck axle groups, exceeds a certain limit. This analysis is based on moving loads.

A user-friendly computer software was developed to implement the permitting procedure, one that allows a user to run a route-independent damage analysis for overloaded trucks at the network level, as well as at the project level, for specific pavements and bridges. At both levels, three options are available: (*a*) to check for pavements only, (*b*) to check for bridges only, or (*c*) to check for both (the default). At the project level, a user is allowed to enter all of the cross-section and load parameters. Also, typical values for material properties are available as default values.

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