

Analysis of Axle Loads and Axle Types for the Evaluation of Load Limits on Flexible Pavements

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The Commonwealth of Pennsylvania is responsible for 44,000 mi of roads, the majority of which have pavements with limited structural capacity. The state has the authority to restrict axle loads on its roads if it is believed that those axle loads would result in excessive damage to the pavement structure. Consequently, a procedure for establishing axle load restrictions is necessary. As part of the development of a framework for load limit analysis, an evaluation was made of the sensitivity of pavement response and predicted performance to variations in loads, layer moduli, and layer thicknesses. To evaluate the effect of axle loads under a variety of conditions, a theoretical elastic layer analysis was conducted that considered various load magnitudes and configurations for different pavement thicknesses and material properties. It was found that axle configuration (single-, tandem-, and triple-axle assemblies) did not significantly affect theoretical pavement response, provided that the load per tire remained the same. In addition, a comparison of predictions from various performance models indicated that the sensitivity of predicted performance to the design variables considered can vary depending on the performance model and failure criteria used. Equivalence factors calculated for a broad range of pavement structures were also examined. It was found that AASHTO equivalence factors do not vary significantly with different pavement structures. Consequently, the use of these equivalence factors for evaluating the effects of alternative load limit policies is not advisable.

Low-volume roads make up the greater part of most road networks in the world, including in the United States where the Interstate highway system makes up less than 2 percent of total road mileage. Much of the roadway network in this country is composed of thin, flexible pavement structures that are intended to carry low volumes of traffic. In Pennsylvania these are termed Type D (collector) and Type E (local) roads.

Every state has a specified maximum legal load limit for a single axle, for a tandem axle, and for maximum gross vehicle weight (GVW). Often, however, low-volume roads do not have adequate structural capacity to carry axle loads at the legal load limit for all, or part, of the year. In the spring when the ground is thawing, these pavements have significantly reduced bearing capacity, and often the expense of importing non-frost-susceptible materials is prohibitive. To deal with

this problem, some legal codes allow the posting of load limits below the state's legal maximum.

The Commonwealth of Pennsylvania has 44,000 mi of roads under its jurisdiction. About two-thirds of these are low-volume roads that, in other states, would be the responsibility of local governments. Because a majority of these low-volume roads have pavements with limited structural capacity, the state has the authority to restrict axle loads if it is believed that those axle loads would result in excessive damage to the pavement structure. In Pennsylvania, the establishment of load restrictions below the legal load limit is authorized by Section 4902 of the Motor Vehicle Code (*1*). Under this law, commonwealth and local authorities may impose restrictions on the weight or size of vehicles allowed to operate on a particular route whenever it is determined that, without such restrictions, excessive damage may occur to the road. This load limit specification is based on GVW and was selected on the basis of engineering judgment and experience.

The posting of load limits on the basis of GVW poses a fundamental problem. The load from the vehicle is transmitted through the axle tires, and the load applied by each tire depends on the number of tires per axle. Tandem and triple axles have more tires than do single axles, so they can carry a heavier load while putting the same stress on the pavement as a lighter-loaded single axle. Because pavement performance is related more accurately to axle loads and axle types than to GVW, the posting of load limits on flexible pavements should be based on a maximum load for a given axle type.

To determine the appropriate load restrictions for various axle types and pavement conditions, it is important to evaluate how predicted performance varies with different axle loads and axle configurations and with various pavement layer thicknesses and material properties. In this paper the effects of these design variables on calculated pavement response and predicted pavement performance are examined. The results of the analysis were important in the development of a procedure for determining load restrictions in Pennsylvania.

ANALYSIS OF AXLE LOADS AND AXLE TYPES

The analysis of axle loads and axle types was conducted by examining theoretical solutions of a linear elastic pavement analysis computer program called BISAR (*2*). A three-layer

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pavement structure (surface, base, and subgrade) was selected for the analysis because it is representative of typical pavements on low-volume roads in Pennsylvania. Three different levels (associated with low, medium, and high values) were chosen for various pavement parameters (surface thickness, surface modulus, base thickness, base modulus, and subgrade modulus). Because of the importance of load magnitude in this study, five different levels were selected for this variable. The values chosen for the different factor levels (Table 1) represent a broad range of pavement and loading conditions.

The possible combinations of all values of all factors result in $3^5 \times 5$, or 1,215, observations for each axle configuration included in the study. For all of these combinations, pavement deflections, horizontal strain at the bottom of the asphalt concrete layer, and vertical strain at the top of the subgrade were calculated. These pavement response parameters are commonly used for predicting pavement performance, and it was therefore important to evaluate how they are affected by the different variables included in the study. In the discussion that follows, the findings from the analysis are presented. The discussion has been limited to subgrade strain because this pavement response parameter has been strongly related to pavement performance. The trends observed for the other pavement response parameters were found to be similar to those for subgrade strain, and they are therefore not reported separately.

Effect of Variables on Pavement Response

Plots are shown in Figures 1-3 of maximum vertical subgrade strain versus load per tire for the three axle configurations (single, tandem, and triple) for cases in which the layer moduli and thicknesses are fixed at the low, middle, and high levels selected for these variables (Table 1). These plots indicate that an increase in load results in an increase in subgrade strain, as would be expected. The significant observation is that the plots for the three different axle configurations are almost identical in both shape and magnitude. This indicates that, theoretically, similar pavement response will occur with different axle configurations as long as the load per tire is constant.

To study the effect of axle configuration on subgrade strain along the direction of vehicle movement (longitudinal direc-

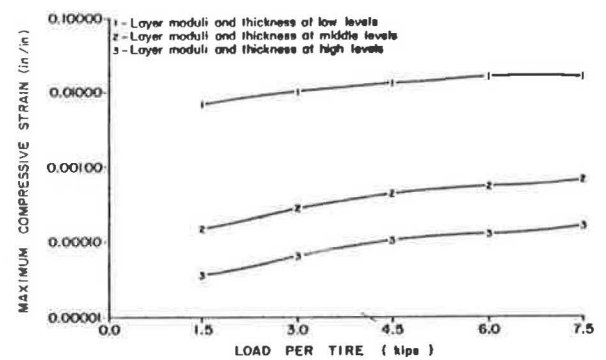


FIGURE 1 Maximum subgrade compressive strain versus load per tire for a single-axle configuration.

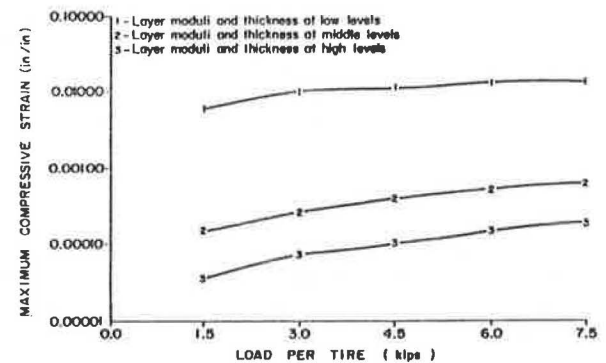


FIGURE 2 Maximum subgrade compressive strain versus load per tire for a tandem-axle configuration.

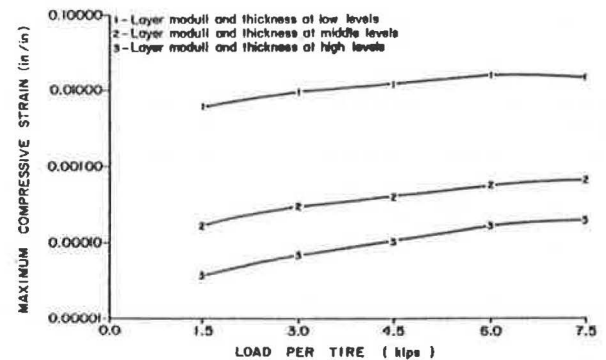


FIGURE 3 Maximum subgrade compressive strain versus load per tire for a triple-axle configuration.

TABLE 1 LEVELS OF VARIABLES USED IN THE STUDY

Variable	Level	Unit
Load (all dual tires)		
Single axle	6; 12; 18; 24; 30	Kips
Tandem axle	12; 24; 36; 48; 60	Kips
Triple axle	18; 36; 54; 72; 90	Kips
Surface thickness (T_1)	1; 5.5; 10	Inches
Surface modulus (E_1)	80×10^3 ; 540×10^3 ; $1,000 \times 10^3$	psi
Granular base thickness (T_2)	3; 9; 15	Inches
Granular base modulus (E_2)	10×10^3 ; 40×10^3 ; 70×10^3	psi
Subgrade modulus (E_3)	3×10^3 ; 10×10^3 ; 17×10^3	psi

tion), plots of subgrade strain versus longitudinal position for 18-kip single, 36-kip tandem, and 54-kip triple axles were drawn using the same scale. The plots that resulted when all factors were at middle levels are shown in Figures 4-6. The plots indicate that the distribution of the subgrade strain along the longitudinal direction is different for the three axles. Although there is one cycle of strain for the single-axle configuration, there are two cycles of strain for the tandem-axle and three cycles of strain for the triple-axle configurations.

These plots suggest that the damaging effect of axle configurations may be different, although the magnitude of the maximum subgrade compressive strain is the same for all three cases. The triple axle may be more damaging than the single or tandem axle because it causes more cycles of strain in the pavement. Similarly, the effect of a tandem-axle load may be more damaging than that of a single-axle load. To evaluate this factor more closely, an analysis was performed on data collected at the AASHO Road Test.

The AASHTO design procedure is one of the most widely used methods for designing flexible pavements. The procedure is based on the results of the extensive AASHO Road Test conducted in Ottawa, Illinois, from 1958 to 1960. The road test site contained six main loops, of which Loop 3 had traffic loads of 12-kip single axles and 24-kip tandem axles, respectively, on two separate lanes (3). These are the only data from the road test for single and tandem axles carrying the same load per tire on identical pavement sections.

Plots of performance data from Loop 3, for 24-kip tandem axles versus 12-kip single axles, are shown in Figures 7 and 8. The data points are scattered along the line of equality, indicating that the two axle configurations caused similar pavement performance. To provide a measure of the variation in the observed performance, a root-mean-square (RMS) statistic was calculated as follows:

$$RMS = \left[\frac{\sum_{i=1}^n (\log_{10} N_{12} - \log_{10} N_{24})^2}{n} \right]^{1/2} \quad (1)$$

where

$\log_{10} N_{12}$ = logarithm of the number of 12-kip single-axle load applications before failure,

$\log_{10} N_{24}$ = logarithm of the number of 24-kip tandem-axle load applications before failure, and

n = number of pairs of identical pavement sections.

For terminal serviceability indices of 1.5 and 2.5, the RMS statistics were calculated to be 0.19 and 0.20, respectively. Similarly, RMS statistics were calculated for the replicate sections at the AASHO Road Test and were found to have values of 0.15 and 0.16 for terminal serviceability indices of 1.5 and 2.5, respectively. Because the RMS statistics calculated for the Loop 3 sections are close to those for the replicates, it is unlikely that significant variations in observed pavement performance can be attributed to the difference in axle configurations. This provides some measure of plausibility to

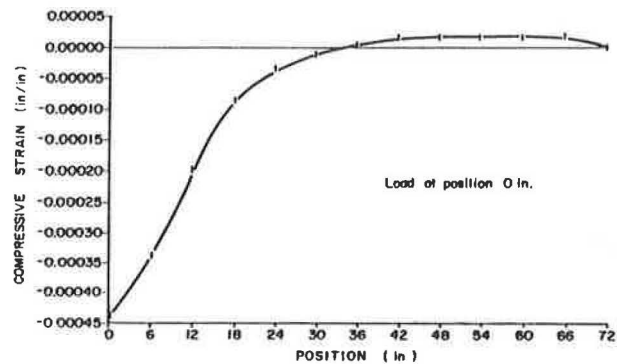


FIGURE 4 Subgrade compressive strain versus position, with factors at middle levels, for an 18-kip single-axle load.

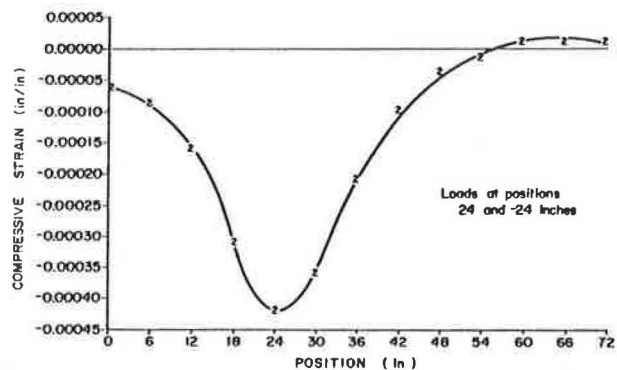


FIGURE 5 Subgrade compressive strain versus position, with factors at middle levels, for a 36-kip tandem-axle load.

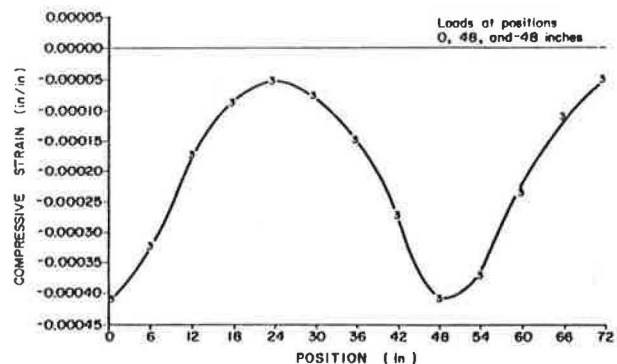


FIGURE 6 Subgrade compressive strain versus position, with factors at middle levels, for a 54-kip triple-axle load.

the theoretical inference that different axle configurations will cause no significant variations in pavement performance provided that the load per tire is constant for all axle configurations.

One possible explanation of the similar pavement performance resulting from 12-kip single-axle loads and 24-kip tandem-axle loads, even though Figures 4 and 5 indicate that the tandem axle causes two strain cycles versus one strain cycle for the single axle, is that the theoretical strain basins are calculated assuming static loading conditions. Under dynamic loading conditions the pavement stiffness will be higher, and there will be a smaller difference between the strain basins caused by single- and tandem-axle configurations.

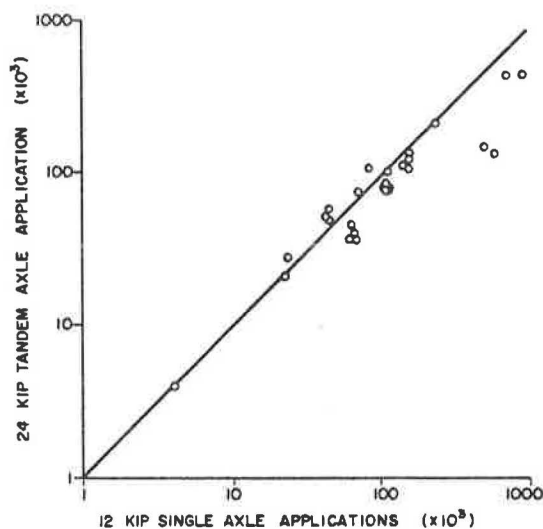


FIGURE 7 Comparison of the performance of identical pavement sections subjected to 12-kip single-axle and 24-kip tandem-axle loadings [weighted axle applications to present serviceability index (PSI) = 1.5].

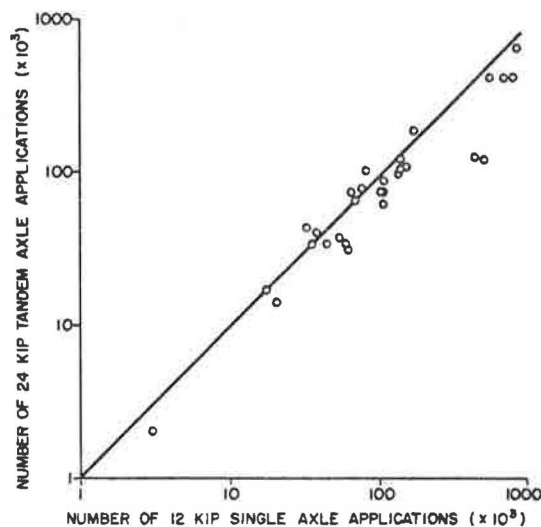


FIGURE 8 Comparison of the performance of identical pavement sections subjected to 12-kip single-axle and 24-kip tandem-axle loadings (weighted axle applications to PSI = 2.5).

In addition to the study of the effects of axle load and axle configuration, an evaluation was made of the effects of layer moduli and thicknesses on calculated pavement response. For this evaluation, each of the independent variables considered was varied from low to high levels, while the other independent variables were kept at low, middle, and high levels successively. Figures 9-11 show the effect of the six independent variables on the calculated value of subgrade compressive strain. The arrows in the boxes indicate whether the variable in question had a positive (pointing right) or negative (pointing left) effect on maximum subgrade strain.

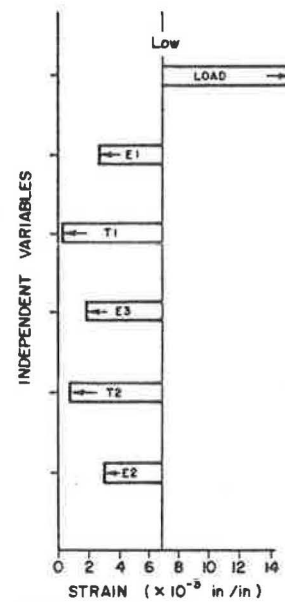


FIGURE 9 Change in subgrade strain when each factor is varied from low to high levels, with all other factors at low levels.

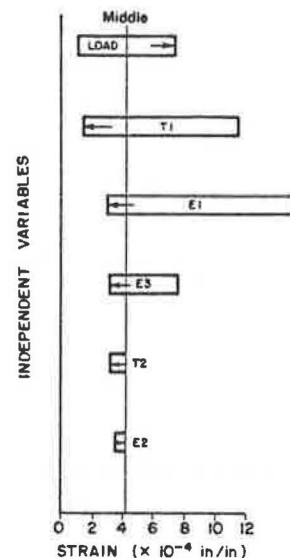


FIGURE 10 Change in subgrade strain when each factor is varied from low to high levels, with all other factors at middle levels.

The levels selected for the pavement parameters cover a wide practical range. The vertical line indicates the value when all variables are held at one level. These figures give a good indication of how sensitive the dependent variable (subgrade strain) is to the variation of any one of the independent variables.

It can be seen that at low levels pavement response is highly sensitive to load, surface thickness, and base thickness. It can therefore be inferred that, for pavements with weak materials and on poor subgrade, subgrade strain can be reduced by increasing the thickness of the surface and the base layers. At

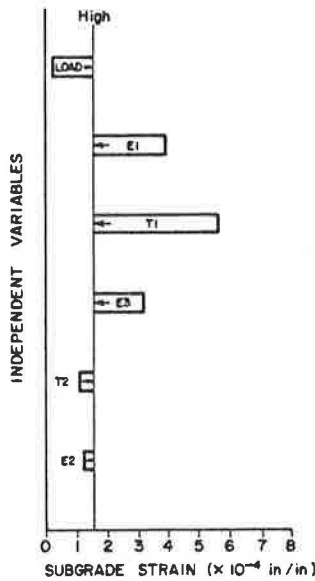


FIGURE 11 Change in subgrade strain when each factor is varied from low to high levels, with all other factors at high levels.

the middle and high levels, pavement response is quite sensitive to load, surface thickness, and surface modulus. For these pavements the subgrade strain can be reduced by increasing the thickness and improving the quality of the surface. At the middle and high levels, pavement response is not particularly sensitive to base thickness and base modulus. Subgrade modulus affects pavement response at all levels.

Effects of Variables on Predicted Pavement Performance

In addition to evaluating the sensitivity of pavement response to axle loads, axle configurations, layer moduli, and layer thicknesses, the sensitivity of predicted pavement performance to these design variables was examined. Even though pavement response is correlated with pavement performance, the relationship between these two variables is usually nonlinear, and it is therefore important to evaluate the sensitivity of predicted pavement performance separately. For this evaluation, performance estimates were calculated using several existing models in order to determine whether the effects of the design variables vary depending on the performance model used. The prediction equations selected for this study were (a) the simplified rational pavement design (SRPD) performance equation developed by Luhr (4); (b) the Shell performance models based on subgrade and asphalt strain criteria (5, 6); (c) the fatigue relationship developed by ARE for FHWA (7); and (d) the performance model developed for the Pennsylvania load limit analysis procedure (8). All of these models use multilayer linear elastic theory for evaluating pavement response parameters used in predicting pavement performance.

Figure 12 shows a summary of the performance prediction equations considered for this particular study. The fatigue relationships developed by Shell for pavement design

A. SRPD model:

$$\log_{10} N_x = 2.15122 - 597.662 (\epsilon_{sg}) - 1.32967 \log_{10} (\epsilon_{sg}) + \log_{10} [(PSI_i - TSI) / 2.7]^{1/2}$$

where

N_x = number of weighted applications of axle load x before pavement reaches a specified terminal serviceability index (TSI),

ϵ_{sg} = subgrade compressive strain due to axle load x ,

PSI_i = initial present serviceability index of pavement, and

TSI = terminal serviceability index.

B. Shell model based on subgrade strain:

$$\epsilon_{sg} = 0.028 N^{-0.25}$$

where ϵ_{sg} is permissible compressive strain in subgrade and N is number of strain repetitions.

C. ARE model:

$$W_{18} = 9.73 \times 10^{-15} (1/\epsilon_t)^{5.16}$$

where W_{18} is weighted 18-kip applications before Class 2 cracking and ϵ_t is tensile strain at the bottom of the asphalt surface layer.

D. Performance model for Pennsylvania load limit analysis procedure:

$$\begin{aligned} \log_{10} N_x = & 4.508 - 436.992 (\epsilon_{sg}) + 0.092 (H_2 + H_3) \\ & + 0.141 (PSI_i * TSI) - 0.014 [TSI(H_1 + H_2 + H_3)] \\ & + 3.382 \log_{10}(H_1 + H_2) - 0.319 \log_{10}[(PSI_i * H_2) + 1] \\ & - 1.987 \log_{10}(TSI * H_1) - 0.299 H_2 - 0.00018 P \\ & + 0.041 (H_1 * H_2) \end{aligned}$$

where

N_x = number of applications of axle load x ,

ϵ_{sg} = maximum subgrade vertical strain,

H_1 = surface layer thickness (inches),

H_2 = base layer thickness (inches),

H_3 = subbase layer thickness (inches),

PSI_i = current present serviceability index,

TSI = terminal serviceability index, and

P = load per tire (lb).

FIGURE 12 Performance models used in the sensitivity analysis.

purposes are shown in Figure 13. Two sets of fatigue curves for two different asphalt fatigue characteristics ($F1$ and $F2$), are shown in the figure. As a general guide, the $F1$ curves are indicative of the fatigue characteristics of asphalt mixes with moderate bitumen and voids content, and the $F2$ curves characterize the fatigue performance of mixes with relatively higher voids content (6).

Strain data generated in the sensitivity analysis of pavement response were used in the selected performance models to determine performance estimates for various combinations of the independent variables included in the study. The independent variables considered were load, surface modulus ($E1$), base modulus ($E2$), subgrade modulus ($E3$), surface thickness ($T1$), and base thickness ($T2$). Only one type of axle configuration (single axle) was considered because the results presented previously indicated that this factor has no significant effect as long as the load per tire is constant.

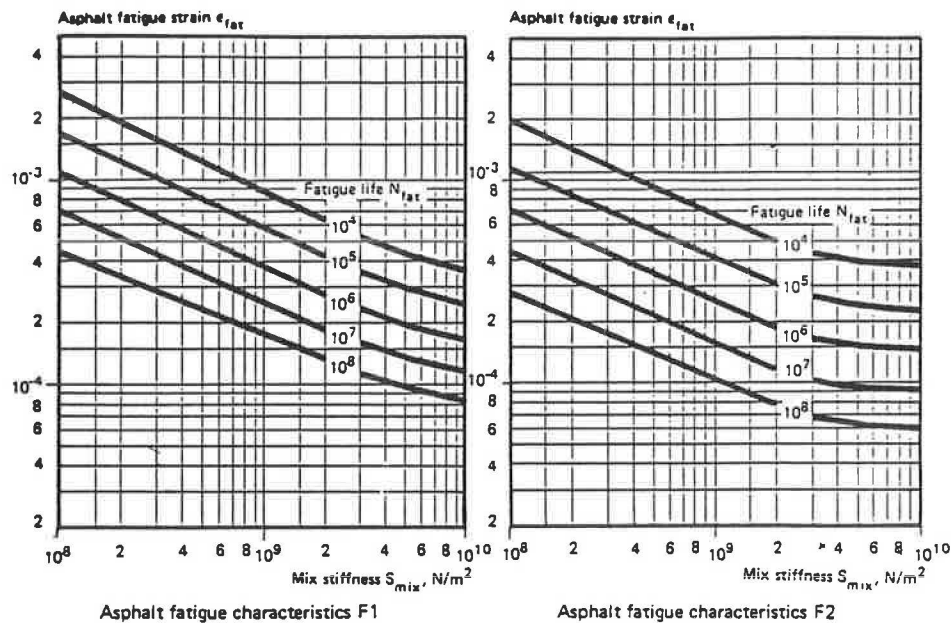


FIGURE 13 Shell fatigue relationships for flexible pavement design (6).

As was the case in the sensitivity analysis for pavement response, each of the independent variables considered was varied from low to high levels while the other independent variables were kept at one level (low, middle, or high). Figures 14-18 show the effect of each of the six independent variables on the performance estimates calculated from the prediction equations. Each figure shows the change in the predicted number of applications to failure when each independent variable is varied from low to high levels while all other variables are kept at middle levels. The vertical line in each of the figures indicates the value for predicted performance when all variables are held at middle levels. The bar charts give a fairly good indication of the sensitivity of predicted pavement performance to variations in any one of the independent variables for an average set of conditions.

From the figures, it can be observed that predicted pavement performance is quite sensitive to load; to surface thickness; and, to a lesser degree, to the surface modulus and the subgrade modulus. The effect of the base modulus is relatively small for performance models based on subgrade strain, but it is relatively significant for performance models based on asphalt tensile strain. In addition, the effect of base thickness is minor for performance models based on subgrade strain, with the possible exception of the prediction equation developed for the Pennsylvania load limit analysis procedure. The results therefore indicate that the sensitivity of predicted performance to the different independent variables can vary according to the model used. In addition, performance predictions are also affected by performance criteria. For the conditions considered, the predicted number of applications to failure using asphalt strain are less than for those performance models based on subgrade strain. It should be recognized, however, that the subgrade strain models may govern in other cases. Consequently, for the development of a load limit analysis procedure, it may be important to consider different performance criteria in order to determine the appropriate load restrictions for different pavement structures.

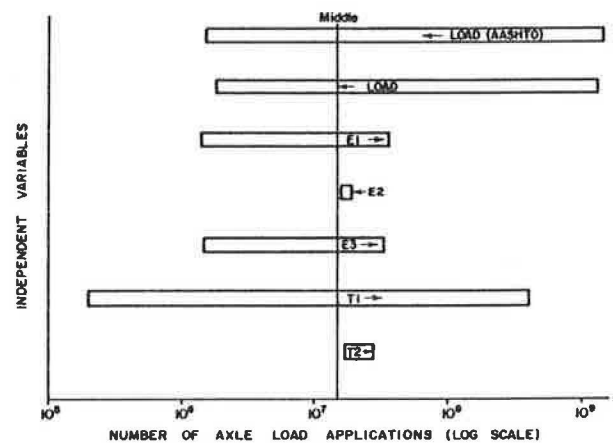


FIGURE 14 Change in applications to failure when each factor is varied from low to high levels, with all other factors at middle levels (Shell model based on subgrade strain).

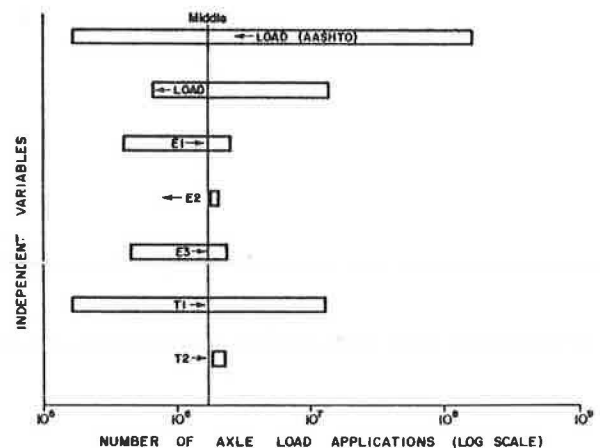


FIGURE 15 Change in applications to failure when each factor is varied from low to high levels, with all other factors at middle levels (SRPD model).

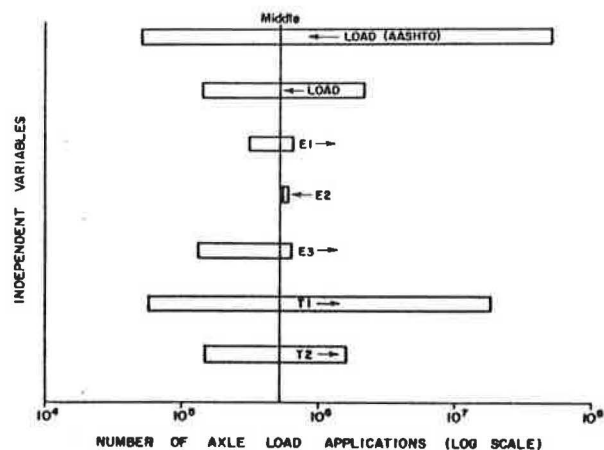


FIGURE 16 Change in applications to failure when each factor is varied from low to high levels, with all other factors at middle levels (Pennsylvania load limit performance equation).

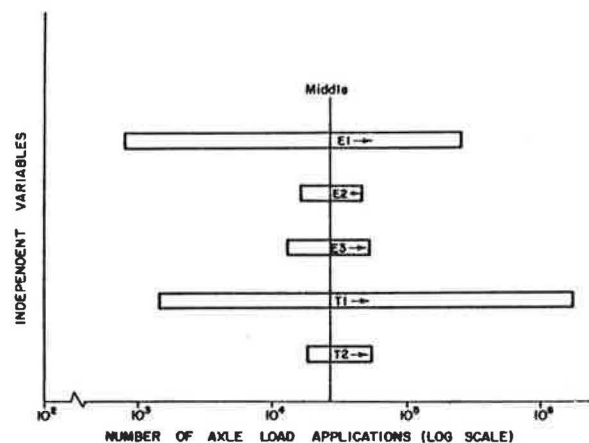


FIGURE 17 Change in applications to failure when each factor is varied from low to high levels, with all other factors at middle levels (ARE model).

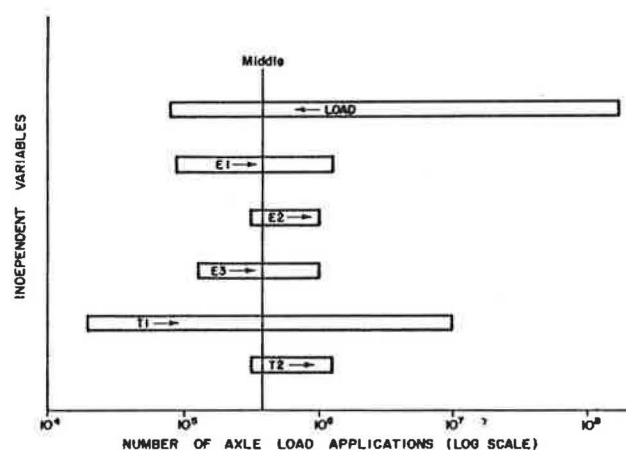


FIGURE 18 Change in applications to failure when each factor is varied from low to high levels, with all other factors at middle levels (Shell fatigue performance relationships).

EVALUATION OF AXLE LOAD EQUIVALENCE FACTORS

Figures 14-16 also show the sensitivity of performance predictions to load when AASHTO equivalence factors are used to determine the predicted number of applications to failure. As mentioned previously, the vertical line in each figure shows the value for the predicted number of allowable load applications when all variables considered are at middle levels. Inasmuch as an 18,000-lb axle load represents the middle level for the load factor at the single-axle configuration (Table 1), the vertical line also indicates the predicted number of allowable 18-kip applications. By using the AASHTO equivalence factor for 6-kip and 30-kip single-axle loadings, the equivalent number of 6-kip and 30-kip load applications corresponding to the predicted number of allowable 18-kip applications can be determined. The use of AASHTO equivalence factors with the performance predictions from models based on subgrade strain is appropriate because all three models (i.e., Shell, SRPD, Pennsylvania load limit equation) were developed from AASHTO Road Test data using Present Service Index (PSI) as the performance criterion. The horizontal bars [labeled "LOAD (AASHTO)"] at the top of Figures 14-16 show the effect of load on predicted performance as determined from the AASHTO equivalence factors.

It may be observed from Figure 14 that, for the case in which factors are at middle levels, the performance predictions from the Shell model based on subgrade strain agree reasonably well with the predictions using the AASHTO equivalence factors. In contrast, the predictions from the other two performance models based on subgrade strain show significant differences (Figures 15 and 16). For these models, the predicted number of 6-kip applications to failure is much less than that determined using the AASHTO equivalence factor for a 6-kip single-axle loading. However, the predicted number of allowable 30-kip applications is greater than that determined using the appropriate equivalence factor that, for a 30-kip single-axle loading, has a mean value of about 9.0 for a range of structural numbers.

The AASHTO equivalence factors, calculated from the AASHTO performance equation, do not vary significantly with structural number. This is seen in Table 2, which gives the means and the standard deviations of calculated equivalence factors for a range of structural numbers from 1.0 to 6.0. In contrast, the equivalence factors calculated from observed AASHTO performance data show much more variability, as shown in Figure 19. The equivalence factors based on observed data were determined by analyzing identical pavement sections that carried different loads at the AASHTO Road Test. For any particular pavement structure, equivalence factors were calculated using the following equation:

$$e_x = \frac{N_{18}}{N_x} \quad (2)$$

where

TABLE 2 MEANS AND STANDARD DEVIATIONS OF EQUIVALENCE FACTORS CALCULATED FROM AASHTO PERFORMANCE EQUATION

Single-Axle Load (kips)	Terminal Serviceability Index			
	2.0		2.5	
	Mean	Standard Deviation	Mean	Standard Deviation
6	0.01	0.001	0.01	0.003
12	0.18	0.008	0.20	0.019
24	3.48	0.125	3.20	0.262
30	9.28	0.620	8.07	1.240

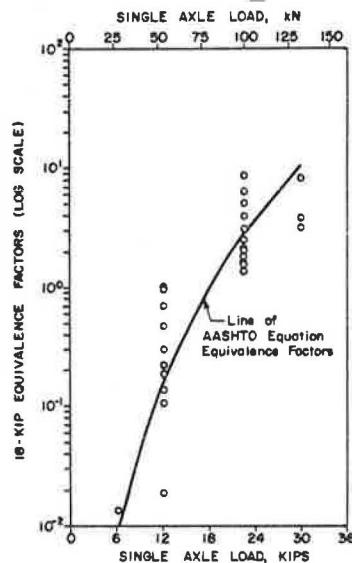


FIGURE 19 Measured and AASHTO-calculated 18-kip equivalence factors for single-axle loads.

- e_x = equivalence factor for axle load x ,
 N_{18} = number of 18-kip applications required for a particular pavement structure to reach a specified value or PSI, and
 N_x = number of applications of load x required for the pavement structure to reach the same value of PSI.

The means and standard deviations of equivalence factors determined from observed data for 6-, 12-, 22.4-, and 30-kip single-axle loads are given in Table 3.

To evaluate the sensitivity of performance predictions to a wide range of pavement designs, 18-kip equivalence factors for 6-, 12-, 24-, and 30-kip single-axle loadings were calculated for each combination of layer moduli and thicknesses included in the load limit factorial study. Inasmuch as comparisons are being made relative to AASHTO equivalence factors, the performance equations based on subgrade strain were used in the calculations. As mentioned previously, these models were developed using AASHTO Road Test data with

PSI as the performance criterion. Table 4 gives the means and standard deviations of the equivalence factors obtained.

It may be observed from the table that the variability in the calculated equivalence factors from the performance models based on subgrade strain is greater than the variability found in the equivalence factors determined using the AASHTO performance equation (Table 2). However, it should be recognized that the statistics presented are for a broad range of pavement designs, and the variability obtained simply reflects the sensitivity of the performance predictions to different designs. That AASHTO equivalence factors show relatively small variations for a range of structural numbers indicates that the AASHTO equivalence factors are not as sensitive to different pavement designs as are those from the other performance models considered. For a terminal serviceability index of 1.5, and for any given axle loading, the AASHTO equivalence factors do not vary with structural number, as determined from the following equations used to calculate AASHTO equivalence factors (9):

$$\log_{10} \frac{W_{t_x}}{W_{t_{18}}} = 4.79 * \log_{10}(18 + 1) - 4.79 * \log_{10}(L_x + L_2) + 4.33 * \log_{10} L_2 + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}} \quad (3)$$

$$G_t = \log_{10} \left[\frac{4.2 - p_t}{4.2 - 1.5} \right] \quad (4)$$

$$\beta = 0.40 + \frac{0.081 * (L_x + L_2)^{3.23}}{(SN + 1)^{5.19} * L_2^{3.23}} \quad (5)$$

where

- L_x = load on one single-axle or one tandem-axle set (kips),
 L_2 = axle code (1 for single axle and 2 for tandem axle),

TABLE 3 MEANS AND STANDARD DEVIATIONS OF EQUIVALENCE FACTORS DETERMINED FROM OBSERVED AASHO ROAD TEST DATA

Single-Axle Load (kips)	Terminal Serviceability Index			
	2.0		2.5	
	Mean	Standard Deviation	Mean	Standard Deviation
6	0.01		0.01	
12	0.43	0.36	0.40	0.35
22.4	3.81	3.47	4.03	2.86
30	4.66	2.02	6.23	3.01

TABLE 4 MEANS AND STANDARD DEVIATIONS OF EQUIVALENCE FACTORS DETERMINED FROM PERFORMANCE MODELS BASED ON SUBGRADE STRAIN

Performance Model	Single-Axle-Load (kips)							
	6		12		24		30	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
SRPD	0.14	0.06	0.45	0.12	2.11	1.23	4.79	7.38
Shell	0.02	0.02	0.24	0.07	2.81	0.43	6.27	1.55
Pennsylvania load limit equation	0.19	0.07	0.43	0.10	2.48	1.00	6.59	6.63

SN = structural number,

p_t = terminal serviceability, and

β_{18} = value of β_x when L_x is equal to 18 and L_2 is equal to 1.

From Equation 3, it is seen that, for a terminal serviceability index of 1.5, G_t becomes zero and the equivalence factor calculated from Equation 2 becomes only a function of axle load magnitude and axle configuration. This would indicate that the equivalence between an 18-kip single-axle load and any other axle load (L_x) for a terminal serviceability index of 1.5 would be the same for any pavement structure. However, no field data exist to support this conclusion, and as indicated in Figure 19, there is a wide range in the observed AASHTO equivalence factors for the axle loads considered in the AASHO Road Test. Consequently, in view of the relative insensitivity of AASHTO equivalence factors to variations in pavement structure, it would be difficult to justify their use for comparing the effects of different axle loads in the evaluation of alternative load limit policies.

SUMMARY AND CONCLUSIONS

The Commonwealth of Pennsylvania has 44,000 mi of roads under its jurisdiction. About two-thirds of these are low-volume roads that, in other states, would be the responsibility of local governments. Because a majority of these low-volume roads have pavements with limited structural capacity,

the state has the authority to restrict axle loads if it is believed that those axle loads would result in excessive damage to the pavement structure. A procedure for posting load limits is therefore necessary.

As part of the development of a framework for load limit analysis, an evaluation of the sensitivity of pavement response and predicted performance to different design variables was conducted with a view to establishing guidelines for the development of a procedure for load limit analysis. To evaluate the effect of axle loads under a variety of conditions, a theoretical evaluation was conducted that considered various load magnitudes and configurations for different pavement thicknesses and material properties.

The following conclusions, based on the results of this study, are drawn with regard to load limits for flexible pavements:

1. It was found that axle configuration (i.e., single-, tandem-, and triple-axle assemblies) did not significantly affect pavement response, provided that the load per tire remained the same. Because pavement response is correlated with pavement performance, it can be inferred that axle configuration will not have a significant effect on performance as long as the load per tire is constant. Performance data from the AASHO Road Test tend to confirm this theoretical inference. In view of this finding, the determination of load limits based on load per tire is recommended.

2. The results of the analysis show that the sensitivity of predicted performance to the different design variables

considered in the study can vary for different performance models. Consequently, it is important to evaluate the performance model selected or developed for a load limit analysis procedure in order to determine whether the sensitivity of the model predictions to the design variables is consistent with observed performance data. In addition, it may be important to consider different performance criteria because the critical mode of pavement failure will vary for different pavement structures.

3. An evaluation of the sensitivity of predicted performance to different pavement designs was made by calculating 18-kip equivalence factors for a broad range of pavement structures using different performance models. It was found that calculated AASHTO equivalence factors do not vary significantly for different pavement designs. In contrast, equivalence factors determined from observed AASHTO Road Test data, and from the other performance models considered, showed a much wider variation for the range of pavement designs investigated. In view of the relative insensitivity of AASHTO equivalence factors to variations in pavement structure, it would be difficult to justify their use in a load limit analysis procedure for evaluating the effects of different load limit policies. In addition, the equivalence factors calculated from the Pennsylvania load limit procedure are more in agreement with AASHTO Road Test data than the AASHTO equivalence factors.

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