Equivalency Factor Development for Multiple Axle Configurations

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Through the analysis of AASHO pavements a fundamental relationship is developed between subgrade compressive strain and equivalency factor. Other elements such as tensile strain in the surface and deflection were examined, but the best relationship evolved when the subgrade compressive strain was used. Once the basic relation of equivalency factor and strain is developed, the equivalency factors for axle configurations other than single and tandem can be computed over a wide range of loads. The elastic-layered theory was used for computing strain. The computed results were compared to extrapolations of the AASHO equations used to compute equivalency factors. These comparisons were good in some instances; in others, they were not. The equivalency-factor concept can be extended to new size and weight configurations of highway vehicles. Thus it will be possible to include these new loads in both new and rehabilitative pavement design procedures that use the concept of equivalent loadings.

The equivalency factor concept for considering traffic mixes in a simplified way was developed in the pavement research studies at the AASHO Road Test. The load equivalencies have received widespread use, but unless a rational basis is established for extending this concept to new vehicles of changing configuration and increased loads, many pavement design procedures will be obsolete. As loads become heavier and axle configurations change, as reported by Peterson (1), Graves (2), and Chu et al. (3), a problem arises when the AASHO equivalency factors are extrapolated outside the range for which they were developed.

One result of the AASHO Road Test was to develop equivalency factors to estimate how many applications of a load being considered would cause the same amount of damage as one application of a standard load. The results are given for two standard axle configurations: single and tandem axles with loads less than 40 to 48 kips (178 to 214 kN), respectively. Equivalency factors for heavier loads and different axle configurations are extrapolated from the AASHO equivalency factors and are outside the boundaries for which they were developed. Therefore, a more fundamental relationship must be found to facilitate the extrapolation to other axle configurations such as triple axles with heavier loads.

EXISTING METHODS

Field performance data do not exist to determine equivalency factors for non-AASHO Road Test axle configurations (single tires, tridems, etc.). As axle configurations change, it becomes necessary to estimate the damage based on assumptions not supported by either theoretical considerations or field observations. For example, the damage caused by tridem axles has been estimated to be the same as that caused by the combination of a single and tandem axles. This estimate is based on equivalency factors for axle configurations that were not used at the AASHO Road Test. The basic assumption is that the load equivalency factor concept is a valid procedure for describing the effects of mixed loading configurations on pavement performance.

Based on the hypothesis that pavement distress is related to the state of stress, strain, or deflection induced by traffic loads, equivalency factors can be developed from computations of these pavement response parameters. Various approaches have been used to derive load equivalency factors. The results for each approach are highly dependent on the parameters, environmental conditions, and methods used to define pavement failure.

A review of different methods for computing or extrapolating equivalency factors for flexible pavements is given by Yoder and Witczak (4) and graphically summarized in Figure 1. Asphalt pavement design methods, such as the Asphalt Institute thickness design procedure (5), account for varying axle loads by using a linear relationship between axle load and the logarithm of equivalency factor derived from the AASHO Road Test data, assuming a terminal serviceability index of 2.5. Southgate et al. (6) reported a similar axle load-damage factor relationship based on experience in Kentucky (Figure 2).

Deacon (7, 8,), Witczak (9), and Terrel (10) used calculated asphaltic tensile strain to evaluate the effect of increased axle weight and different tire configurations on flexible pavements. Damage equivalencies were established based on a flexural fatigue distress. The results showed that single tires produce considerably more pavement damage at the same total load than dual tires, which illustrates the significance of tire configuration. Also, the results showed substantial reductions in pavement life when axle loads were increased.

Layton et al. (11) used the AASHO design method equations and elastic-layered analysis to evaluate the effect of increased vehicle weight. Jung and Phang (12) determined load equivalency factors from theoretically determined subgrade deflections correlated with AASHO Road Test data. Ramsamooj et al. (13) proposed a method of deriving load equivalency factors from longitudinal stress intensity factor profiles obtained from theoretical fracture mechanics concepts. These authors propose to calculate the tandem, axle-load equivalency factors· as the ratio of the sum of the fourth power of the peak. Then calculate the peak-to-trough value of the stress intensity factor produced by the tandem axle load to the fourth power of the peak value produced by the standard axle load as shown in Figure 3.

Although various procedures have been used to compute equivalencies, most are based on a failure criterion of either rutting or fatigue cracking. The procedures for determining equivalencies based on performance are not readily applicable to axle configurations other than single and tandem load axles [see Figure 4 (14)].

RESPONSE VARIABLE

To develop a theoretical evaluation procedure, the response variables must be related to future performance of the pavement; and the location in the pavement structure where this response will be critical must be known. Pavement failure is assumed to be a function of the response to vehicle loadings. The damage produced by an application of an axle load may be calculated from a mathematical equation established from the results of laboratory tests and theoretical considerations and verified by field observation.

Pavement surface deflection has often been ac-

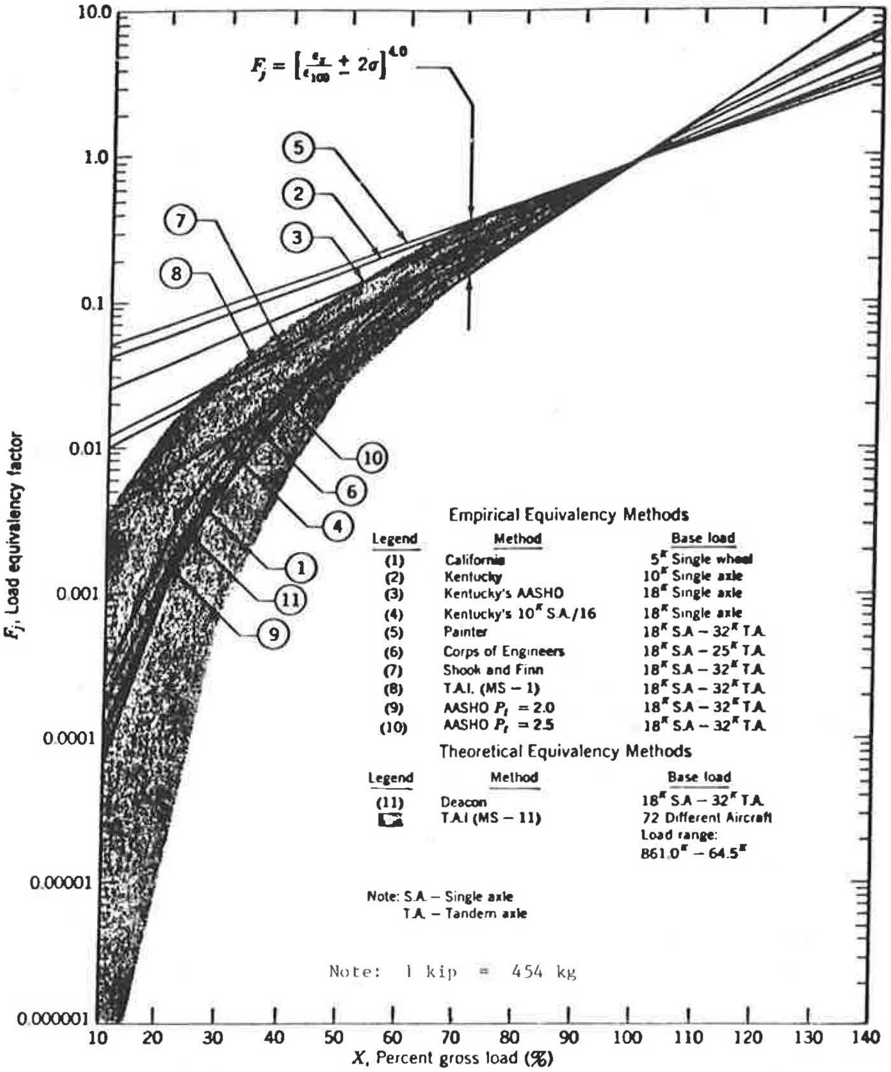


Figure 1. Comparison of various load equivalency methods as a function of percent of gross load (4).

cepted as a good indicator of changes in pavement behavior [Kingham (15), (16)], but surface deflection alone is only a fair indicator of the structural strength of a pavement. High values for surface deflection have been used as limiting criteria for pavement design (Figure 4), as reported by Jung et al. (17); however, maximum surface deflection may not be readily related to performance over a wide range of loading conditions.

Of the various observable distress mechanisms for flexible pavement, fatigue and rutting can be directly related to critical strains in the pavement structure. The horizontal tensile strain at the bottom of the asphaltic concrete can be related to fatigue, whereas vertical compressive strain at the top of the subgrade can be related to rutting. Models that relate pavement failure to repeated applications of vehicle loadings are summarized by Barker et al. (18) and Rauhut et al. (19).

For rigid pavements, horizontal tensile stress has generally been accepted as the response variable providing the best relationship to the pavement distress of cracking. The Vesic equation (20) and the stress ratio used by the Portland Cement Association (21) are most commonly used to predict failure, although many failure-prediction equations exist as stated by Treybig et al. (22).

SINGLE AND DUAL TIRES

An equivalent single wheel load (ESWL) has commonly been used in various design or evaluation procedures to aggregate the effects of different wheel configurations, as described by Van Buren (23). Normally, either equal contact area (U.S. Army Corps of Engineers) or pressure is used to represent the dual tire load for determining ESWL.

The greatest difficulty in applying the ESWL concept is that the failure mechanism in a given pavement structure may vary for different loadings. Thus, the critical parameters do not remain constant for the same pavement structure with a change in axle load. Deacon (24) reported that axles with single tires are three times more damaging than dual tires with the same load, whereas Terrel et al. (10) and Christison et al. (25) reported them as 7 to 10 times more damaging.

Considering the previously mentioned information, it can be concluded that a single tire of the same contact area as a dual tire cannot be used to accurately represent a dual tire configuration; and hence, the single-tire axles should be identified and treated separately in equivalency studies.

Because of the data collection techniques at the AASHO Road Test, the present AASHO equivalency

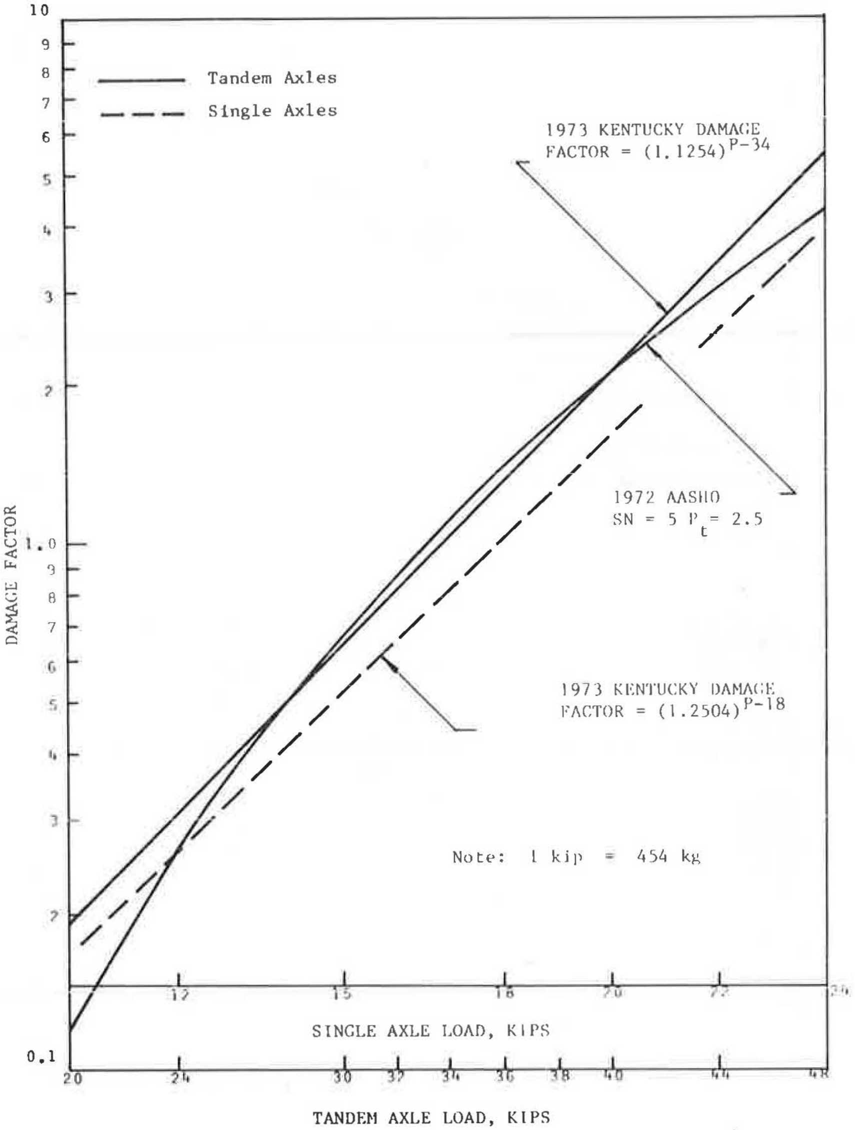
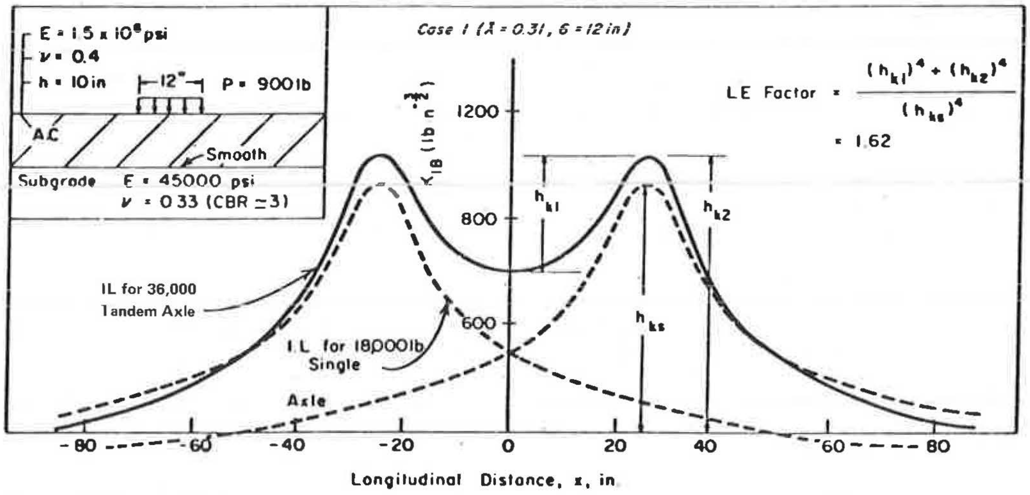


Figure 2. Damage factor versus tandem and single axle load based on experience in Kentucky.



Note: 1 lb = 454 kg
1 in = 2.54 cm

Figure 3. Load equivalency factor for 36-kip tandem axle (13).

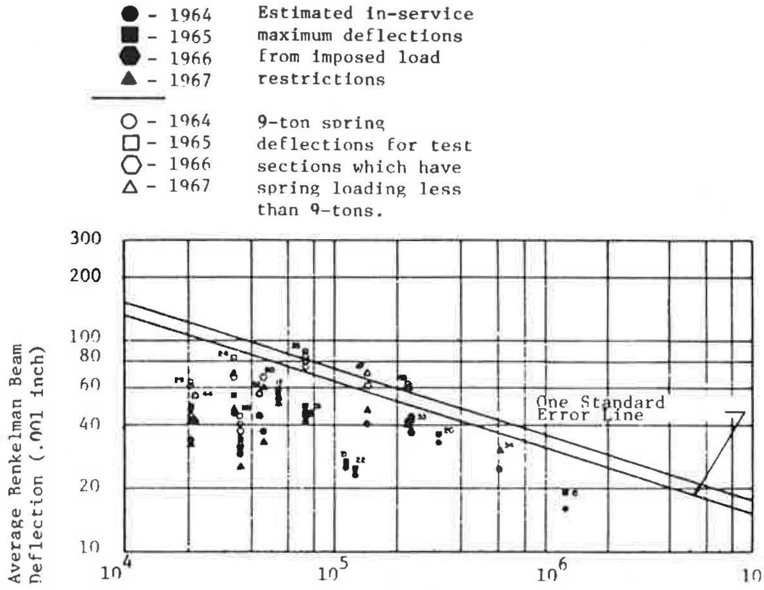


Figure 4. Variation of measured spring deflections with total equivalent 18-kip axle load through 1966 (14).

factors combine the damage caused by a single-tire, steering-axle loading with damage caused by the trailing axles (26). It is possible to determine equivalencies for these single tires by separating the damage caused by single and dual tires at the AASHO Road Test. The equations for calculating this separation of damage are developed and explained in FHWA Report No. RD-79-73 (27). Table 1 gives the resulting new equivalency factors for the specific AASHO conditions for the flexible pavements. As shown, there is little difference between the equivalency factors reported by AASHO and those developed for the load axles after steering axle damage was separated out. As also shown, the single tire loadings produce significantly more damage than does a comparable loading of dual tires as was shown in Deacon's theoretical studies (7) and Christison's theoretical and field studies (25).

The same analysis was used to develop the rigid pavement load equivalency factors in an attempt to separate the damage resulting from dual and single tires. The results of this procedure produced less damage for tire loads on rigid pavements, whereas more damage was computed for single tire loads on flexible pavements than that produced during the AASHO Road Test. Therefore, it was concluded that

Table 1. Comparison of equivalency factors with and without the effect of steering axles based on performance criteria for SN = 4.0, P_t = 2.0, and a flexible pavement.

	Steering Axle Load		Tandem Axle Load		
Total Axle Load (kips)	Predicted Without Single Tires	AASHO With Single Tires	Predicted Without Single Tires	AASHO With Single Tires	Steering Axle
2	.00009	.002	--	--	--
4	.002	.002	--	--	.009
6	.009	.01	--	--	.05
8	.08	.08	.006	.01	.25[a]
10	.08	.08	.006	.01	
12	.18	.18	.01	.01	.46
14	.34	.35	.02	.03	--
16	.61	.61	.04	.05	--
18	1.00	1.00	.07	.08	--
20	1.56	1.55	.11	.12	--
22	2.34	2.31	.16	.17	--
24	3.39	3.33	.23	.25	--
26	4.77	4.68	.33	.35	--
28	6.53	6.42	.45	.48	--
30	8.75	8.65	.61	.64	--
32	11.51	11.46	.80	.84	--
34	14.89	14.97	1.03	1.08	--
36	18.98	19.28	1.32	1.38	--
38	23.87	24.55	1.66	1.72	--
40	29.68	30.92	2.06	2.13	--
42	--	--	2.53	2.62	--
44	--	--	3.09	3.18	--
46	--	--	3.73	3.83	--
48	--	--	4.47	4.58	--

Note: 1 kip = 454 kg.

[a] Equivalency factor for the 9-kip steering axle load.

the damage produced by single tire loads could not be separated from the total damage included in the rigid equivalency factors by the techniques used and information available.

DYNAMIC EFFECTS

As repeated applications of loads pass over pavements, forces are imposed that are a combination of vehicle static weight and induced dynamic forces. These dynamic forces result from the motions imparted to the vehicle by road surface irregularities, and their magnitude depends on vehicle characteristics, vehicle speed, and the nature of the road surface irregularities as explained by Whittmore et al. (28). Dynamic forces have an influence on the life expectancy of pavements, but the actual amount has not been fully determined or explained. The variable nature of the dynamic response of vehicles severely complicates the problem of predicting load equivalency factors for pavement performance. Because the AASHO equivalency factors were developed from in service data, some amount of dynamic force influence is built into the factors.

It may be assumed that the increase or decrease in the response variable caused by the dynamic forces produced by the base load is proportionate to the increase or decrease in the response caused by some other axle load or configuration. This assumption should result in the same ratio of response variable for the dynamic and static conditions for a specific pavement structure, but there is no conclusive evidence to support this assumption. Hence, for simplicity, the equivalency factors determined from the analytical techniques given below are assumed to be constant for the static and dynamic loading conditions.

MODELS

Two computer models were used extensively to calculate response variables for predicting equivalency factors.

1. Elastic-layered analysis (ELSYM 5, 29).
2. Discrete element analysis (SLAB 49, 30).

Currently, elastic-layered theory is the most promising approach for evaluating pavement response to varying loads because it is simple and inexpensive. These procedures have been used by various authors including Jung et al. (12) and Deacon (7). The limiting factor in this procedure is the inability to estimate the modulus of elasticity and Poisson's ratio for each material in the pavement structure. A discrete element analysis model was used to analyze rigid pavements. This model (SLAB 49) permits analysis of interior, edge, and corner loading conditions and provides output that can be used to evaluate their effect on rigid equivalency factors.

MECHANISTIC APPROACH

For purposes of these analyses, it was assumed that a relationship could be developed between a component of strain, stress, or deflection in the pavement and AASHO performance-based equivalency factors. A relationship was first formulated for single loads on AASHO pavement cross sections (Figure 5) and then used to predict AASHO equivalency factors for tandem loads. If these tandem equivalency factors were comparable to the AASHO performance equivalencies, the response variable, equivalency relationship could be extended to other load configurations. These relationships could then be compared with pavement flexural fatigue and rutting criteria used to define pavement failure and would provide support for the concepts and methodology used in other studies for deriving equivalency factors for various loading conditions.

FLEXIBLE PAVEMENTS

Results of computations for surface deflections and interfacial strains in the asphaltic concrete and the subgrade were used to obtain quantitative assessments of the relative damaging effects caused by different loading configurations on flexible pavements. Because equivalency factors based on performance are a function of load and structural number (31), computations were performed for both single and tandem axle loads over a range in the structural number (SN). The use of Equation 1 produced estimates of equivalence factors that corresponded closely to those based on AASHO performance. Equation 1 will be referred to, hereafter, as the Curvature Method.

$$F(x_n) = [\epsilon_1(x_n)/\epsilon(18_s)]^B + \sum_{i=1}^{n} \left\{[\epsilon_{i+1}(x_n)] - [\epsilon_{i-i+1}(x_n)]/\epsilon(18_s)\right\}^B \qquad (1)$$

where

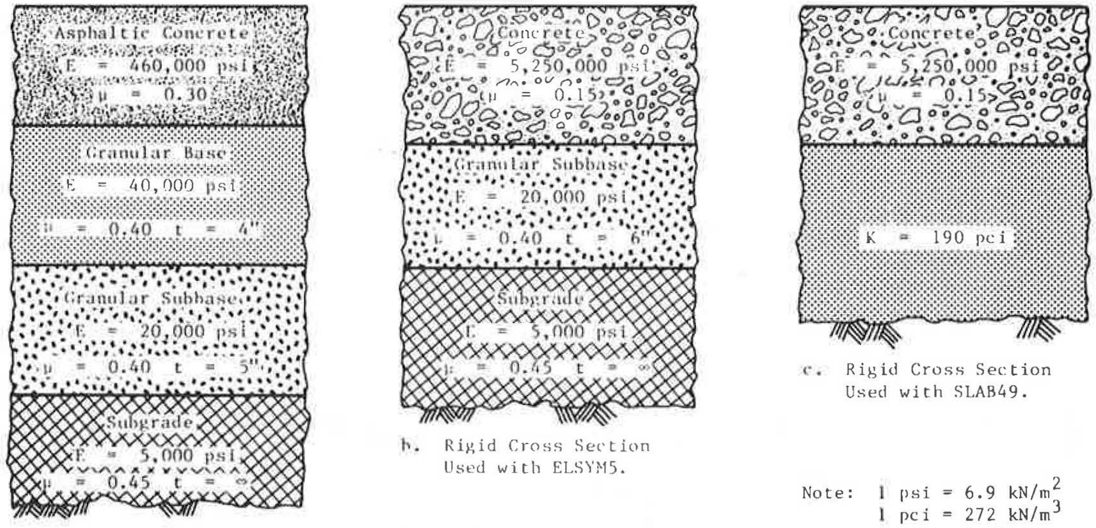
$$B = \mathrm{Log}\, F(x_s)/\mathrm{Log}\, [\epsilon(x_s)/\epsilon(18_s)] \qquad (1a)$$

$F_i(x_n)$ = predicted equivalency factor for axle configuration n of load x.
$\epsilon(18_s)$ = maximum asphalt tensile strain or subgrade vertical strain for the 18-kip (80 kN) equivalent single axle load (ESAL), in./in.
$\epsilon_1(x_n)$ = maximum asphalt tensile strain or subgrade vertical strain under the leading axle or axle configuration n of load x, in./in.
$\epsilon_{i+1}(x_n)$ = maximum asphalt tensile strain or subgrade vertical strain under axle i+1 of axle configuration n of load x, in./in.
$\epsilon_{i-i+1}(x_n)$ = asphalt tensile strain or subgrade vertical strain, in critical direction, between axles i and i+1 of axle configuration n of load x, in./in.
$F(x_s)$ = AASHO performance equivalency factor for an x-kip single axle load.
$\epsilon(x_s)$ = maximum asphalt tensile strain or subgrade vertical strain for an x-kip single axle load, in./in.

Tensile Strain

ELSYM 5 was used to compute maximum tensile strain at the bottom of the asphalt concrete as a function of axle load for different structural numbers. These computations were completed for the pavement cross section and material properties given in Figure 5. Material properties selected to represent AASHO Road Test conditions were taken from References (22) and (26), and AASHO structural coefficients must be used in computing structural numbers for the analysis. The relationship between AASHO equivalency factor and maximum tensile strain is illustrated in Figure 6.

Using Equation 1a and asphalt tensile strain, the B value was computed to be 5.06 for a structural number of 3.75 and a terminal serviceability of 2.0. Results of numerous reported laboratory fatigue tests indicate that the exponent B is primarily dependent on mix composition. Numerous studies have yielded values ranging from 3.0 to 5.0 as reported by Monismith and Salam (32). [Finn et al. (33), Rauhut et al. (19), and Treybig et al. (34).]



a. Flexible Cross-Section Used with ELSYM5.

b. Rigid Cross Section Used with ELSYM5.

c. Rigid Cross Section Used with SLAB49.

Note: 1 psi = 6.9 kN/m^2
1 pci = 272 kN/m^3
1 in = 2.54 cm

Figure 5. Pavement material properties used to develop an initial relationship to predict the AASHO tandem equivalency factors.

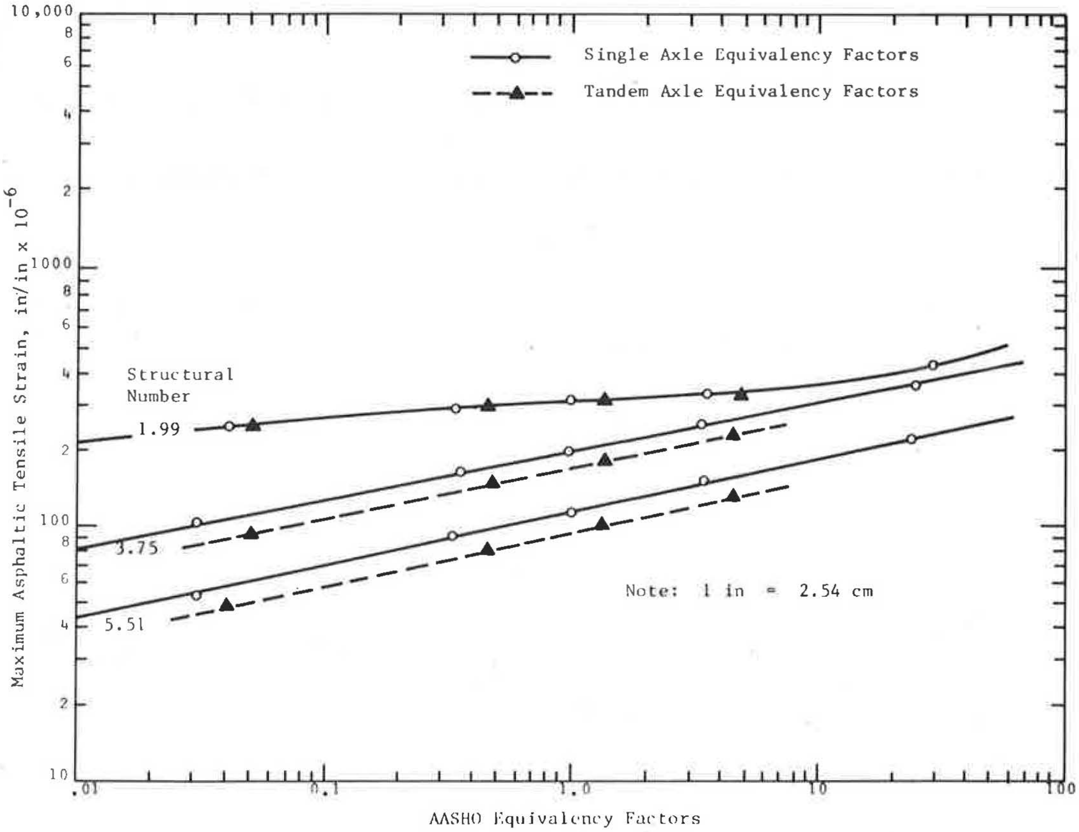


Figure 6. Comparison of AASHO equivalencies with maximum asphaltic concrete tensile strain, computed with ELSYM 5.

Equivalency factors predicted by Equation 1 are shown in Figures 7 and 8. In Equation 1, zero strain should be used in computing the difference in strain values between and under axles if the asphalt tensile strain between the axles is compressive. Equivalency factors were predicted using this procedure for numerous axle loads and configurations and are published in FHWA Report No. RD-79-73 (27).

Subgrade Strain

ELSYM 5 was also used to calculate maximum compressive strain at the top of the subgrade as a function of axle load for different structural numbers. These calculations were completed for the pavement cross section and material properties given in Figure 5. The relationship between AASHO equivalency

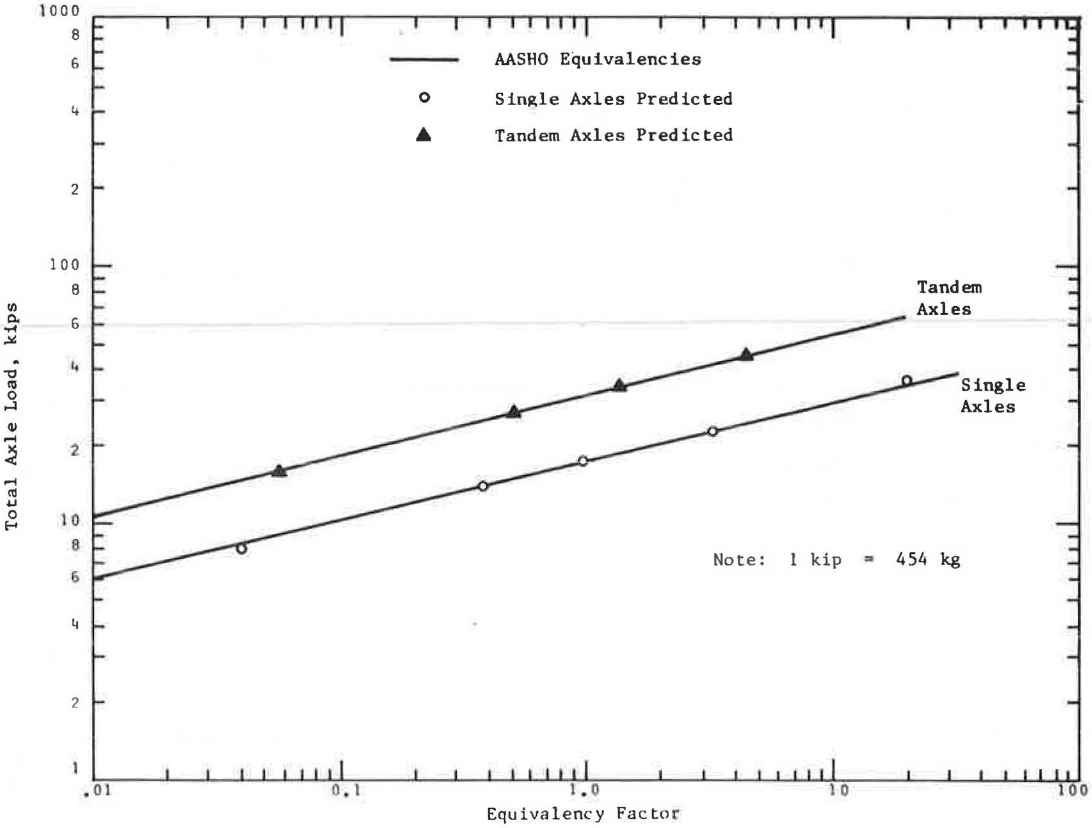


Figure 7. Development of equivalency factors based on asphalt concrete tensile strain using the Curvature Method—SN = 3.75.

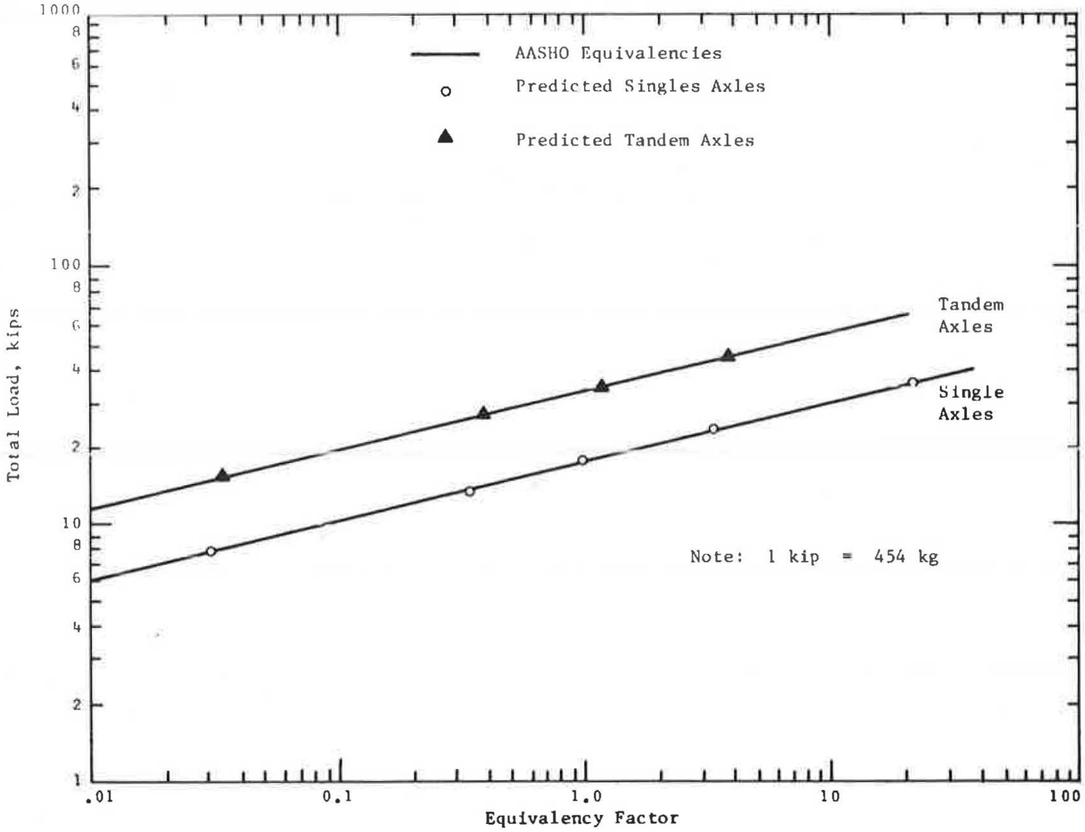


Figure 8. Development of equivalency factors based on asphalt tensile strain using Curvature Method—SN = 5.51.

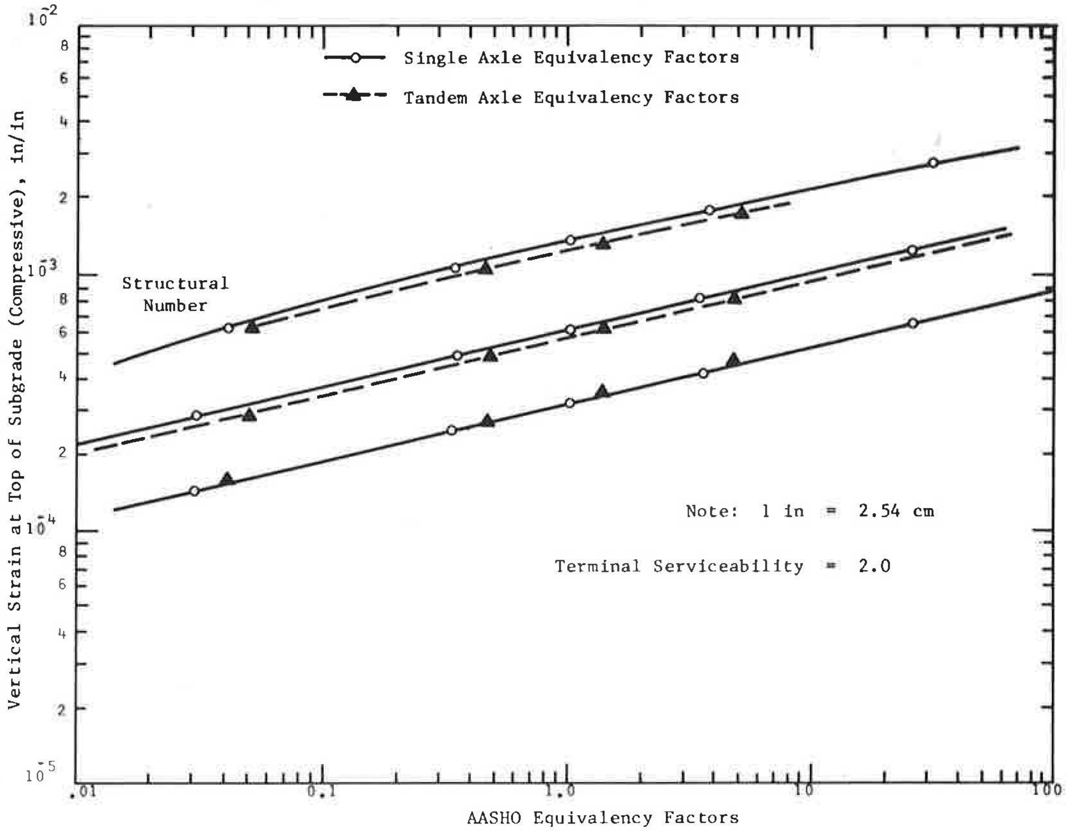


Figure 9. Comparison of AASHO equivalencies with subgrade compressive strain at the top of the subgrade computed with ELSYM 5.

factor and maximum compressive strain is presented in Figure 9.

The B value calculated for this condition was 4.49 for a structural number of 3.75 and a terminal serviceability of 2.0. Similar values have been reported by Shell (35) and Santucci (36). The results using the Curvature Method of Equation 1 are given in Figures 10-12. If the subgrade vertical strain between the axles is tensile, then zero strain should be used in computing the difference in strain values between and under axles. Equivalency factors were predicted for numerous axle loads and configurations using this procedure and are published in FHWA Report No. RD-79-73 (27).

RIGID PAVEMENTS

Computations of concrete tensile stresses and surface deflections caused by various loading configurations on a rigid pavement were used to obtain quantitative assessments of the relative damage effects on pavements. Based on AASHO performance, equivalency factors are a function of load and concrete thickness. Therefore, both single and tandem axle loads were used along with a range of thicknesses in predicting the AASHO equivalency factors. Both ELSYM 5 and SLAB 49 were used to calculate the response variables for predicting the equivalencies. The pavement cross section and material properties used by each model in calculating the critical response variables are given in Figure 5.

The same type of relationship described in Equation 1 was used in predicting rigid equivalency factors. By using the response variables of deflection and stress computed with the various models, the predicted equivalency factors were not within reasonable accuracy for the AASHO material properties and general cross sections. The predicted equivalency factors were different from those developed at the AASHO Road Test by a factor of two or greater. Some examples of predicted versus AASHO equivalency factors are shown in Figures 13-15. Equivalency factors were shown to depend to some degree on the model and loading conditions used to simulate field conditions. The following interrelated explanations are given as to why the AASHO equivalency factors were not predictable using the given analytical techniques.

1. Loss of Support. The analytical models cannot be used to simulate the effect of pumping with time. Because the tandem axle loads have a much larger deflection basin than the single axle loads, the effect of pumping on pavement performance may be more severe for tandem axle loads than single axle loads.
2. Load Transfer. The loss of load transfer at joints could increase at a greater rate for applications of tandem axles than single axles resulting in higher tensile stresses for tandem axles.
3. Dynamic Loads. The effect of dynamic loads at joints may be much greater for tandem axles than for single axles. Also, this dynamic effect at joints (corner loading) could have a larger influence on pavement performance than the dynamic effect based on interior loading conditions, which is normally simulated for asphalt pavements. Hence, the assumption of equal relative effect for the static, as well as the dynamic load effect, could be in error for jointed concrete pavements.
4. Slab Curling. When considering the movement of a tandem axle across a joint as opposed to a single axle, curling stresses could cause the tandem axles to be more damaging.

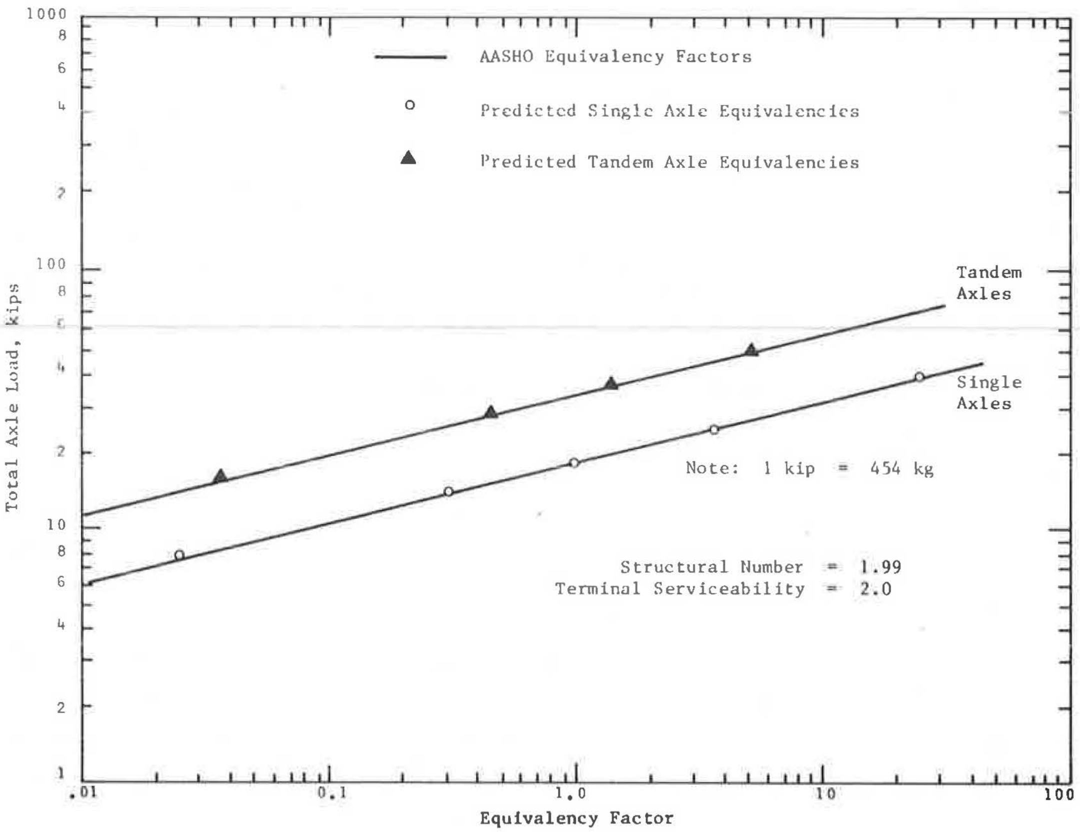


Figure 10. Development of AASHO equivalency factors based on subgrade compressive strain using the Curvature Method—SN = 1.99.

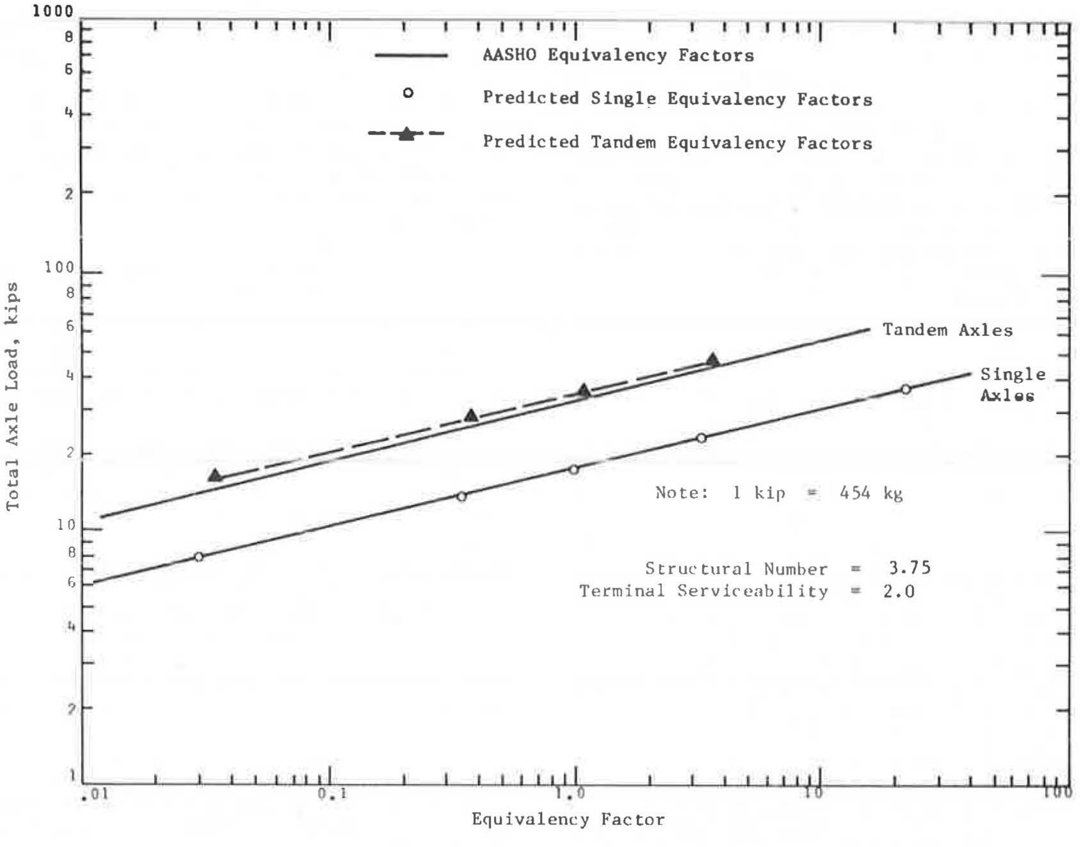


Figure 11. Development of AASHO equivalency factors based on compressive strain using the Curvature Method—SN = 3.75.

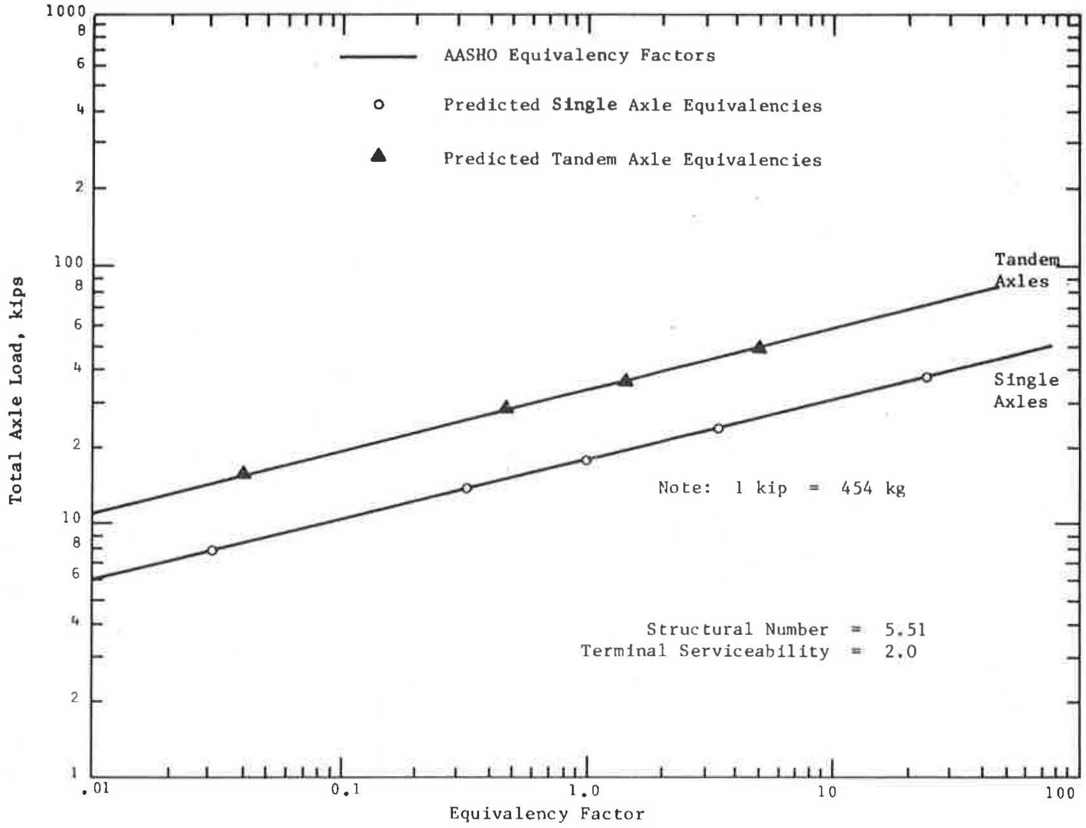


Figure 12. Development of AASHO equivalency factors based on subgrade compression strain using the Curvature Method—SN = 5.51.

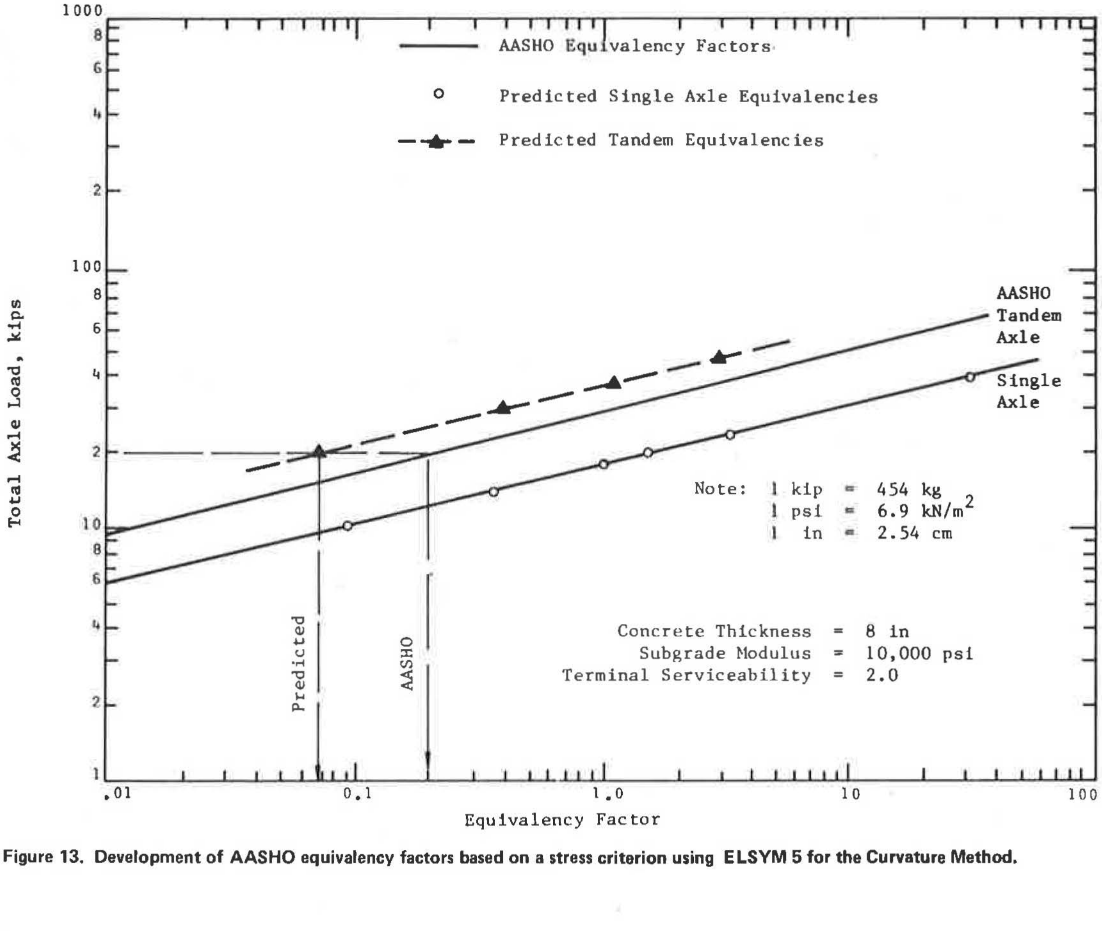


Figure 13. Development of AASHO equivalency factors based on a stress criterion using ELSYM 5 for the Curvature Method.

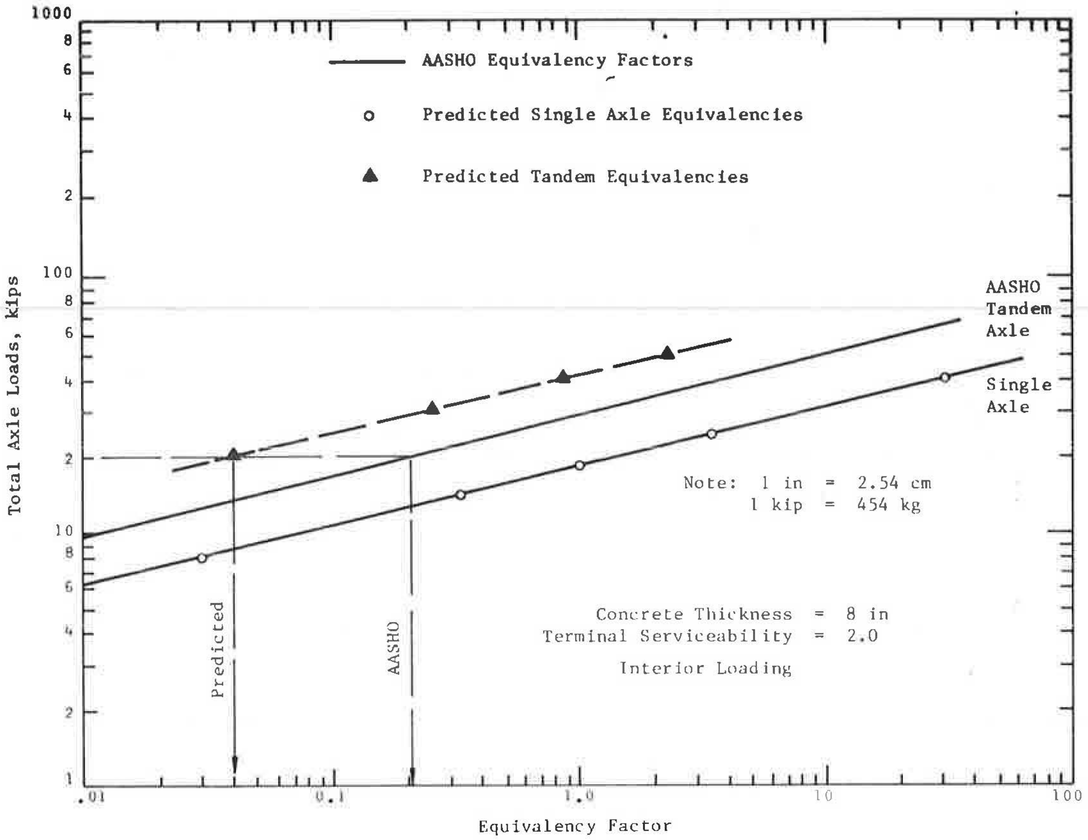


Figure 14. Development of AASHO equivalency factor based on a stress criterion using SLAB 49 for the Curvature Method—interior loading.

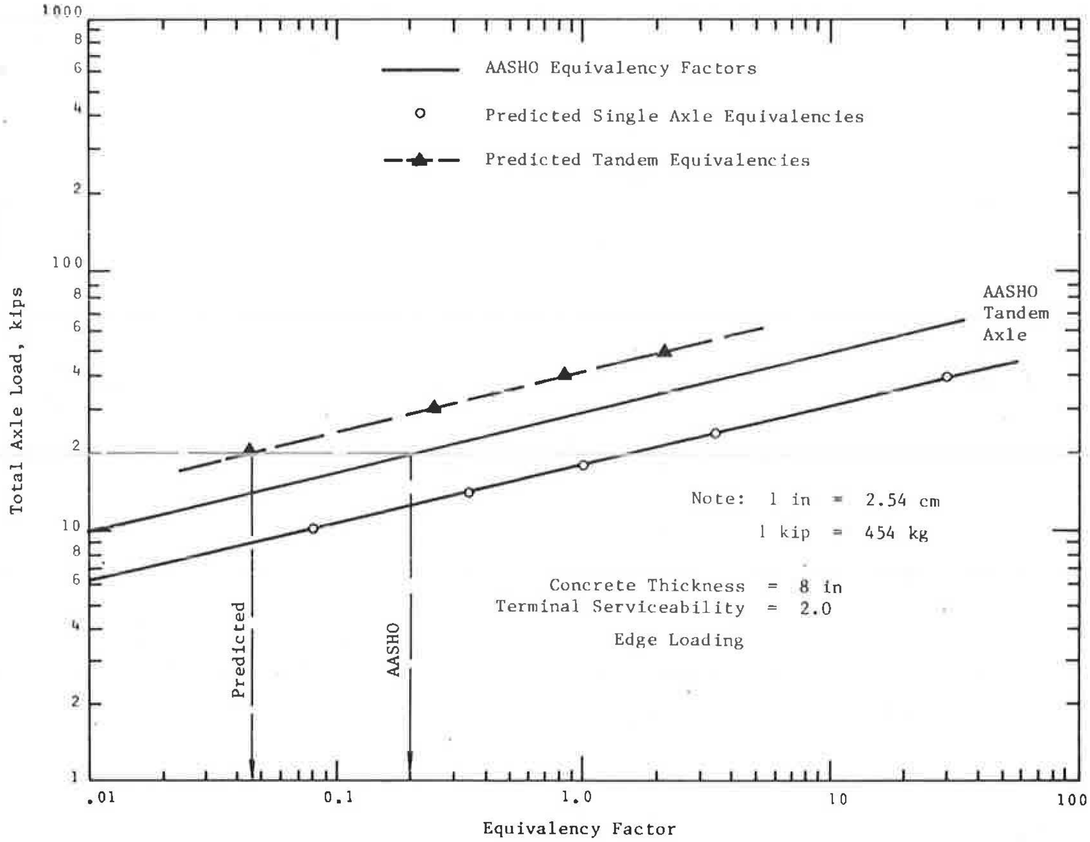


Figure 15. Development of AASHO equivalency factor based on a stress criterion using SLAB 49 for the Curvature Method—edge loading.

SUMMARY

Relationships between performance equivalency factors and asphalt tensile strain and subgrade vertical strain were developed for flexible pavements loaded with the AASHO axle configurations. Using this relationship, equivalency factors were generated for triple- and five-axle configurations. Because of the volume of those tables, the reader is referred to FHWA Report No. RD-79-73 (27), Appendix B and C. Because asphalt concrete strain correlates better with AASHO load equivalency factors under comparable loading conditions, Appendix C of FHWA Report No. RD-79-73 is recommended when triple- and five-axle configurations are expected. If the pavement structures under evaluation vary significantly from the AASHO material properties and thicknesses, the engineer should consider developing equivalency factors for site-specific situations. Care must be exercised in using load equivalency factors obtained from AASHO correlations if actual longitudinal spacing between axles or transverse spacing between dual tires change from those used at the AASHO Road Test.

The performance equivalency factors for other axle configurations were extended based on a structural number of approximately 3.75. The structural number becomes an important variable in determining equivalency factors for terminal serviceability greater than 2.5. Therefore, caution should be used in applying these developed values for terminal serviceabilities greater than 2.5.

In predicting equivalency factors based on asphalt tensile strain, only asphalt thicknesses greater than 3 in. (7.6 cm) should be used. The reason is that elastic layer theory (ELSYM 5) for certain conditions computes compressive strains in thin asphalt concrete layers. If less than 3 in. (7.6 cm) of asphaltic concrete exists, then subgrade vertical strain should be used to compute the equivalency factor as shown in Figures 10-12.

Equivalency factors were shown to be dependent on pavement type and loading condition. The rigid pavement equivalency factors were not predicted adequately by the mechanistic analysis (stress-strain analysis) procedures used in this study. Therefore, the AASHO equations must be relied on to generate equivalency factors for other than standard axle configurations. It is recommended that the dynamic effect of tandem loads on jointed concrete pavements as compared to single axles be reviewed and evaluated in further detail. This should determine whether the initial assumption is correct and illustrate why a 36-kip (160 kN) ESAL tandem axle load is approximately 2.45 times as damaging as an 18-kip (80 kN) ESAL single axle load for rigid pavements and only 1.38 times more damaging for flexible pavements.

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