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**RESEARCH REPORT
KTC-93-1**

**AN ANALYTICAL INVESTIGATION
OF AASHTO LOAD EQUIVALENCIES**

by

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in cooperation with
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and

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16. Abstract An objective of this study was to develop procedures and/or refined relationships between Kentucky ESALs and AASHTO ESALs. Kentucky load equivalency relationships are the result of mechanistic analyses based on elastic theory. AASHTO load equivalency relationships were developed from recorded empirical data collected at the AASHTO Road Test. Comparison of Kentucky and AASHTO ESALs necessitated in-depth analyses of AASHTO load equivalency equations C-16, D-19, and their developmental equations given in the 1972 AASHTO Interim Guide. These equations evolved from the basic format used in analyzing AASHTO Road Test data. In this investigation, the repetitions reported in Appendix A of AASHTO Road Test Special Report 61E were converted to ESALs using Equation C-16. For Loop 3 (12-kip (53-kN) single axleload and 24-kip (108-kN) tandem axleload), the ESALs at serviceabilities of 3.0, 2.5, and 2.0 exceeded the ESALs at failure ($P_f = 1.5$). The AASHTO design equation, C-13, was used to calculate the design ESALs for each of the AASHTO Road Test pavement sections. The ratio of ESALs at a given P_f to ESALs at failure and the ratio of repetitions at the same P_f to repetitions at failure were calculated. Direct correlations of the averages of these calculated ratios occurred for Lane 1 of Loops 5 and 6 and Lane 2 of Loop 6. This suggests that the AASHTO load equivalency relationships correlate best for loads greater than the legal limits. From recorded Kentucky loadometer data collected at stations located on Interstate routes, over 95 percent of all single and tandem axleloads are less than legal limits. This suggests that the AASHTO load equivalency relationships are not as appropriate to actual traffic loads. Ratios of AASHTO ESALs to Kentucky ESALs may be calculated using Equation 6 for flexible pavements and Equation 7 for rigid pavements to estimate combinations of P_f and SN, or P_f and slab thickness. AASHTO load equivalencies are based on pavement serviceability and structural number for flexible pavements, or slab thickness for rigid pavements, respectively. Pavement serviceability is based upon measurements of surface roughness, cracking, patching, and rut depth. Pavement fatigue is an inherent parameter. In the Kentucky system, load equivalencies are based upon strain-repetitions relationships developed from laboratory tests and matched with theoretical calculated strains based on elastic theory. Inherently included in the Kentucky system is the assumption that surface roughness will increase with traffic, cracking may develop, patches may be constructed, and ruts may develop. The common factor between the two systems is traffic. Measured parameters in one system are inherent in the other system and vice versa.					
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EXECUTIVE SUMMARY

An objective of this study was to develop procedures and/or refined relationships between Kentucky ESALs and AASHTO ESALs. An initial investigation of the AASHTO Load Equivalencies indicated some relationships that required more intensive investigations. To confirm or deny the anomalies, data from the AASHTO Road Test were analyzed using the actual loads applied to the respective Loops and Lanes at the AASHTO Road Test. Regression equations for ESALs vs Structural Number, SN, were obtained for each individual loop and lane and superimposed on the same graph. Plots of the equations were noted to cross one another. The plot for the equation for Loop 3 crossed plots for equations for Loops 4-6. Regression equations were obtained for observed repetitions vs SN and the equations were nearly parallel to each other and definitely in the correct order of progression. Equations C-16 and D-19, published in the 1972 AASHTO Interim Guide for Design of Pavement Structures are the basis for calculating load equivalencies. One example of the findings is the load equivalency value is nearly identical for SNs of 1 or 6 but have different values for SNs of 3 or 4. For loads less than 18 kips (80 kN), the load equivalency value for SNs 3 and 4 is greater than for SNs of 1 or 6. The reverse pattern occurs for loads greater than 18 kips (80 kN). However, SN has no influence upon the equivalency value for 18 kips (80-kN) (see Figure 2). These discrepancies gradually disappear as the serviceability level decreases until at P_t of 1.5, the load equivalency values are constant without regard to SN.

A more critical investigation of the calculated AASHTO ESALs for the pavement sections for the AASHTO Road Test revealed that the calculated ESALs increased as repetitions increased for Loops 4-6. However, for 16 of 18 pavement sections having an AC thickness of 3 or 4 inches (76 or 102 mm, respectively) for both lanes of Loop 3, AASHTO ESALs for $P_t = 3.0, 2.5,$ and 2.0 exceeded the AASHTO ESALs at $P_t = 1.5$. Comparison of AASHTO Road Test repetitions converted to AASHTO ESALs with their AASHTO design ESALs produces patterns similar to Figure 9 as shown in Figure 20. Whatever part(s) of Equations C-16 and C-19 cause these phenomena also affect the calculated AASHTO ESALs for the other Loops.

Investigations suggest that the AASHTO load equivalency relationships were biased to the heavier loads because the pavement structures having the greater SN values survived the testing program while pavements having lesser SN values and lighter loads failed (see Figure 20). Under these circumstances, regression analyses would be biased to the greater SN values associated with the larger axleloads.

AASHTO load equivalencies are a function of pavement serviceability and SN, or D, for flexible or rigid pavements, respectively. Pavement serviceability is determined by measurements of surface roughness, cracking, patching, and rut depth. Inherent is

accumulated fatigue. Kentucky load equivalencies are based upon laboratory tests resulting in strain-repetitions relationships. These relationships have been correlated with theoretical calculated strains resulting from given axleloads applied to pavements and analyzed by elastic theory. Inherent in the Kentucky system are the assumptions that with traffic, surface roughness of the pavement will increase, cracking may develop, patches may be constructed, and rutting may develop. In summary, the common factor between the two systems is traffic, but load equivalencies are based on measurements of different sets of parameters with the opposite set of one included inherently in the other.

From results of this study, the combinations of SN and P_t that matches Kentucky ESALs lie between SN = 3 to 6 for P_t = 2.77 to 3.33, respectively, and may be estimated by

$$P_t = 2.1907 + 0.1941(SN).$$

These values are different from the combination of SN = 5 and P_t = 2.5 used in the FHWA W-4 Loadometer Tables. Equations 6 and 7 may be used to determine ratios of AASHTO ESALs to Kentucky ESALs for flexible and rigid pavements, respectively.

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INTRODUCTION

This report is part of a study to develop a method to estimate the accumulated fatigue of an existing pavement. One objective of the study was to determine what combination of AASHTO Structural Number, SN, and pavement serviceability, P_v , should be used to equate calculated equivalent single axleloads, ESALs, by both the AASHTO and Kentucky methods. This report addresses that objective by using one set of Kentucky loadometer data to make the comparisons.

KENTUCKY METHODS

The Kentucky flexible pavement design method (1) was developed using mechanistic analyses based on elastic theory. Load equivalency relationships were developed as a part of that design procedure (1). A computerized procedure (2) was developed that utilizes loadometer, average daily traffic (ADT), and vehicle classification data (both manual and automated) to estimate design ESALs. The automated procedure (2) incorporates the same load equivalency relationships used in pavement design (1).

The Kentucky rigid pavement design procedure (3) was developed using mechanistic analyses based on elastic theory and uses the same ESALs calculated for flexible pavements. Strain-based fatigue criteria were developed and adjusted to permit using the same ESALs calculated for flexible pavements. Thus, Kentucky ESALs are the result of one set of calculations for a given set of traffic data. As a comparison, AASHTO procedures require a minimum of two sets of

calculations and possibly more depending upon the difference between the resulting design thickness and the thickness used to select the set of load equivalency relationships.

INVESTIGATION OF AASHTO METHODS

Comparison of the Kentucky and AASHTO methods required investigating the 1986 AASHTO Design Guide. The 1986 AASHTO Design Guide (4) provides Traffic Equivalency Tables for terminal serviceabilities of 2.0, 2.5, and 3.0. Inspection of these tables revealed:

1. the numerical value varied as a function of pavement thickness for a constant load,
2. the value generally decreased with increasing pavement thickness, then increased with increasing thickness, and
3. the values changed according to level of serviceability.

Equivalency factors were computed for flexible pavements (40-kip (178-kN) single axleload and 48-kip (214-kN) tandem axleload) and for rigid pavements (32-kip (142-kN) single axleload and 52-kip (231-kN) tandem axleload) at serviceabilities of 1.5, 2.0, 2.5, 3.0, and 3.5. Figure 1 illustrates the variations. At a terminal serviceability of 1.5, the load equivalency value is constant without regard to pavement type or thickness. Conversely, for a serviceability of 3.5, the variation is greatest. Load equivalencies for the various serviceability levels tend to become

nearly equal for thin flexible pavements (Figures 1a and 1b) and thick rigid pavements (Figures 1c and 1d). This suggests that the basic equations required further investigation. The equations involve pavement thickness, magnitude of loads, and level of serviceability.

AASHTO EQUATIONS FOR FLEXIBLE PAVEMENTS

Structural Number

From the 1972 AASHTO Guide (5),

"...an SN for the entire pavement is obtained and is represented by the general equation:

$$SN = a_1 D_1 + a_2 D_2 + a_3 D_3$$

where SN = structural number,

a_1 , a_2 , and a_3 = layer coefficients representative of surface, base, and subbase course, respectively.

D_1 , D_2 , and D_3 = actual thickness, in inches, of surface, base, and subbase courses, respectively.

Layer Coefficients

... Average values of layer coefficient for materials used in the AASHTO Road Test pavements were determined from the results of the test, and were as follows:

Asphaltic concrete surface course	0.44
Crushed stone base course	0.14

Derivations of the load equivalency equations are not contained in the 1986 AASHTO Guide (4), but are provided in the 1972 AASHTO Interim Guide (5) and is quoted as follows:

$$G_t = \beta(\log W_t - \log \rho) = \log((4.2 - P_t)/(4.2 - 1.5)) \quad \text{C-1}$$

and $G_t/\beta = \log W_t - \log \rho$

$$\beta = 0.40 + (0.081(L_1 + L_2)^{3.23}) / ((SN+1)^{5.19}(L_2)^{3.23}) \quad \text{C-2}$$

$$\log \rho = 5.93 + 9.36 \log(SN+1) - 4.79 \log(L_x + L_2) + 4.33 \log(L_2) \quad \text{C-3}$$

where W_t = axleload applications at end of time t ,

SN = structural number,

L_x = axle load in kips,

L_1 = load on one single axle or on one tandem-axle set, kips.

L_2 = axle code (1 for single axle and 2 for tandem axle),

ρ = a function of design and load variables that denotes the expected number of axle load applications to a serviceability index of 1.5.

G_t = a function (the logarithm) of the ratio of loss in serviceability at time t to the potential loss taken to a point where $P_t = 1.5$.

β = a function of design and load variables that influence the shape of the p-versus-W serviceability curve.

P_t = serviceability at end of time t."

When $P_t = 1.5$,

$$G_t = \log((4.2-1.5)/(4.2-1.5)) = \log(2.7/2.7) = \log(1) = 0.0,$$

$$G_t/\beta = \log W_t - \log \rho, \text{ and}$$

$$\log W_t = \log \rho.$$

Equation C-3 was developed to estimate the number of repetitions of a given axleload that a given pavement thickness could be expected to carry at a specific level of serviceability.

Load equivalency is the ratio of the repetitions assigned to a given level of serviceability caused by one 18-kip (80-kN) axleload to the repetitions assigned to the same level of serviceability caused by some other axleload, L_x . The ratio of two numbers is the same as the antilog of difference between the logarithms of the two numbers. Thus, when $P_t = 1.5$, G_t/β has a value of 0.0 leaving:

$$\log W_{118} = 5.93 + 9.36\log(\text{SN}+1) - 4.79\log(18+1) + 4.33\log(1) \quad 1$$

$$\log \rho = 5.93 + 9.36\log(\text{SN}+1) - 4.79\log(L_x + L_2) + 4.33\log(L_2) \quad 2$$

Subtracting $\log(\rho)$ from $\log(W_{118})$ leaves:

and $\log(L_2)$ is eliminated for a single axle because $\log(1)$ is zero. Note also that all terms involving SN have been eliminated.

AASHTO EQUATIONS FOR RIGID PAVEMENTS

Equation D-1 (5) for rigid pavements is identical to Equation C-1 for flexible pavements. Equations D-2 and D-3 for rigid pavements are identical in format to Equations C-2 and C-3 for flexible pavements, respectively, except for the numerical values of the respective coefficients and exponents.

$$G_t = \beta(\log W_t - \log \rho) = \log((4.5 - P_t)/(4.5 - 1.5)) \quad \text{D-1}$$

$$\beta = 1.00 + (3.63(L_1 + L_2)^{5.20}) / ((D + 1)^{8.46})(L_2)^{3.52} \quad \text{D-2}$$

$$\log(\rho) = 5.85 + 7.35\log(D + 1) - 4.62\log(L_1 + L_2) + 3.28\log(L_2) \quad \text{D-3}$$

where L_1 = load on one single axle or on one tandem axle set, kips.

L_2 = axle code (1 for single axle and 2 for tandem axle).

D = thickness of slab, inches.

As discussed, $\log(W_t) = \log(\rho)$ when the terminal serviceability, P_t , is 1.5. The ratio

of repetitions is the antilog of the difference between the logs of the two numbers and the remaining terms are:

$$\log(W_t) - \log(\rho) = 4.62\log(L_x + L_1) - 4.62\log(19) - 3.28\log(L_2) \quad 4$$

and $\log(L_2)$ is eliminated for a single axle because $\log(1)$ is zero. Just as Equation 3 is a general equation for flexible pavements, Equation 4 is a general equation for rigid pavements and axle configurations when $P_t = 1.5$. Note that pavement thickness is not included in either Equations 3 or 4. The numerical value for the load equivalency differs by pavement type and is a function of the different numerical constants of 4.79 and 4.33 shown in Equation C-3 corresponding to 4.62 and 3.28 shown in Equation D-3, respectively.

β TERM

The β term essentially is an expression of the effects of load divided by a combination of structural number and axle configuration. For a given load, increasing the thickness in the denominator results in a smaller quotient, thus a smaller value for β results in a larger value for the term G_t/β . Conversely, a pavement structure having a lesser structural number results in a larger β and in turn a smaller value for G_t/β . When structural number is held constant and the load is increased for a given axle configuration, then β increases and the value of G_t/β is decreased. In summary, the G_t/β term is the addition of another log when

using the equation in a log format, or a multiplier of a non-log equation.

TERMINAL SERVICEABILITY > 1.5

The $\log(\rho)$ and $\log(W_t)$ equations contain non-zero values for G_i/β_x and G_i/β_{18} . When the difference is taken between the two logs, the terms $9.36\log(SN+1)$ (for flexible pavements), or $7.35\log(D+1)$ (for rigid pavements), are eliminated, but the G_i/ρ terms containing SN, or D, remain. Therefore, the G_i/ρ terms are included when calculating load equivalencies and these terms cause a variation in load equivalency value as a function of SN or D for the same axleload, W_t .

SERVICEABILITY LEVELS

The instrument used for recording longitudinal profile variations was the longitudinal profilometer and the output was referred to as the pavement slope.

From page 14 (6):

"To correlate profile variation with serviceability ratings made by the panel the hundreds of slope measurements taken in each section were reduced to a single statistic intended to represent the roughness of the section. Investigation of several alternative statistics led to the choice of the variance of the slope measurements computed from:

in which

$$SV = \frac{\sum_{i=1}^n X_i^2 - \frac{1}{n} \left(\sum_{i=1}^n X_i \right)^2}{n-1} \quad (1)$$

SV = slope variance;

X_i = the i^{th} slope measurement; and

n = total number of measurements."

Pavement deteriorate with time and applications of loads. The concept of pavement serviceability and an associated rating scale was developed while conducting the AASHO Road Test. Initial testing resulted in the new pavements at the AASHO Road Test being assigned a Pavement Serviceability Index, PSI, of 4.2 for flexible pavements and 4.5 for rigid pavements. The first visible signs of deterioration corresponded to a value of 3.5. A value of 1.5 was considered as failure.

Serviceability was not a direct function of fatigue. From page 23 (6):

"Eq. 11 was used to determine the level of serviceability of the surviving flexible pavement sections every two weeks during the period of traffic operation.

$$p = 5.03 - 1.91 \log(1 + SV) - 0.01(C + P)_{0.5} - 1.38(RD)_2 \quad (11).$$

in which p = the present serviceability index;

SV = the mean of the slope variance in the two wheelpaths;

C + P = a measure of cracking and patching in the pavement surface;

and

RD = a measure of rutting in the wheelpaths."

Inspection of the recorded number of load applications published in Appendix A, AASHO Road Test Report 61E (6), shows that a wide variation in the number of load applications existed for the same pavement thickness and axleload. The service life of a pavement is influenced directly by thicknesses of the various layers, the mix design for the bound layer, quality of aggregates and asphalt cement, construction control, stiffness of the subgrade, and environment. In this discussion, environment will not be considered since all AASHO Road Test pavements were subjected to the same weather. Analyses (7) using elastic theory indicated that the influential factors affecting pavement behavior in decreasing order are stiffness of subgrade, pavement thickness, axleload, and stiffness of the bound layer.

For rigid pavements, the following is quoted from pages 142-143 (6):

"Eq. 59 was used to determine the level of serviceability of the surviving rigid pavement test sections every two weeks during the period of traffic operation.

$$p = 5.41 - 1.80\log(1 + SV) - 0.09(C + P)^{0.5} \quad (59).$$

...When it was not feasible to use the project's longitudinal profilometer to determine the serviceability of a test section, the Bureau of Public Roads roughometer was used. The roughometer was equipped with a special counter and operated at a speed of 10 mph. Through a study correlating the output of the roughometer with that of the profilometer, a pavement roughness expressed in inches per mile was substituted for SV with the following result:

$$p = 5.41 - 1.80\log(0.40R - 33) - 0.09(C + P)^{0.5} \quad (60)$$

in which R is the roughometer reading in inches per mile, and the other symbols are as previously defined. The roughometer was used only in cases where sections were nearing failure, and it appeared that maintenance would be required before the next regular 2-week index day period."

The definition for patching, P, is the same for flexible or rigid pavements. The definition for cracking, C, depends on the type of pavement. For flexible pavements, Page 23 (6) states:

"Cracking, C, in Eq.11 is defined as the area, in square feet per 1,000 sq ft of pavement surface, exhibiting class 2 or class 3 cracking. Class 2 cracking is defined as that which has progressed to the stage where cracks have connected together to form a grid-type pattern. Class 3 cracking is

that in which the bituminous surfacing segments have become loose."

For rigid pavements, Page 142 (6) states:

"Cracking, C (Eq.59), is defined as the total linear feet of Class 3 and Class 4 cracks per 1,000 sq ft of pavement area. The length of a crack is taken as the length of its projection parallel or perpendicular to the pavement centerline, whichever is greater. A Class 3 crack is defined as a crack opened or spalled at the surface to a width of 1/4 in. or more over a distance equal to at least one-half the crack length, except that any portion of the crack opened less than 1/4 in. at the surface for a distance of 3 ft or more is classified separately. A Class 4 crack is defined as any crack when has been sealed."

Thus, the definition of pavement serviceability is a function of pavement type.

AASHTO LOAD EQUIVALENCY EQUATIONS

The 1986 AASHTO Guide (4) does not provide the equations used to develop the load equivalency equations. The 1972 AASHTO Guide (5) provides the equations and are identified herein as Equations C-13 through C-16 for flexible pavements, and D-16 through D-19 for rigid pavements. These equations are quoted here for the benefit of those who may not have access to them.

"The design equation for flexible pavements developed in Section C.1"

(Equations C-2 and C-3), "may also be written as:

$$\begin{aligned}\log(W_t) &= 5.93 + 9.36 \log(\text{SN} + 1) - 4.79 \log(L_1 + L_2) \\ &+ 4.33 \log(L_2) + G_t/\beta\end{aligned}\tag{C-13}$$

...If L_1 equals 18 kips (80 kN), and L_2 equals 1 for single axles, equation (C-13) becomes:

$$\log(W_{t18}) = 5.93 + 9.36 \log(\text{SN} + 1) - 4.79 \log(18 + 1) + G_t/\beta\tag{C-14}$$

For any other axle load L_1 , equal to X, equation (C-13) becomes:

$$\begin{aligned}\log(W_{tx}) &= 5.93 + 9.36 \log(\text{SN} + 1) - 4.79 \log(L_x + L_2) \\ &+ 4.33 \log(L_2) + G_t/\beta_x\end{aligned}\tag{C-15}$$

Subtracting Equation C-14 from Equation C-15 gives:

$$\begin{aligned}\log(W_{tx}/W_{t18}) &= 4.79 \log(18 + 1) - 4.79 \log(L_x + L_2) \\ &+ 4.33 \log(L_2) + G_t/\beta_x - G_t/\beta_{18}\end{aligned}\tag{C-16.}$$

For rigid pavements:

"The design equation for rigid pavement developed in Section D.1"

(Equations D-2 and D-3) "may also be written as:

$$\begin{aligned} \log(W_t) = & 5.85 + 7.35 \log(D + 1) - 4.62 \log(L_1 + L_2) \\ & + 3.28 \log(L_2) + G_t/\beta \end{aligned} \quad \text{D-16}$$

...If L_1 equals 18 kips and L_2 equals 1, for single axles, equation (D-16) becomes:

$$\log(W_{t18}) = 5.85 + 7.35 \log(D + 1) - 4.62 \log(18 + 1) + G_t/\beta_{18} \quad \text{D-17}$$

For any other axleload L_1 equal to X, equation D-16 becomes:

$$\begin{aligned} \log(W_{tx}) = & 5.85 + 7.35 \log(D + 1) - 4.62 \log(L_x + L_2) \\ & + 3.28 \log(L_2) + G_t/\beta_x \end{aligned} \quad \text{D-18}$$

Subtracting equation (D-17) from equation (D-18) gives:

$$\begin{aligned} \log(W_{tx}/W_{t18}) = & 4.62 \log(18 + 1) - 4.62 \log(L_x + L_2) \\ & + 3.28 \log(L_2) + G_t/\beta_x - G_t/\beta_{18} \end{aligned} \quad \text{D-19.}"$$

Note that Equation C-2 and D-2 are designated as β . The values for coefficients and exponents are very different resulting in quite different values for β . Equations C-3, C-13 through C-16 for flexible pavements, and D-3, D-16 through

D-19 for rigid pavements, contain terms involving layer thicknesses. However, when $P_t = 1.5$, all terms involving layer thicknesses are eliminated when calculating load equivalencies because $G_i = 0$. Equations C-3 and D-3 were developed to estimate the number of repetitions a given axleload may be carried by that pavement structure by the time the pavement reached the specified level of serviceability.

Load equivalency factors included in the 1986 AASHTO Guide (4) may be duplicated provided that the inverse of Equations C-16 and D-19 are used. Taking the inverse of equations involving logarithms simply requires that the algebraic sign be reversed for each term in the equation. For tridem axles, a value of 3 must be used for L_x .

PATTERNS OF LOAD EQUIVALENCIES

The AASHTO load equivalency equations, C-16 and D-19, were evaluated for SN values of 1 through 6 and D from 6 to 11 inches (150 to 279 mm, respectively) for each of the levels of serviceability of 1.5 to 3.5 in increments of 0.5. Single axleloads of 10, 14, 18, 22, 26, and 28 kips (44, 62, 80, 98, 116, and 125 kN respectively) were substituted for L_x . Tandem axleloads of 18, 28, 36, 44, and 52 kips (80, 125, 160, 196, 231 kN, respectively) were used. Figures 2 and 3 summarize the calculations for flexible and rigid pavements, respectively. Figures 2a, 3a, 2c, and 3c correspond to a P_t of 3.5 and Figures 2b, 3b, 2d, and 3d correspond to a P_t of 1.5. Appendix A contains similar figures for P_t of 3.0, 2.5,

and 2.0.

From analyses using elastic theory, rational relationships for strain and thickness of asphaltic concrete appear to be valid for thicknesses of 3, or more, inches (76 mm) and become irrational for thicknesses less than 3 inches (76 mm) (7). The mean SN for AASHO Road Test pavements of 3 inches (76 mm) of asphaltic concrete was approximately 2.8. Comparison of single axleload equivalencies between Figures 2a and 3a indicates quite similar patterns and values for a SN range of 2.8 to 6 and slab thicknesses of 6 to 11 inches (36 to 279 mm, respectively). For tandem axleloads, the patterns are similar but the rigid pavement values approach a factor of 2 compared to flexible pavements. Figure 4 was developed from data contained in Table 54 of Report 61E (6) and illustrates that the volume of soil pumped from under pavement slabs subjected to tandem axles was approximately twice that for pavements subjected to single axles. The following is quoted from Page 2, Report 61G (8):

"Flexible pavements lost serviceability through the development of ruts and roughness in the wheelpaths and by cracking in the asphaltic concrete surfacing, eventually requiring patching of the surface...Rigid pavements lost serviceability by the development of roughness along the wheelpaths, by slab cracking or by the necessity of patching the pavement surface due to severe cracking and roughness. All of the failures in the rigid pavements were preceded by pumping of material from beneath the concrete

slabs...Practically all pumping occurred along the pavement edge."

From Page 38, Report 61G (8):

"At the end of test traffic, data indicated that pumping increased as load increased (the greater the load the more the pumping, given equal slab thickness) and decreased as slab thickness increased (the thicker the slab the lesser the pumping, given equal load)."

It appears that the concrete slabs failed because they behaved as cantilevered slabs over the voids caused by pumping and not due to fatigue of a supported concrete slab. The flexible pavements deformed to maintain contact with the base layer. Thus, load equivalencies for the two types of pavements probably do not reflect similar pavement behavior.

For both types of pavements, pavement structure has no influence upon load equivalencies at $P_i = 1.50$. As stated earlier, G_i has a value of 0.0 and SN does not appear in Equations C-16 or D-19 for either flexible or rigid pavements. For rigid pavements, Figure 3 provided the basis for the following observations:

1. There is no influence of slab thickness on load equivalency for an 18-kip (80 kN) single axleload. Thickness does have an influence for any other load, but the influence is less than for flexible pavements.

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For both types of pavements, pavement structure has no influence upon load equivalencies at $P_1 = 1.50$. As stated earlier, G_1 has a value of 0.0 and SN does not appear in Equations C-16 or D-19 for either flexible or rigid pavements. For rigid pavements, Figure 3 provided the basis for the following observations:

1. There is no influence of slab thickness on load equivalency for an 18-kip (80 kN) single axleload. Thickness does have an influence for any other load, but the influence is less than for flexible pavements.

2. For single axleloads less than 18 kips (80 kN), load equivalencies decrease for slab thicknesses increasing from 6 inches (152 mm) to 8 inches (203 mm) where the rate of decrease changes but continues to decrease as slab thickness increases from 8 to 11 inches (203 mm to 279 mm, respectively).
3. For single axleloads greater than 18 kips (80 kN), load equivalencies decrease as slab thickness increases from 6 inches to approximately 7 inches (152 mm to 178 mm, respectively), then increases as slab thickness increases.
4. Similar observations were noted for tandems.

Table 54 (6) lists the volume of soil pumped from under the rigid slabs at the AASHO Road Test. Figure 4 illustrates the relationship of the volume of soil pumped from under the rigid slab for the tandem axle vs single axle (Lane 2 vs Lane 1) and each data point is for the same constructed slab thickness on the same loop. The volume of soil for tandem axles is approximately twice that for single axles. This suggests that the volume of soil pumped from under the slab was a function of the number of impacts by individual axles and not the number of axle groups.

Because serviceability was strongly influenced by the pavement profile (slope variance or roughness), it appears that the volume of soil pumped from under the rigid pavements eventually allowed the pavement slabs to crack and deform. This

might account for an increased roughness compared to the flexible pavement sections. This may also explain why the load equivalencies for rigid pavements are so much greater than for flexible pavements.

Figure 2 provided the basis for the following observations:

1. There is no influence of SN on the load equivalency for an 18-kip (80 kN) single axleload, but SN does have a prominent influence for any other load.
2. For loads less than 18 kips (80 kN), the equivalencies increase from SNs of 1 to 3, then decrease from SNs of 3 to 6.
3. For loads greater than 18 kips (80 kN), the equivalencies decrease from SNs of 1 to 3, then increase from SNs of 3 to 6.
4. Similar observations were noted for tandems.

From Report 61E (6),

"The structural design of the sections in each test tangent of the traffic loops was varied...about a nominal design determined from designs submitted by four highway departments...In the traffic loops (2 through 6) surfacing thickness varied in 1-in. increments, base thickness in 3-in. increments, and subbase thickness in 4-in. increments."

AASHO ROAD TEST DATA

On Page 36 of Report 61E (6), equations 13-15 are of the same format as Equations C-1 through C-3 (5) quoted earlier in this report. Analyses of the AASHO Road Test data provided the bases for the equations used in the AASHTO Design Guides (4-5).

ANALYSES OF AASHO ROAD TEST DATA

Appendix A, Report 61E (6), provides the number of repetitions of load for each pavement section by loop and lane and serviceability levels. Layer thicknesses were converted to SN using $a_1 = 0.44$, $a_2 = 0.14$, and $a_3 = 0.11$ (2). The data for repetition, SN, and serviceability were inserted into Equation C-16 to calculate 18-kip (80-kN) ESALs. Regression equations relating ESALs and SNs were obtained for each loop, lane, and level of serviceability. Figures 5c, 5d, 6c, 6d, and 7b illustrate the ESAL-SN relationships between regression equations for serviceability levels of 3.5, 3.0, 2.5, 2.0, and 1.5 respectively. Appendix B contains similar figures for all levels of serviceability for the tandem axle data. In Figures 5c, 5d, 6c, 6d, and 7b, logic would suggest that the positions of the regression equation for each loop should increase in SN for increasing loop number (increasing loads). Note that plots of regression equations for some loops cross the plots of equations for other loops and in some cases may be in reverse positions. Additional analyses resulted in Figures 5a, 5b, 6a, 6b, and 7a that illustrate the relationship of regression equations through the observed repetitions of load and

Figures 8a and 8b are compilations of the regression equations from Figures 5-7 for Loop 4, Lanes 1 and 2, respectively. All regression equations are located in a logical, progressive sequence. This confirms that the observers performed excellent work in determining the serviceability rating and recording the number of repetitions of loadings.

NORMALIZING AASHO ROAD TEST DATA

The AASHO Road Test data provided in Appendix A of Report 61E (6) were loaded into a personal computer spread sheet. Equation C-16 was used to convert observed repetitions at the AASHO Road Test to AASHTO 18-kip (80-kN) equivalent axleloads for each pavement section and level of serviceability for both lanes of Loops 3-6. Trends are difficult to determine when looking at the resulting wide range in ESALs. Data were normalized by obtaining the ratio of repetitions at any given level of serviceability to the repetitions at failure ($P_i = 1.5$) and the ratio of ESALs at any given level of serviceability to the ESALs at failure (P_i). For this investigation, those pavement sections not having values of observed repetitions for each of the five levels of serviceability were eliminated, leaving 176 sections for analyses. For each loop and each lane, the average ratio was calculated for the ratios at each level of serviceability. Figures 9a and 9b illustrate the relationship between the two sets of ratios for single axle trucks and tandem axle trucks, respectively.

The curves for Loop 3 in Figures 9a and 9b indicate that the ratio of ESALs for P_i s of 3.0, 2.5, and 2.0 exceed a value of 1.0 and would indicate that the accumulated fatigue exceeded failure during the middle of the test period and then the accumulated fatigue was decreased to failure. Upon reinspection of the calculated ratios for the Lane 1, Loop 3 (12.15-kip (54-kN) single axleloads), ratios exceeded 1.0 for 13 of 17 sections at $P_i = 2.5$ and 15 of 17 at $P_i = 2.0$. For Lane 2 (24-kip (107-kN) tandem axleloads) of Loop 3, the ratios for 16 of 20 sections exceeded 1.0 for $P_i = 2.0$ and 2.5. To verify the accuracy of these calculations, fixed values of SN and load were substituted into appropriate locations in the spread sheet and the repetitions were changed to a value of 1 resulting in load equivalency factors. These factors duplicated the values given in appropriate serviceability and axle configuration tables of the 1986 AASHTO Design Guide (4). This confirms that the calculations within the spread sheet were correct.

ANALYSES USING RECORDED WEIGHT DISTRIBUTIONS

An objective of this study was that Weigh-In-Motion data for 1989 and 1990 would be used to compare ESAL calculations. After inspecting the data, it was determined that the data would require extensive checks prior to analyses. An alternative source of weigh data was sought.

Prior to 1987, Kentucky Department of Highways officials utilized portable scales or permanent loadometer stations to measure axleloads. A portion of the data reported to FHWA included the sum of axles weighed at 11 permanent loadometer

stations. Stations were located on interstates, rural primary roads, and urban arterials. These data were used by FHWA to form the "W-4 Tables". To analyze the effects of axleloads, eight years of data from Kentucky "W-4 Tables" were recorded by appropriate weight groups for both single and tandem axle arrangements. The numbers of recorded axleloads were summed for the eight years for each weight range and the totals are listed in Table 1. As a simulation, the number of axles in each weight range should be proportioned according to some rate of accumulated traffic, pavement deterioration, and as a function of loss of serviceability.

The best history of pavement deterioration, as a function of loadings, was assumed to be the data collected at the AASHO Road Test as shown in Figures 6-8. A method was required to proportion the number of loadings in Table 1. Methodology for development of the method is contained in Appendix C and results are shown in Figure 10a. The relationship shown in Figure 10a was used to proportion the total number of axles to simulate a loss in serviceability as shown in Table 1. Figure 10b might be used to estimate the future volume of trucks required to cause pavement failure based upon the number of trucks that have travelled over the pavement and the existing level of serviceability.

The numbers of axles shown in Table 1 were converted to accumulated percentages as a function of increasing single and tandem axles in Figures 11a and 11b, respectively. Approximately 98 percent of the single axles had loads less

than 18 kips (80 kN) (Figure 11a) and 95 percent of the tandem axles had loads less than 33 kips (148 kN) (Figure 11b). Use of AASHTO load equivalencies should lead to specific relationships for SN and serviceability based upon results shown in Figures 1-3 and 5-7. Figure 12 illustrates the calculated fatigue for the distribution of axles shown in Table 1.

Figure 13 illustrates the load equivalency relationships for various tire and axle configurations developed by Kentucky (1,11). A description of the methodology used to develop these relationships is included in Appendix D. Table 2 (11) contains the general log-log polynomial equation and the appropriate values for the constants for each tire and axle configuration. Kentucky load equivalencies were based on theoretical mechanistic analyses using the Chevron N-layer computer program for a wide range of loads applied to each of the theoretical 100 possible combinations of AASHTO Road Test flexible pavements of which 67 were constructed. Kentucky load equivalency relationships include the variations of pavement thicknesses but do not include serviceability.

The single and tandem axle Kentucky relationships were applied to the same axle distributions shown in Table 1. Figure 14 is another presentation of Figure 12 and includes the curve based upon Kentucky load equivalencies for the same axleload data. The curve for SN = 3 has the greatest calculated fatigue of any SN. The Kentucky curve passes through the AASHTO curves and follows the same general trend.

Equation C-16 was used to calculate the 18-kip (80-kN) ESALs for Section Number 121 in Lane 1, Loop 3 of the AASHO Road Test. Pavement Section Number 121 was chosen for analyses based upon a single axleload less than 18 kips (80-kN), layer thicknesses of 3 inches (76 mm) of asphaltic concrete, 3 inches (76 mm) of base, and 4 inches (216 mm) of subbase. The observed repetitions for each level of serviceability (from Appendix A, ref. 6) are shown in the box on the right side of Figure 15. The curve with the solid round points is the result of calculations using Equation C-16 and the curve with the open round points is the result of calculations using the Kentucky load equivalency equation for a 4-tired, single axle.

Figure 15 suggested that similar analyses should be made by individual lanes and loops that are surrogates for axle arrangements and loads, respectively. The same spread sheet used to develop the curve in Figure 10a was used to obtain the 18-kip (80 kN) ESALs and the mean value of ratio of those ESALs (not repetitions as in Figure 10a) by loop, lane, and level of serviceability. Only those pavement sections having both weighted and unweighted data for all serviceability levels were used. The calculated mean ratios and ESALs were obtained for 16, 24, 25, and 22 pavement sections for single axles on Loops 3-6, respectively, and 19, 25, 25, and 22 pavement sections for tandem axles on Loops 3-6, respectively. For Loop 3, pavements having 2 inches (51 mm) of asphalt were not included. Figures 16 and 17 illustrate the relationship between serviceability and the respective mean ESALs for the single and tandem axle arrangements, respectively. Figures

16 and 17 contain a separate curve for the unweighted ESALs, weighted ESALs, and design ESALs as calculated by Equation C-16. Figures 9a and 9b illustrate the resulting mean ratios for the weighted ESALs for the single and tandem axles, respectively. Because the loops are surrogates for loads, analyses for loads less than 18 kips (80 kN) for single axles and 32 kips (142 kN) for tandems indicate that calculated fatigue based on Equation C-16 results in calculated fatigue for the mid range of serviceability levels greater than the final fatigue at pavement failure for Loop 3 data. Inspection of the ratios for Loop 3 indicates that 14 of 16 sections in Lane 1 (single axles) and 15 of 19 sections in Lane 2 (tandem axles) exceeded 1.0 at serviceability levels of 2.5 and 2.0.

The same procedure used to produce Figure 9 was duplicated except that Kentucky load equivalencies were substituted for the AASHTO load equivalencies. The results are shown in Figure 18a and 18b for the single and tandem axle data (lanes 1 and 2), respectively. Because the Kentucky load equivalency relationships do not include serviceability, the serviceability relationship is reflected in the observed repetitions assigned to the respective serviceability value. The ratio of repetitions and the ratio of ESALs resulting from the Kentucky load equivalency relationships are identical because the load equivalency is the same regardless of serviceability. The values for the ratios of repetitions are identical in Figures 9 and 18. The variability in ratios for each level of serviceability is the direct reflection of the observed repetitions for each loop and lane.

Figure 9 displays the relationship between ratio of observed repetitions at the AASHO Road Test versus the ratio of the repetitions converted to ESALs using Equation C-16. Figure 19 displays the relationship between the ratio of observed repetitions converted to ESALs and the ratio of ESALs based on the AASHTO Design Equation C-13. Inspection of Figure 19 indicates there are even greater differences than shown in Figure 9. The ratio of repetitions at a given level of serviceability to repetitions at failure should be the same as the ratio of design ESALs at the same level of serviceability to ESALs at failure provided the design equation represented observed behavior. Figure 20 shows the relationship between ratio of repetitions and ratio of ESALs for the AASHO Road Test data and actual loads. The data points are averages of calculations using the same personal computer spread sheet except that the ESALs are calculated for each pavement section using Equation C-13.

Figure 20a indicates that the AASHTO Design Equation C-13 matches single axleloads of 22.4 kips (100 kN) used on Loop 5 and 30 kips (133 kN) used on Loop 6. Figure 20b indicates that the best match was for a tandem axleload of 48 kips (214 kN) used on Loop 6. The AASHTO Design Equation appears biased toward the heavier loads. Figures 11a and 11b indicate that the axleload distribution for actual traffic is for the lighter axleloads, i.e., more typical for Loops 3 and 4.

To determine whether the AASHO Road Test data (6) or the Kentucky loadometer data were biased in some way to produce trends shown in Figures 1-3, 5-7, 12, and

14-18, analyses were made for 599 five-axle, semi-trailer trucks weighed by Weigh-In-Motion scales on a Kentucky interstate. Both AASHTO and Kentucky load equivalency relationships were used. For the Kentucky load equivalency relationships, equations have been developed to account for the additional fatigue resulting from uneven load distributions between the axles within a tandem or tridem axle assembly. Previous analyses (11) indicate that loads are distributed evenly between the axles of the same assembly for only 12 percent of tandems or tridems. On the average, the additional fatigue due to uneven loading is 1.4 times that for even loading for tandems and 2.4 for tridems. Figure 21 shows the results of the analyses of the 599 trucks using the AASHTO load equivalencies (Equation C-16), the Kentucky load equivalencies assuming the loads are evenly distributed between the axles within an assembly (left vertical line), and the Kentucky fatigue adjusted for uneven loading as recorded (the vertical line in the middle of the Figure 21).

EQUALITY BETWEEN AASHTO AND KENTUCKY LOAD EQUIVALENCIES

ESALs has been the term used to describe the effects of traffic upon pavement design and behavior. The AASHTO and Kentucky definitions of ESAL are based on effects of traffic, but are quite different. The Kentucky load equivalency relationship is based on fatigue (strain versus repetitions) and developed from a correlation of laboratory test data with theoretical analyses of static axleloads applied to pavements and analyzed using elastic theory (see Appendix D). For

Kentucky, the same fatigue criterion is used as the basis for pavement thickness designs or estimating accumulated fatigue for existing pavements. In the Kentucky design system, accumulated ESALs based on fatigue and inherently assumes that pavement roughness will increase with traffic, cracking may form, patches may be constructed, and rutting probably will develop. The measurements of roughness, cracking, patching, and rut depth are not a part of Kentucky's definition of ESAL.

AASHTO ESALs are based upon pavement serviceability and structural number for flexible pavements or slab thickness for rigid pavements. Pavement serviceability is based upon measurements of pavement roughness, cracking, patching, and rut depth. Inherent in the AASHTO ESAL is accumulated fatigue. Both systems involve the same characteristics, but the difference is in what is measured and what is inherently included. They are not the same, but traffic is the common item. To make a true comparison requires the application of both definitions of load equivalencies to the same traffic stream and the resulting calculations would be considered to be equal.

Figure 14 illustrates that the Kentucky analyses using load equivalencies intersect the AASHTO iso-structure lines. Because the distribution of axleloads were common to both sets of calculations, there should exist some combination(s) of AASHTO SN and P_1 equivalent to the calculated Kentucky fatigue relationship. Figure 22a is the same as Figure 14 except that the ratio of ESALs has replaced

the calculated ESALs of Figure 14. AASHTO rigid pavement load equivalency equations were applied to the same traffic distribution shown in Table 1 and the results shown in Figure 22b. The vertical line at a ratio of 1 (Figure 22a) represents equality between the two systems and equality would occur in the portion of higher serviceabilities and lower SN. Figure 22b illustrates that the AASHTO rigid ESALs would be over twice that for Kentucky ESALs. Figure 23 illustrates that area of equality in Figure 22a. A pavement design consisting of 4 inches (102 mm) asphaltic concrete on 8 inches (204 mm) of dense graded aggregate is equivalent to a SN of 2.88 using 0.44 for a_1 and 0.14 for a_2 . In Figure 23, the relationship between SN and P_t is nearly a straight line having the following equation:

$$P_t = 2.190682 + 0.194089 * SN \quad 5$$

Ratios other than 1.0 may be calculated for flexible pavements by the following:

$$\begin{aligned} ESAL_{ratio} = & [0.78155 - 0.25235(P_t) + 0.08253(P_t)^2 + \\ & [1.1851 - 1.2417(P_t) + 0.3164(P_t)^2]SN + \\ & [-0.17838 - + 0.18687(P_t) - 0.047618(P_t)^2]SN^2 \end{aligned} \quad 6$$

where $ESAL_{ratio} = (AASHTO \text{ ESALS}) / (KENTUCKY \text{ ESALS})$,

SN = AASHTO Structural Number, and

P_t = pavement serviceability.

Note that the AASHTO lines for serviceability cross each other for SNs less than

4. In Figure 23, the range of equality between the two systems for flexible pavements appears to be a range for SN = 3.0 to 6.0 and Pt = 2.77 to 3.36. Because results shown in Figure 21 are applicable only to five-axle semi-trailer trucks and Figures 14 and 22 are applicable to a normal stream of truck traffic, the more appropriate range of combinations for equality should be considered as SN = 3 to 6 and Pt = 2.77 to 3.36, respectively. A range in SN of 3 to 6 is equivalent to Kentucky 33-percent AC pavement structures of 12.5 inches (318 mm) to 25 inches (635 mm), respectively, and corresponds to a range in design ESAL of approximately 80,000 to 11.5 million, respectively, for a CBR 7 subgrade. Any combination in this suggested range is different from the combination of SN = 5 and Pt = 2.5 used as a reference in the FHWA W-4 Tables.

For rigid pavements, Figure 22b shows that the ratio of AASHTO ESALs to Kentucky ESALs ranges between approximately 2.13 and 2.33. Ratios may be calculated for rigid pavements by Equation 7 provided the proportional distribution of the number of axles in each weight category is approximately the same as shown in Table 3:

$$\begin{aligned} \text{ESAL}_{\text{ratio}} = & (2.327 + 0.03556(P_s) - 0.025201(P_s)^2) + \\ & (-0.070155 + 0.0733(P_s) - 0.01824(P_s)^2)*D + \\ & (0.0027365 - 0.003161(P_s) + 0.0009177(P_s)^2)*D^2 \end{aligned} \quad 7$$

where $ESAL_{ratio} = (AASHTO \text{ ESALS}) / (KENTUCKY \text{ ESALS})$,

D = rigid pavement thickness, inches, and

P_t = pavement serviceability.

Figures 24a and 24b are visual displays of mathematical solutions of Equations 6 and 7, respectively. When the distribution of axles by weight category differs from the proportion listed in Table 3, Equations 6 and 7 will not be valid and new equations will be needed.

SUMMARY

- o AASHTO load equivalency Equations C-16 and D-19 appear to be biased toward loads greater than the current legal load limits as shown in Figure 20.
- o Analyses of the distribution of the number of observed axleloads as a function of load as shown in Table 1 and Figure 11 indicate that the actual traffic passing through loadometer stations consists of a minimum of 95 percent of the single axles weighing less than 18 kips (80 kN) and tandem axles weighing less than 33 kips (147 kN).
- o In comparing the AASHTO and Kentucky systems, the range of equality between the AASHTO and Kentucky systems appears to vary over a range for SN = 3.0 to 6.0 and $P_t = 2.77$ to 3.36, respectively. This combination is different from the combination of SN = 5 and $P_t = 2.5$ shown in the FHWA W-4 Tables. When the proportional distribution of the number of axles is approximately the same as shown in Table 3, Equation 6 may be used to calculate ratios for other

combinations of SN and P_t . For rigid pavements, Equation 7 may be used.

RECOMMENDATIONS

o When comparing AASHTO and Kentucky ESALs, a combination of AASHTO SNs of 3 to 6 at serviceabilities of 2.77 to 3.36, respectively, might be considered as shown in Figure 23. Any combination is different from the combination of SN = 5 and $P_t = 2.5$ shown in the FHWA W-4 Tables. Equations 5 and 6 may be used to calculate ratios for other combinations of SN and P_t (Figure 24a). Equation 7 may be used to adjust Kentucky ESALs to AASHTO rigid ESALs for specific pavement thicknesses (Figure 24b).

LIST OF REFERENCES

1. J. H. Havens, R. C. Deen, and H. F. Southgate, "Design Guide for Bituminous Concrete Pavement Structures", Research Report UKTRP-84-17, Kentucky Transportation Research Program, University of Kentucky, Lexington, KY, August 1981.
2. H. F. Southgate, "Estimation of Equivalent Axleloads Using Data Collected by Automated Vehicle Classification and Weigh-In-Motion Equipment", Research Report KTC-90-11, Kentucky Transportation Center, University of Kentucky, Lexington, KY, June 1990.
3. H. F. Southgate, J. H. Havens, and R. C. Deen, "Development of a Thickness Design System for Portland Cement Concrete Pavements", Research Report UKTRP-83-5, Kentucky Transportation Research Program,

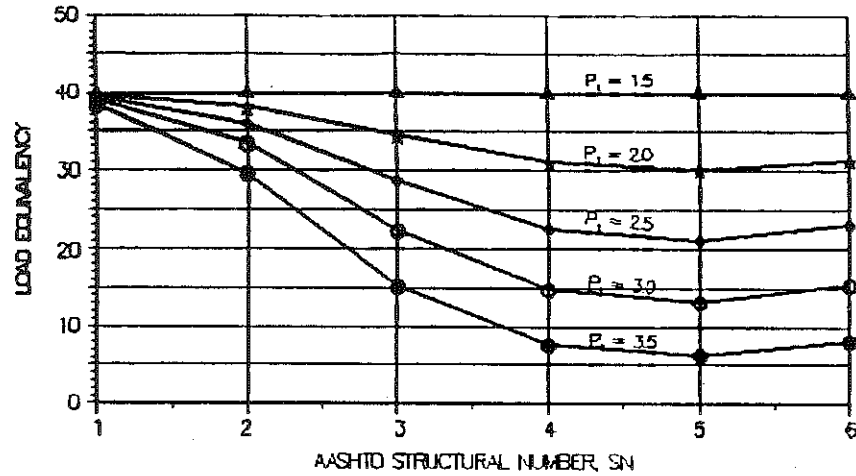
University of Kentucky, Lexington, KY, February 1983.

4. AASHTO Design Guide for Pavement Structures, the American Association of State Highway and Transportation Officials, Washington, D.C., 1986.
5. AASHTO Interim Guide for Design of Pavement Structures, 1972 the American Association of State Highway and Transportation Officials, Washington, D.C., 1974 Printing.
6. The AASHTO Road Test Report 5, Special Report 61E, Highway Research Board, Washington, D.C., 1961.
7. R. C. Deen, H. F. Southgate, and J. H. Havens, "Structural Analysis of Bituminous Concrete Pavements", Research Report 305, Division of Research, Kentucky Department of Highways, Lexington, KY, May 1971.
8. The AASHTO Road Test Report 7, Special Report 61G, Highway Research Board, Washington, D.C., 1961.
9. The AASHTO Road Test Report 3, Special Report 61C, Highway Research Board, Washington, D.C., 1961.
10. T. C. Hopkins, "Relationship between Soil Support Value and Kentucky CBR", Division of Research, Kentucky Department of Highways, Lexington, KY, 1970.
11. H. F. Southgate and R. C. Deen, "Variations of Fatigue Due to Unevenly Loaded Axles within Tridem Groups", Research Report UKTRP-84-11, Kentucky Transportation Research Program, University of Kentucky, Lexington, KY, April 1984.
12. H. F. Southgate, R. C. Deen, and J. G. Mayes, "Strain Energy Analysis of

Pavement Designs for Heavy Trucks", Transportation Research Record 949,

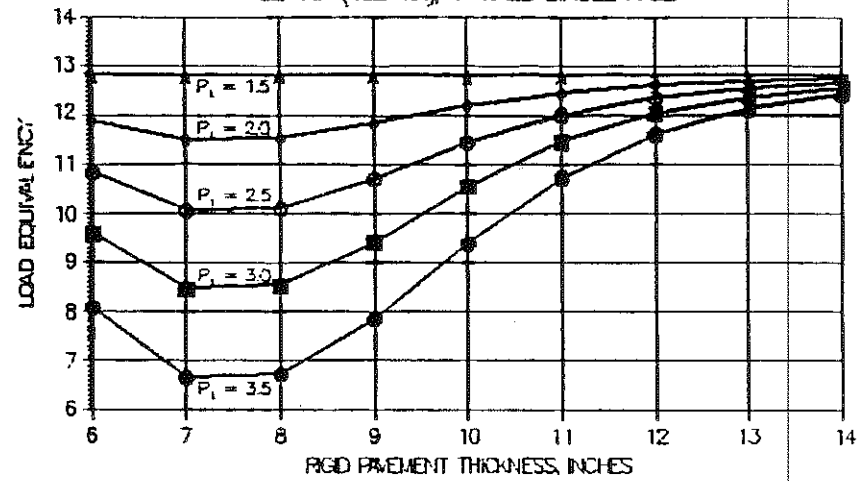
Transportation Research Board, Washington, D. C., 1983.

AASHTO LOAD EQUIVALENCIES
40-KIP (178-kN), 4-TIRED SINGLE AXLE



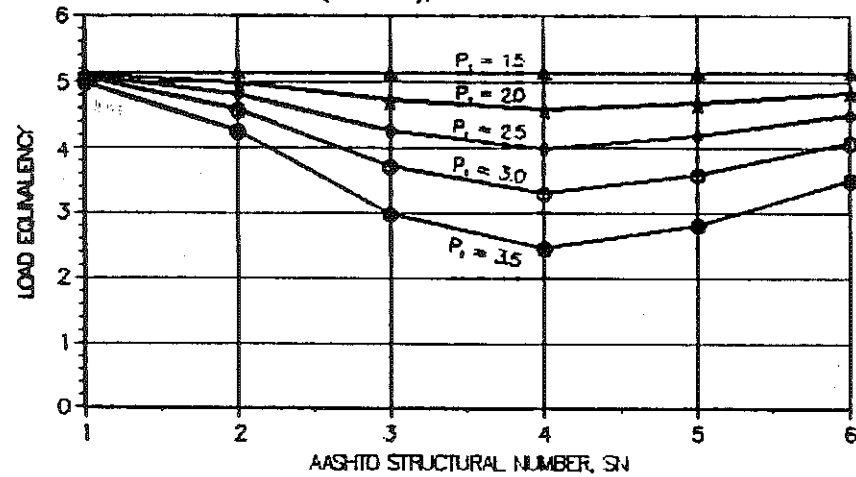
(a)

AASHTO LOAD EQUIVALENCIES
32-KIP (132-kN), 4-TIRED SINGLE AXLE



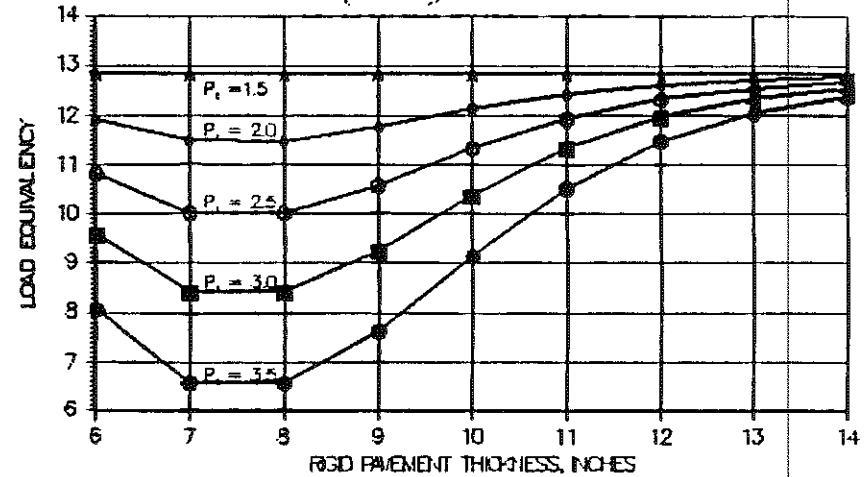
(c)

AASHTO LOAD EQUIVALENCIES
48-KIP (214-kN), 8-TIRED TANDEM AXLE



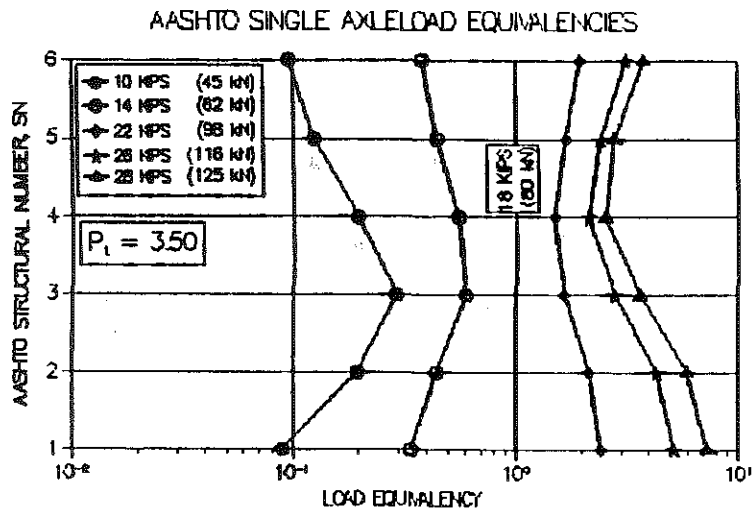
(b)

AASHTO LOAD EQUIVALENCIES
52-KIP (231-kN), 8-TIRED TANDEM AXLE

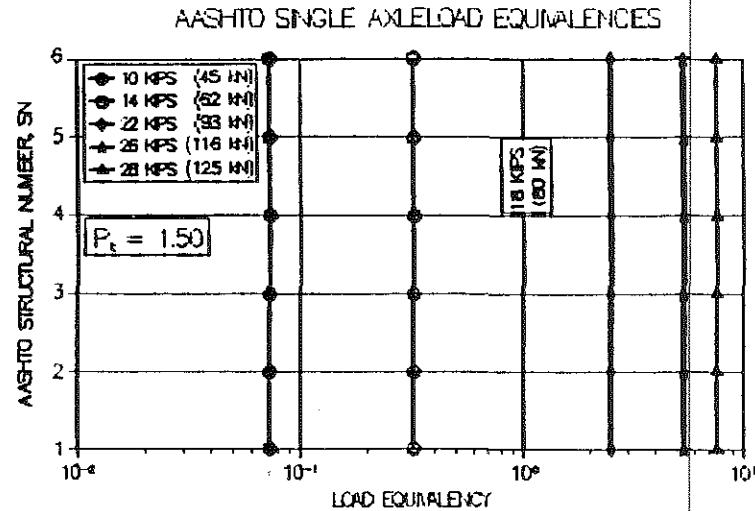


(d)

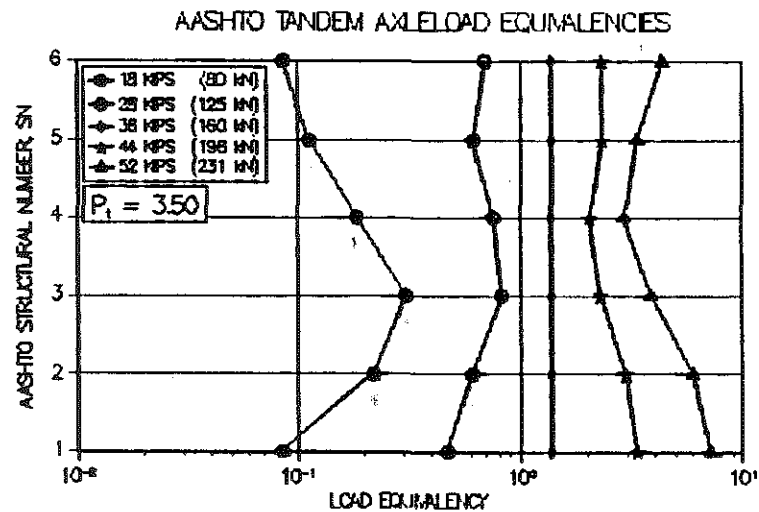
FIGURE 1. VARIABILITY IN AASHTO LOAD EQUIVALENCIES FOR FIXED AXLELOADS.



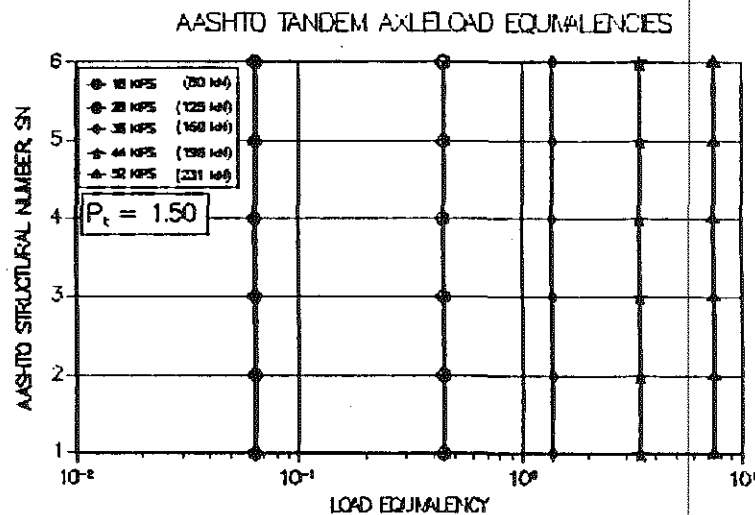
(a)



(b)



(c)



(d)

FIGURE 2. VARIABILITY IN AASHTO LOAD EQUIVALENCIES FOR $P_t = 3.5$ AND 1.5 FOR SINGLE AND TANDEM AXLES FOR FLEXIBLE PAVEMENTS.

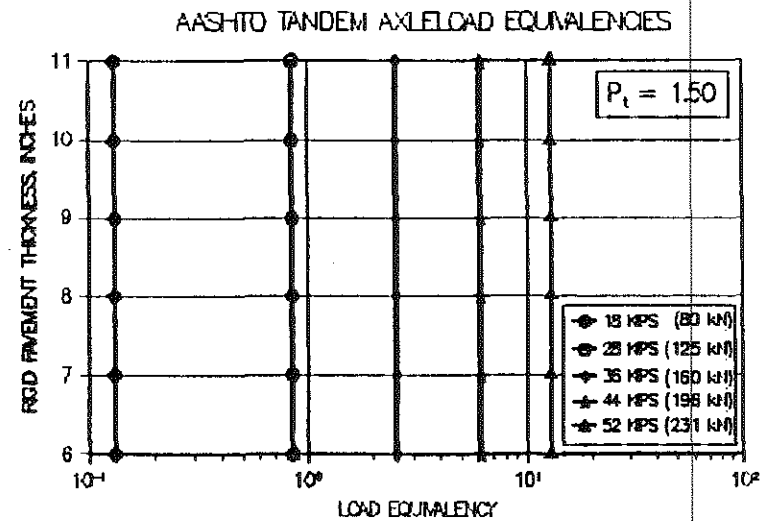
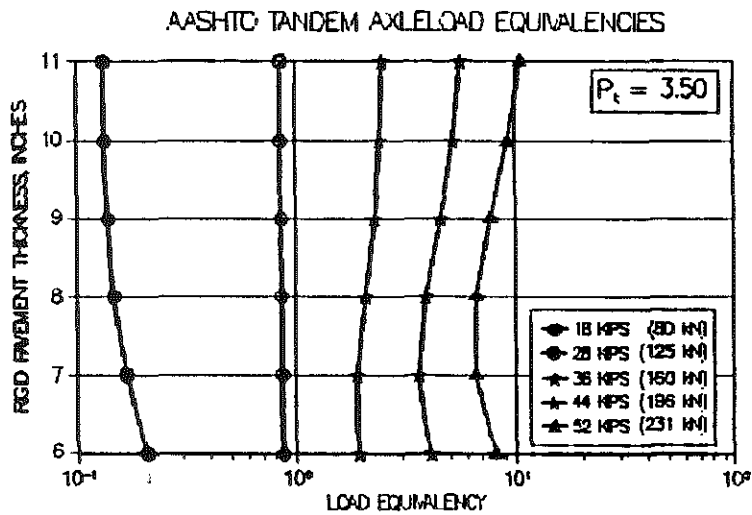
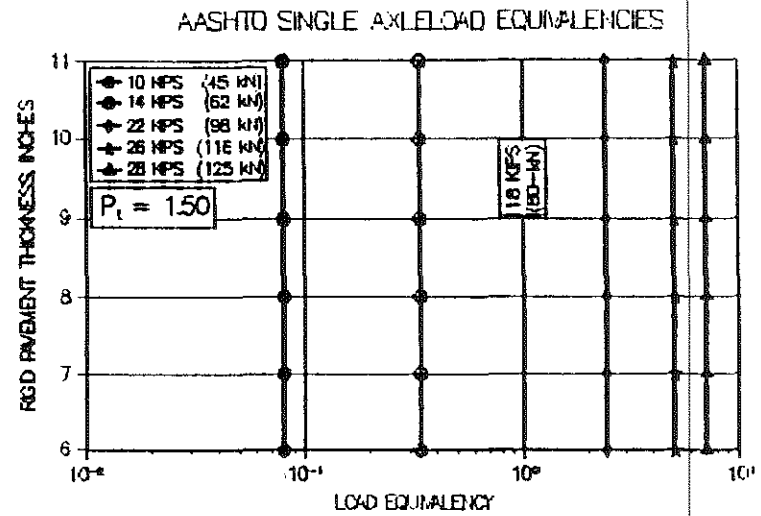
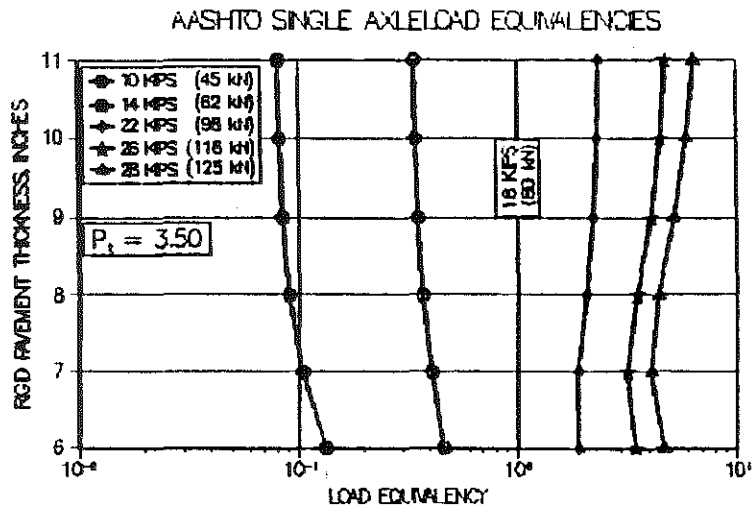


FIGURE 3. VARIABILITY IN AASHTO LOAD EQUIVALENCIES FOR $P_t = 3.5$ AND 1.5 FOR SINGLE AND TANDEM AXLES FOR RIGID PAVEMENTS.

AASHO ROAD TEST PUMPING DATA REINFORCED PAVEMENTS

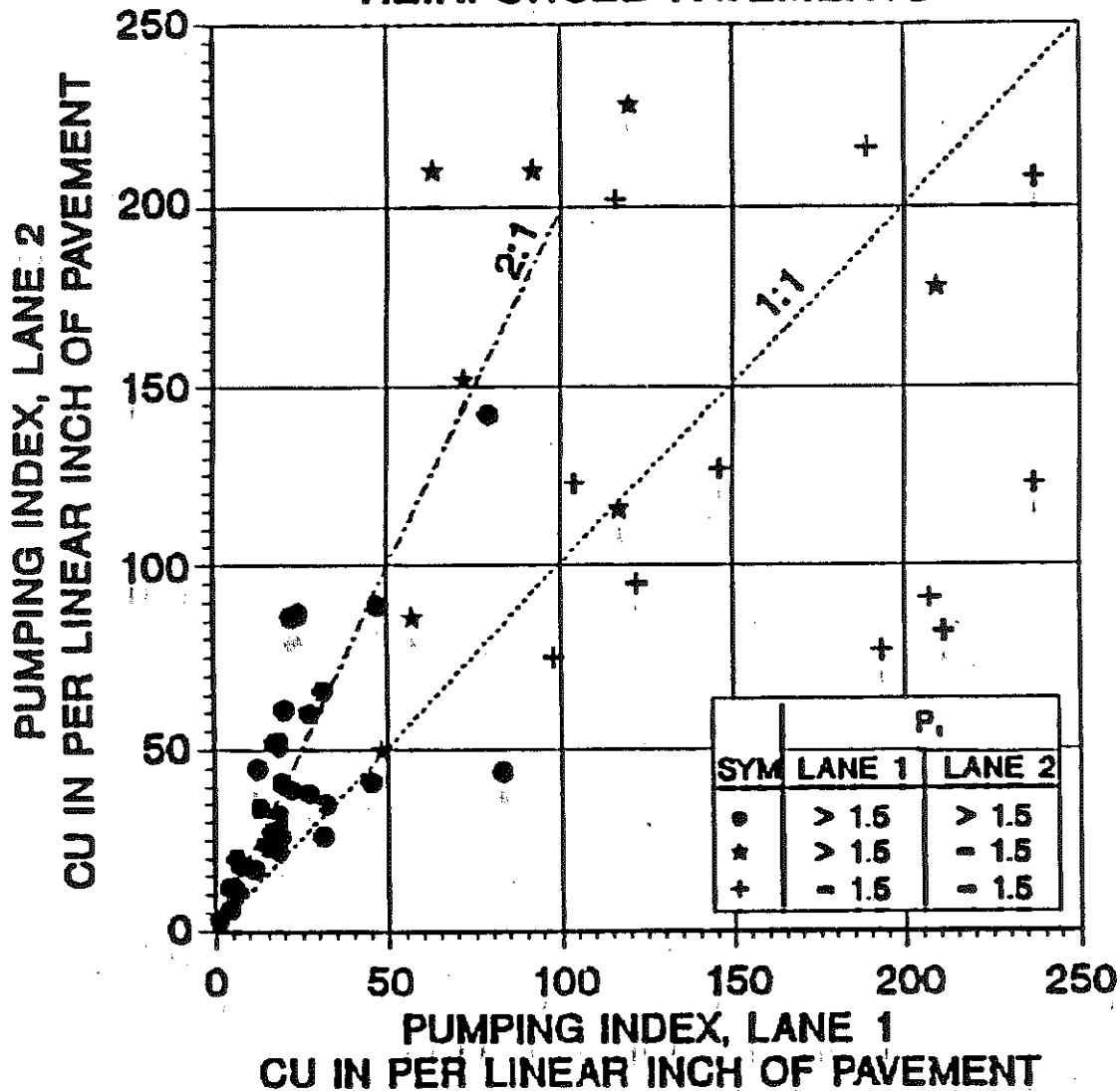
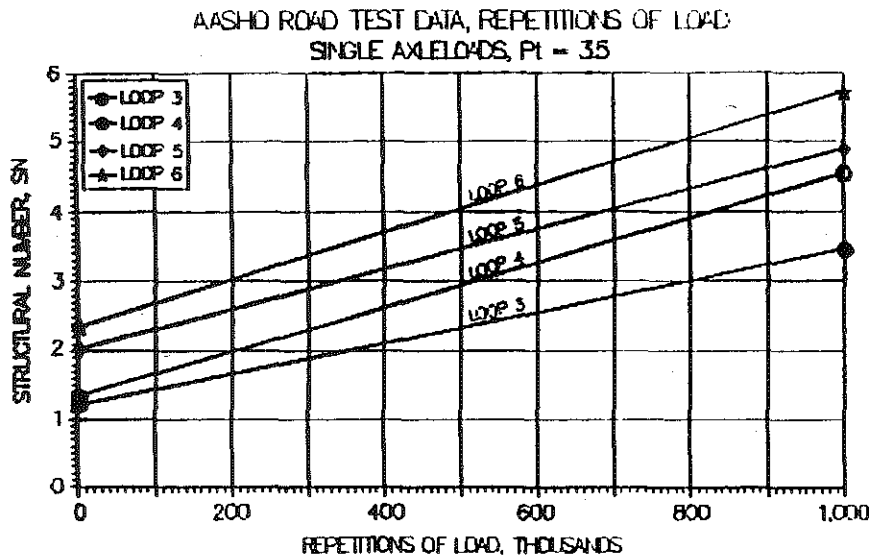
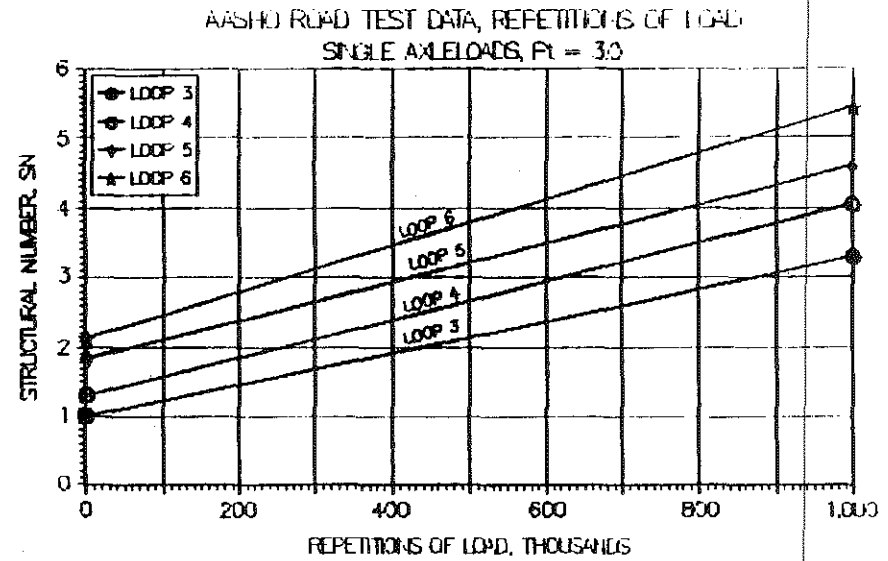


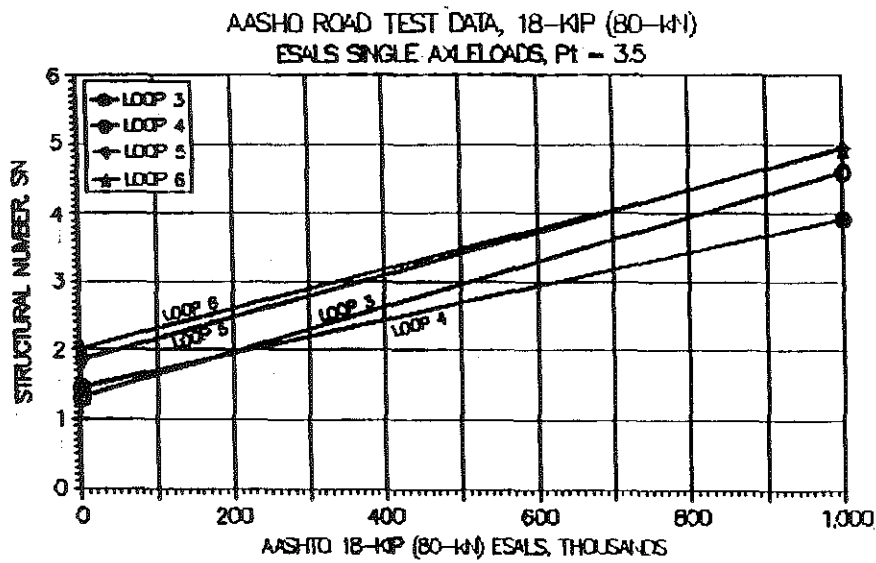
FIGURE 4. AASHO ROAD TEST PUMPING INDEX DATA, LANE 2 (TANDEM AXLES) VERSUS LANE 1 (SINGLE AXLES) (TABLE 54, REFERENCE 3).



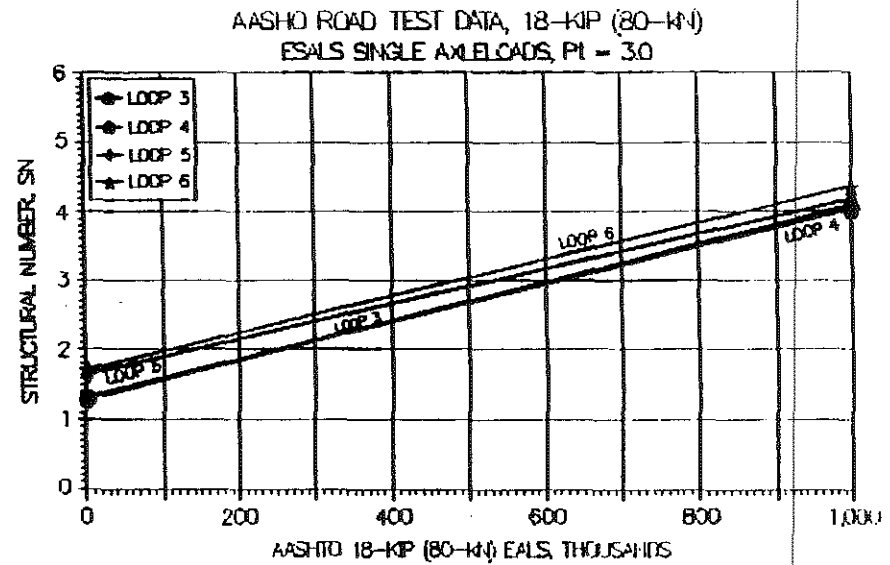
(a)



(b)



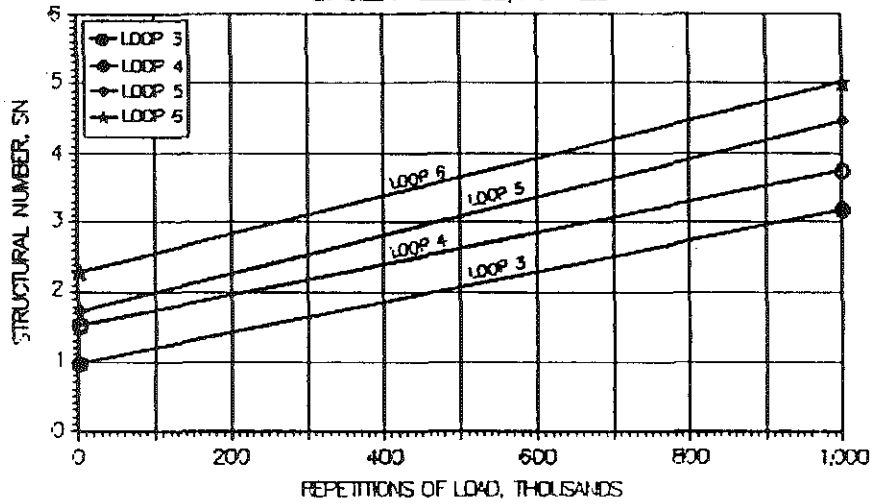
(c)



(d)

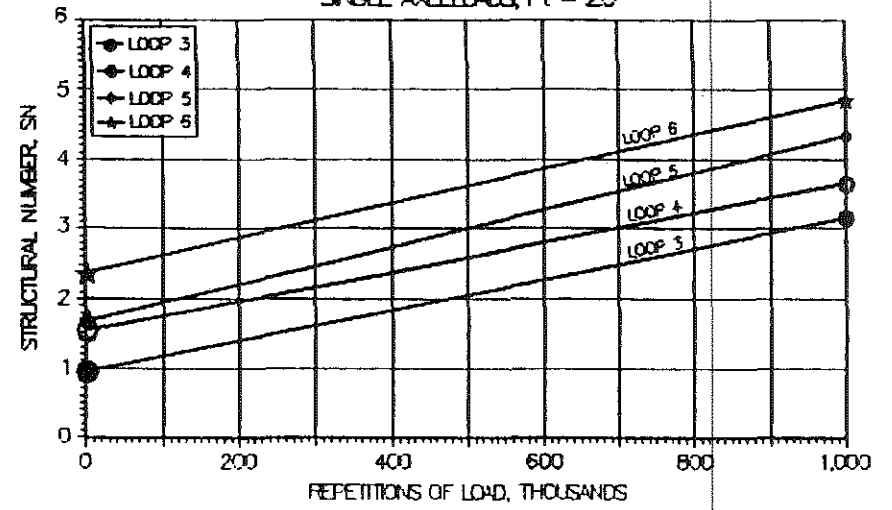
FIGURE 5. COMPARISON OF AASHTO STRUCTURAL NUMBER TO REPETITIONS AND AASHTO ESALS FOR AASHTO ROAD TEST SINGLE AXLE DATA AT $P_1 = 3.5$ AND 3.0 .

AASHO ROAD TEST DATA, REPETITIONS OF LOAD
SINGLE AXLELOADS, $P_t = 2.5$



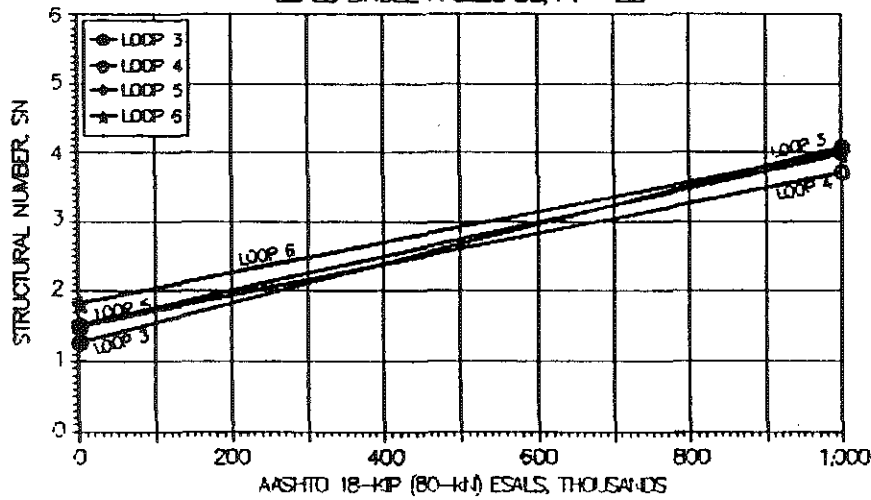
(a)

AASHO ROAD TEST DATA, REPETITIONS OF LOAD
SINGLE AXLELOADS, $P_t = 2.0$



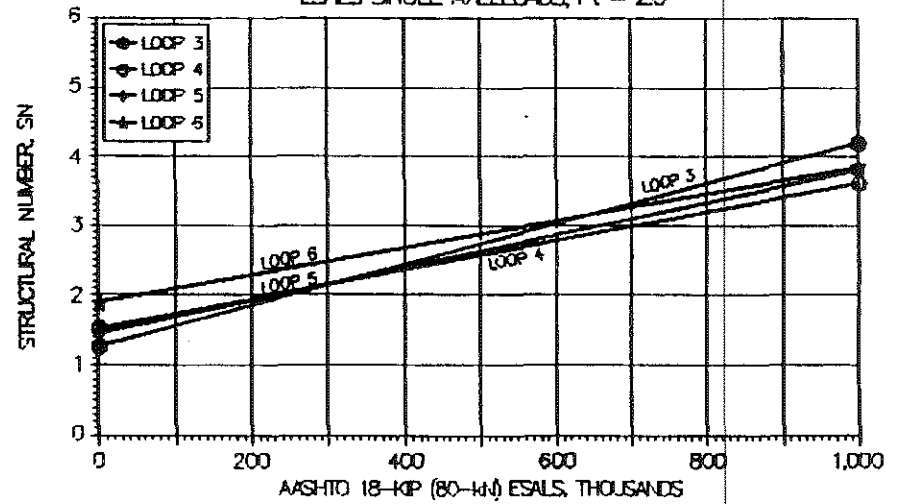
(b)

AASHO ROAD TEST DATA, 18-KIP (80-kN)
ESALS SINGLE AXLELOADS, $P_t = 2.5$



(c)

AASHO ROAD TEST DATA, 18-KIP (80-kN)
ESALS SINGLE AXLELOADS, $P_t = 2.0$



(d)

FIGURE 6. COMPARISON OF AASHO STRUCTURAL NUMBER TO REPETITIONS AND AASHO ESALS FOR AASHO ROAD TEST SINGLE AXLE DATA AT $P_t = 2.5$ AND 2.0.

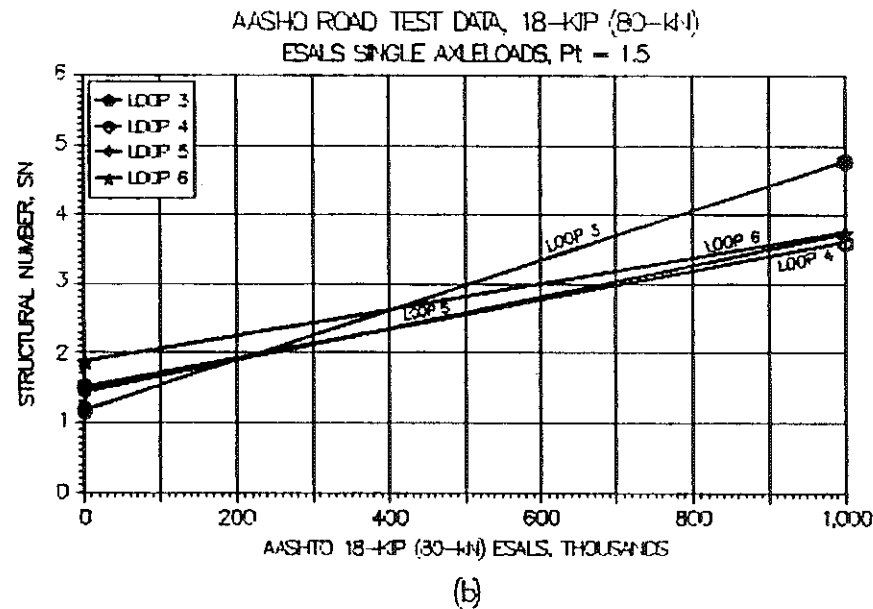
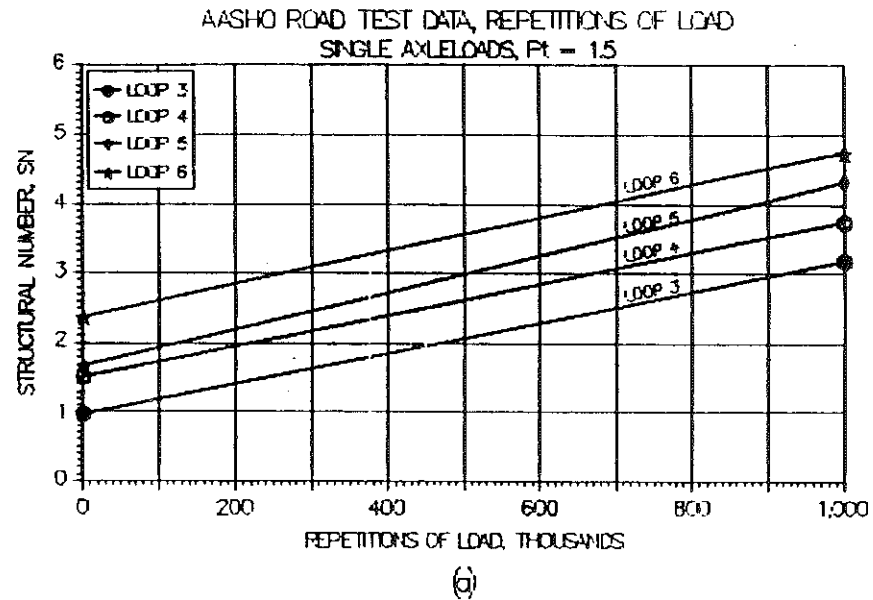
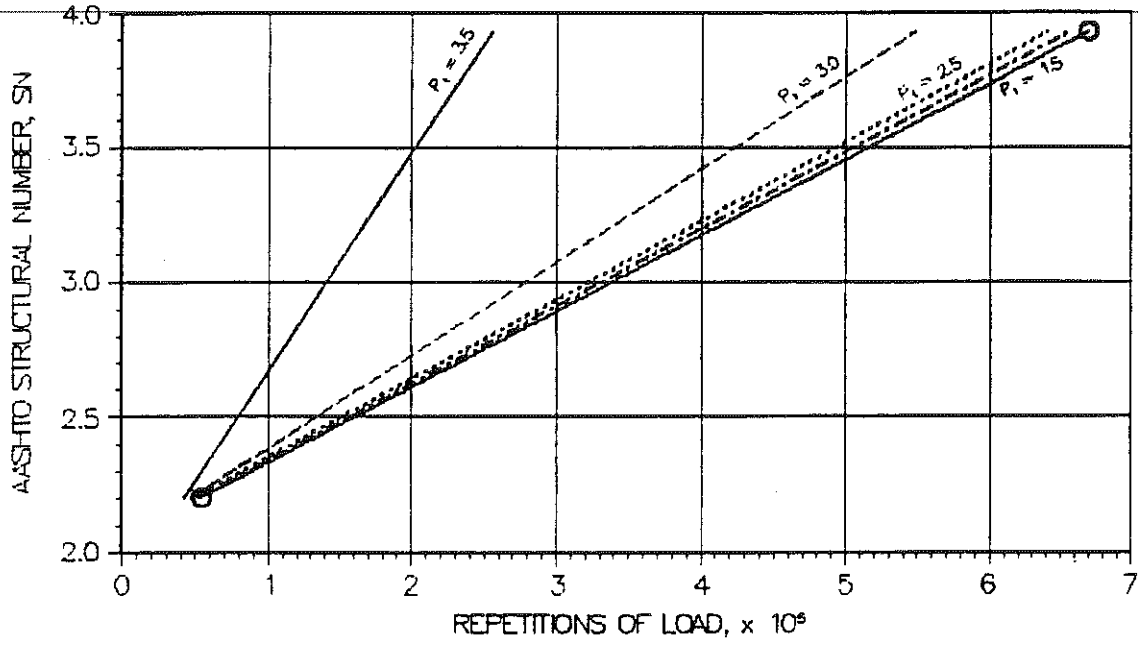


FIGURE 7. COMPARISON OF AASHTO STRUCTURAL NUMBER TO REPETITIONS AND AASHTO ESALS FOR AASHO ROAD TEST SINGLE AND TANDEM AXLE DATA AT $P_t = 1.5$.

AASHO ROAD TEST DATA
 LOOP 4, LANE 1, 18-KIP (80-kN) SINGLE



(a)

AASHO ROAD TEST DATA
 LOOP 4, LANE 2, 32-KIP (142-kN) TANDEM

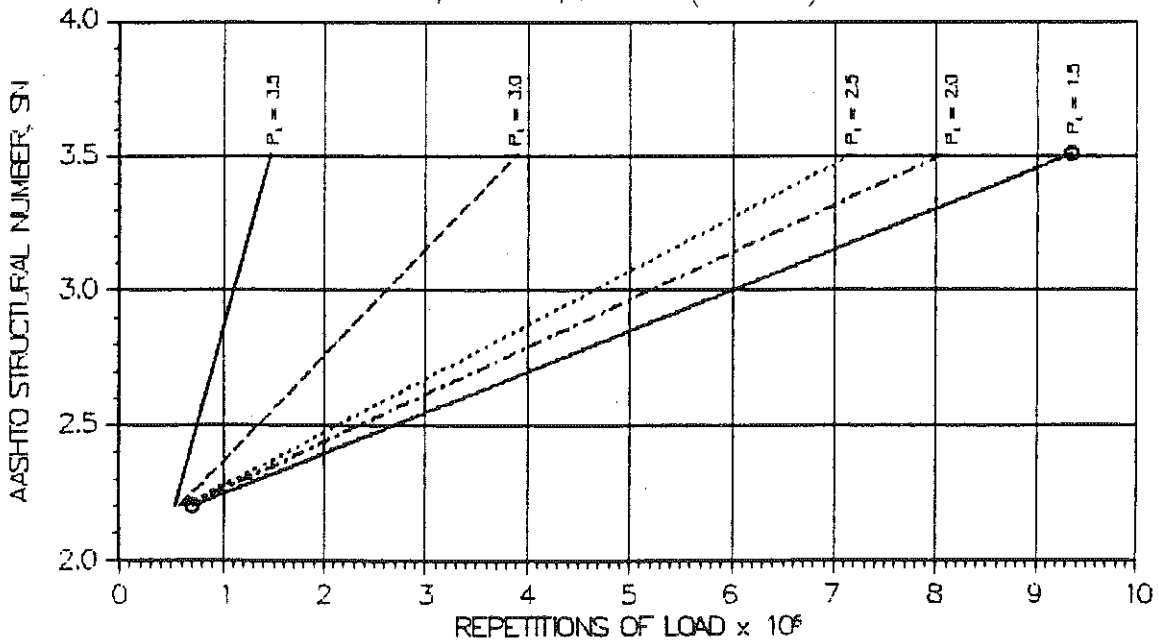
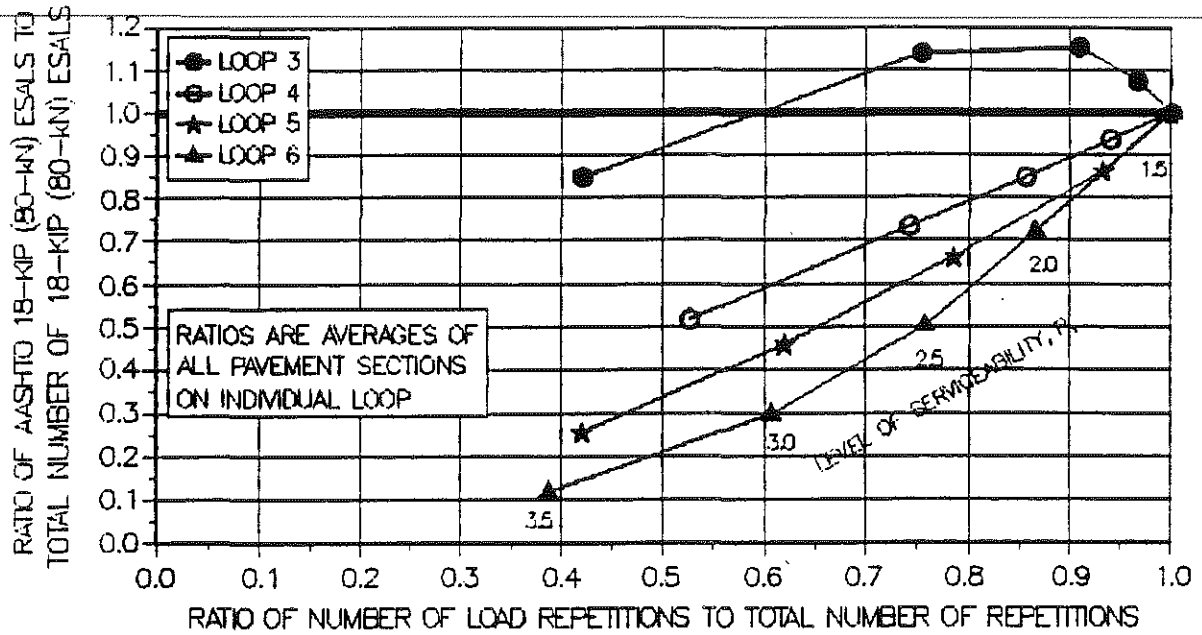


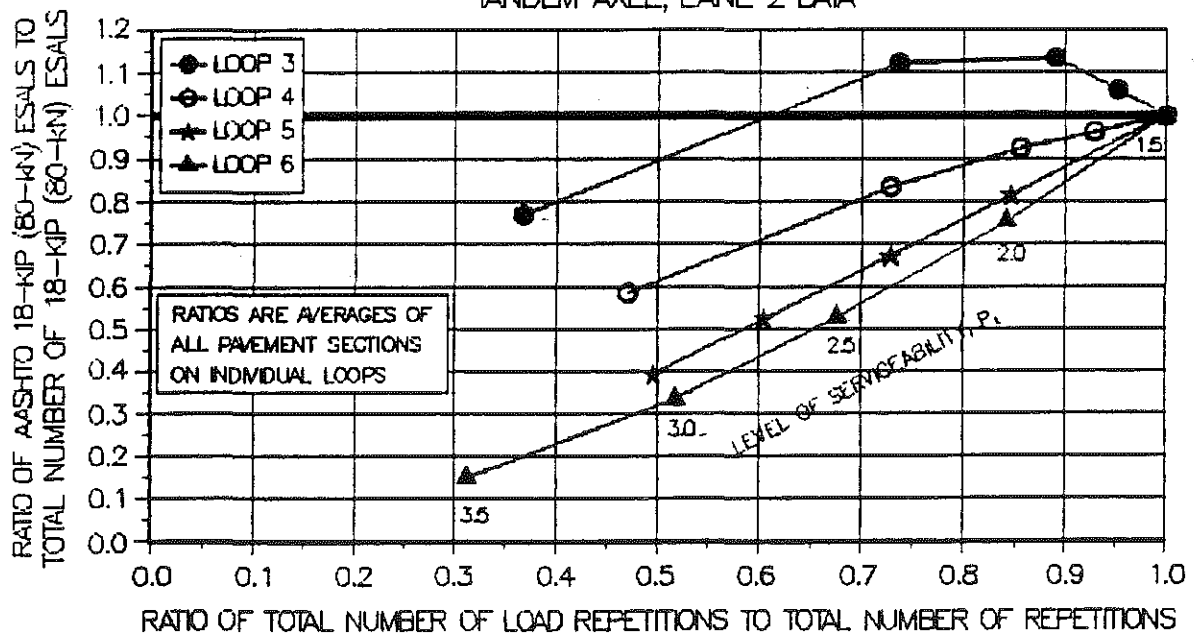
FIGURE 8. COMPARISON OF VARIOUS P₁s FOR AASHTO SN AND REPETITIONS OF SINGLE AND TANDEM LOADS FOR AASHO ROAD TEST LOOP 4 DATA.

AASHO ROAD TEST
SINGLE AXLE, LANE 1 DATA



(c)

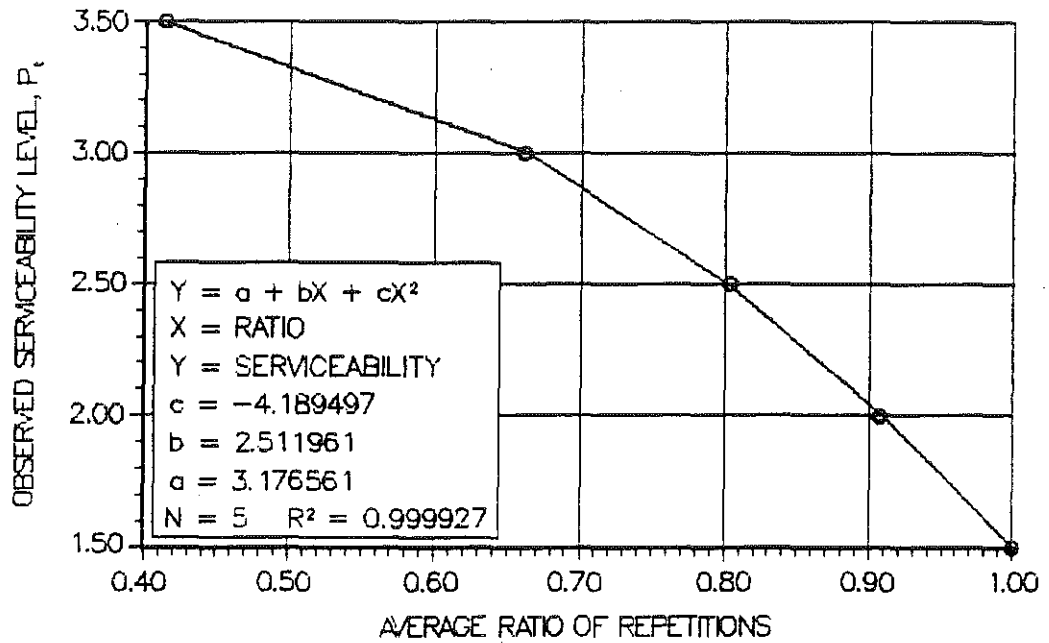
AASHO ROAD TEST
TANDEM AXLE, LANE 2 DATA



(b)

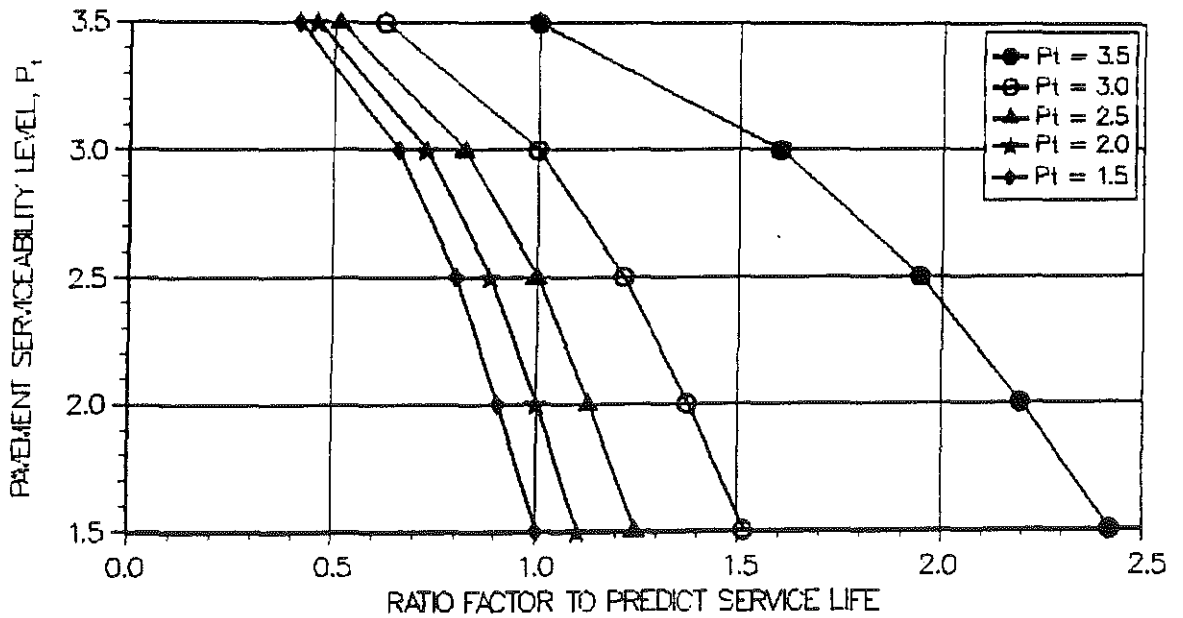
FIGURE 9. RELATIONSHIP BETWEEN RATIO OF AASHO ROAD TEST REPETITIONS VERSUS RATIO OF REPETITIONS CONVERTED TO ESALS USING AASHO EQUATION C-16.

AASHO ROAD TEST DATA ANALYSES
 RATIO OF OBSERVED REPETITIONS FOR 176 SECTIONS



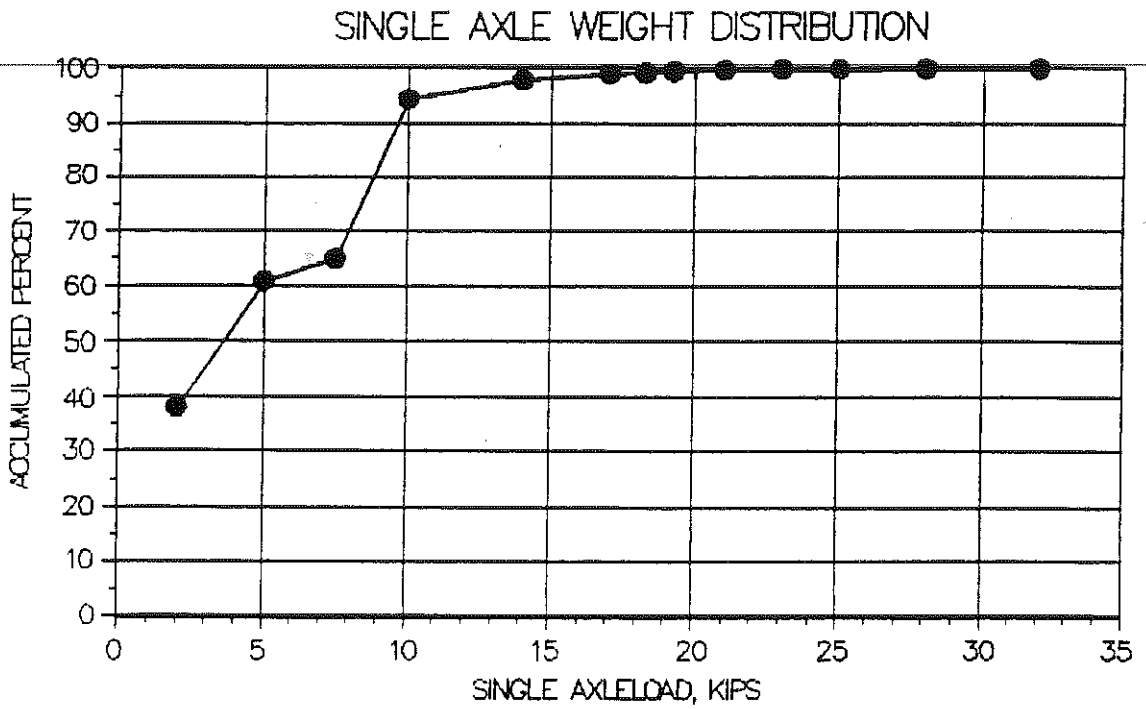
(a)

SERVICEABILITY VS SERVICE LIFE
 BASED ON 176 PAVEMENT SECTIONS AT AASHO ROAD TEST

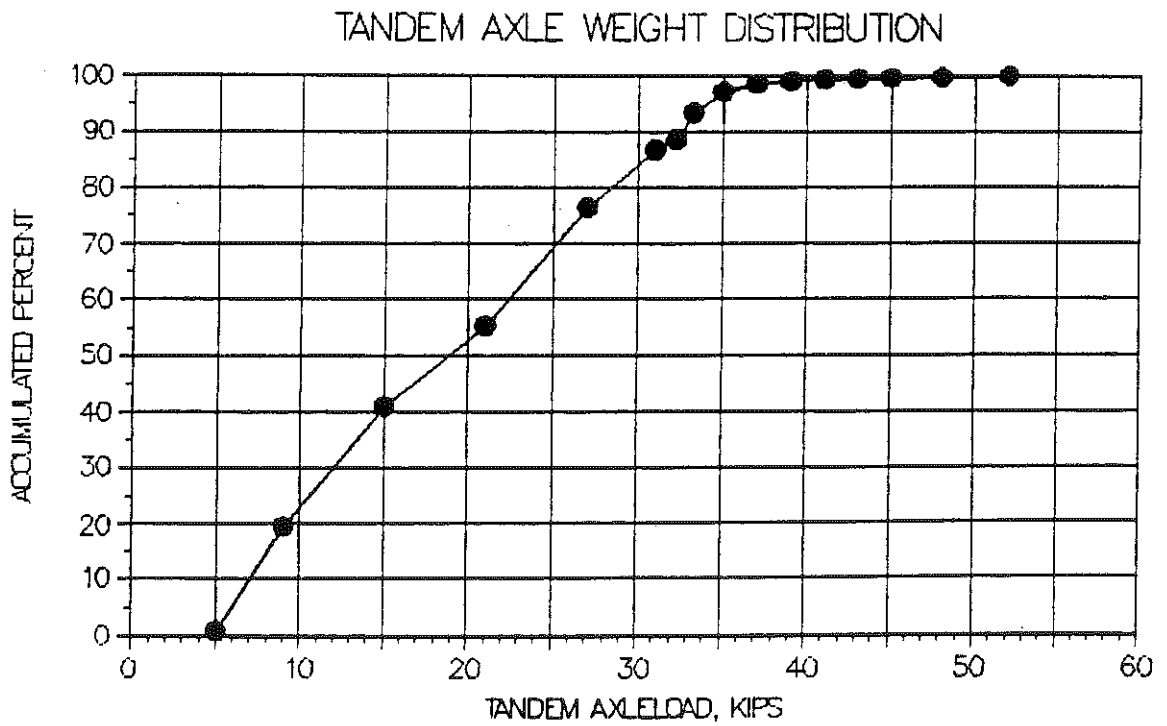


(b)

FIGURE 10. RELATIONSHIP OF OBSERVED AASHO SERVICEABILITY WITH AVERAGE RATIO OF REPETITIONS OF APPLIED LOADS AT AASHO ROAD TEST.



(a)



(b)

FIGURE 11. ACCUMULATED PERCENTAGE VS AXLELOAD FOR KENTUCKY LOADOMETER DATA.

STRUCTURAL NUMBER VS ESAL KENTUCKY LOADOMETER DATA

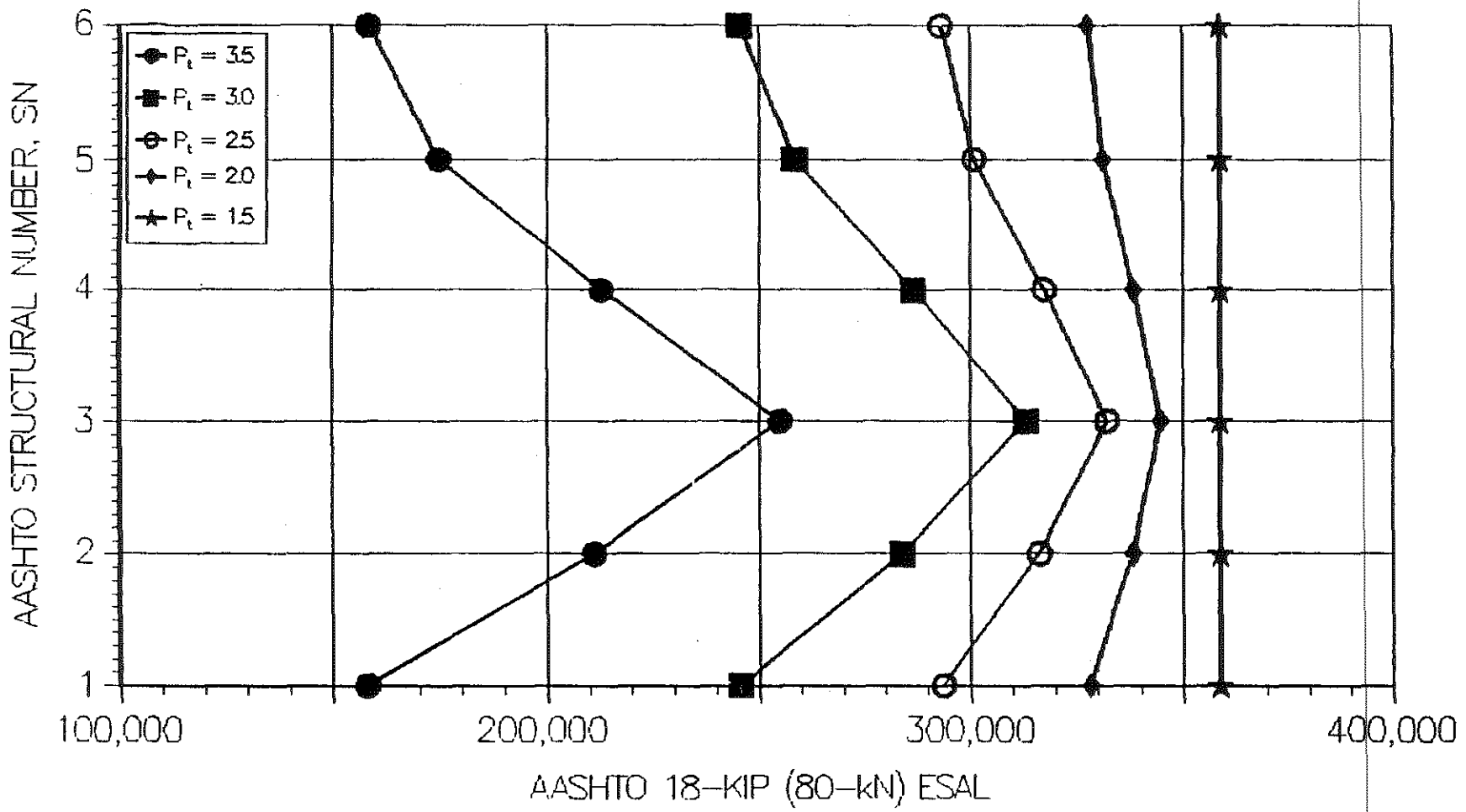


FIGURE 12. COMPARISON OF AASHTO SN VS AASHTO ESALS FOR KENTUCKY LOADOMETER DATA.

KENTUCKY LOAD EQUIVALENCY RELATIONSHIPS

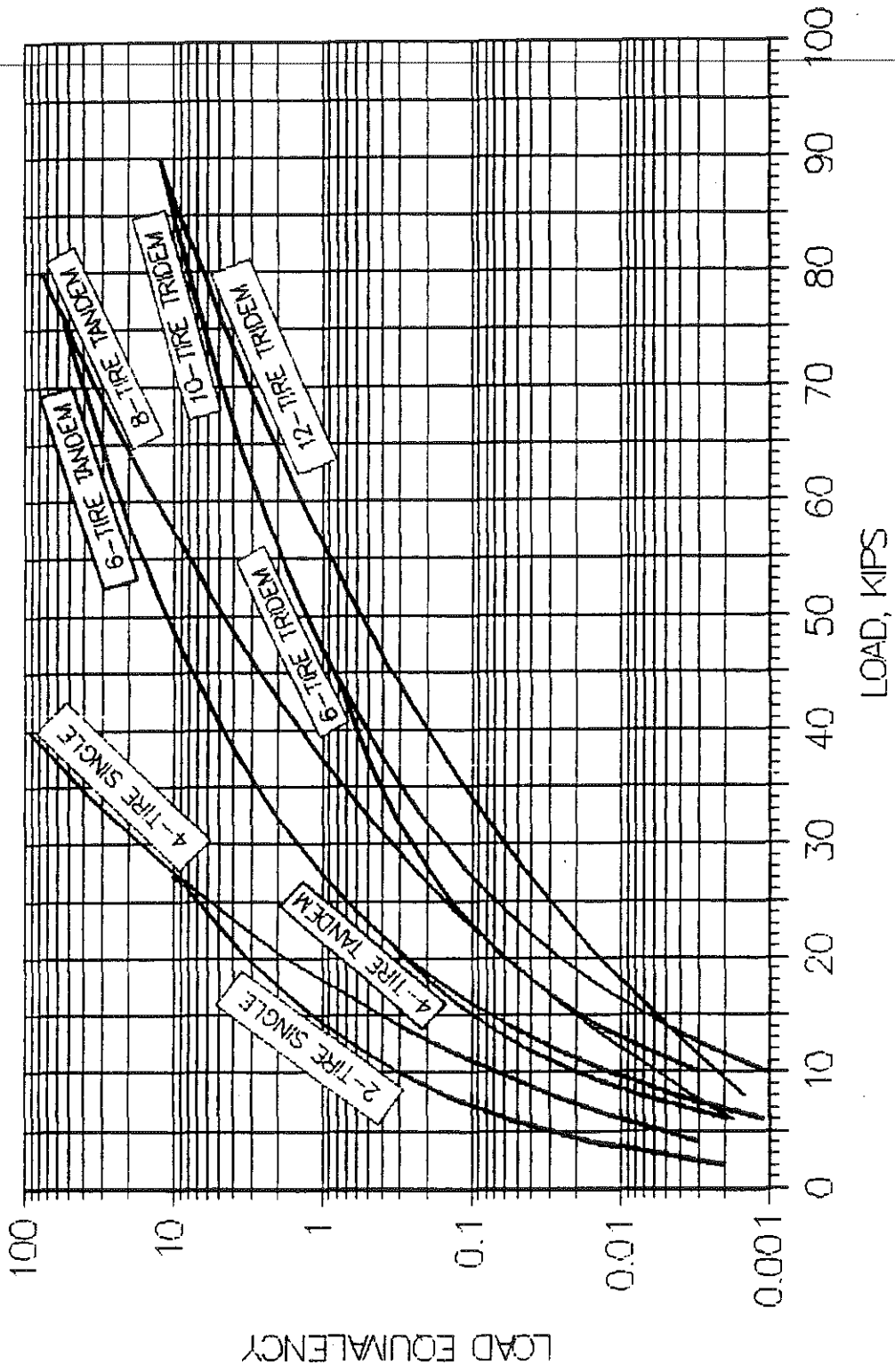


FIGURE 13. KENTUCKY LOAD EQUIVALENCY RELATIONSHIPS.

SERVICEABILITY VS REPETITIONS

KENTUCKY LOADOMETER DATA

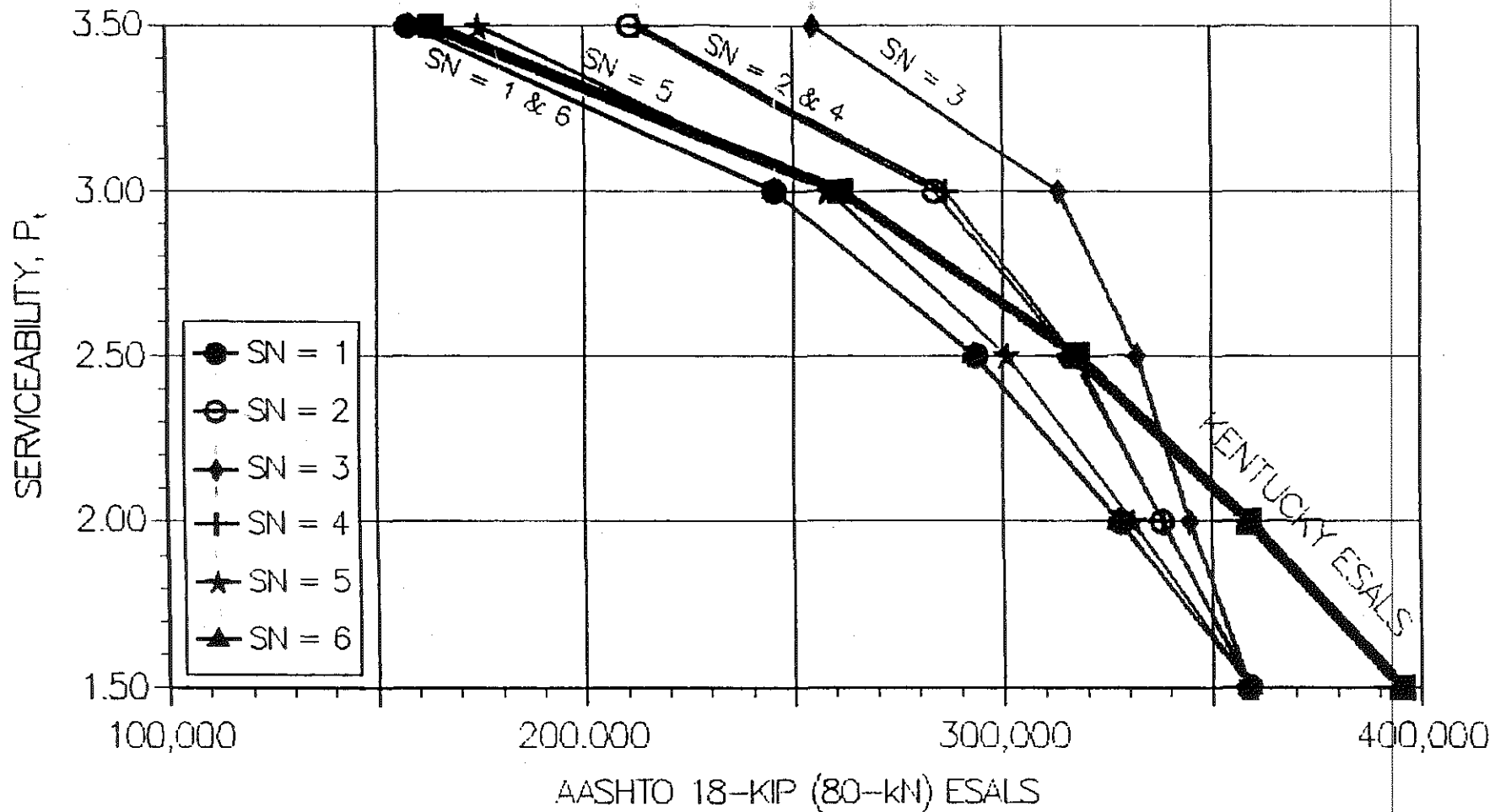


FIGURE 14. KENTUCKY LOADOMETER DATA CONVERTED TO ESALS USING KENTUCKY LOAD EQUIVALENCY RELATIONSHIPS AND SUPERIMPOSED ON AASHTO ESALS SHOWN IN FIGURE 12 BUT REARRANGED AS P_t VS ESALS.

LOAD EQUIVALENCY RELATIONSHIPS
AASHTO AND KENTUCKY

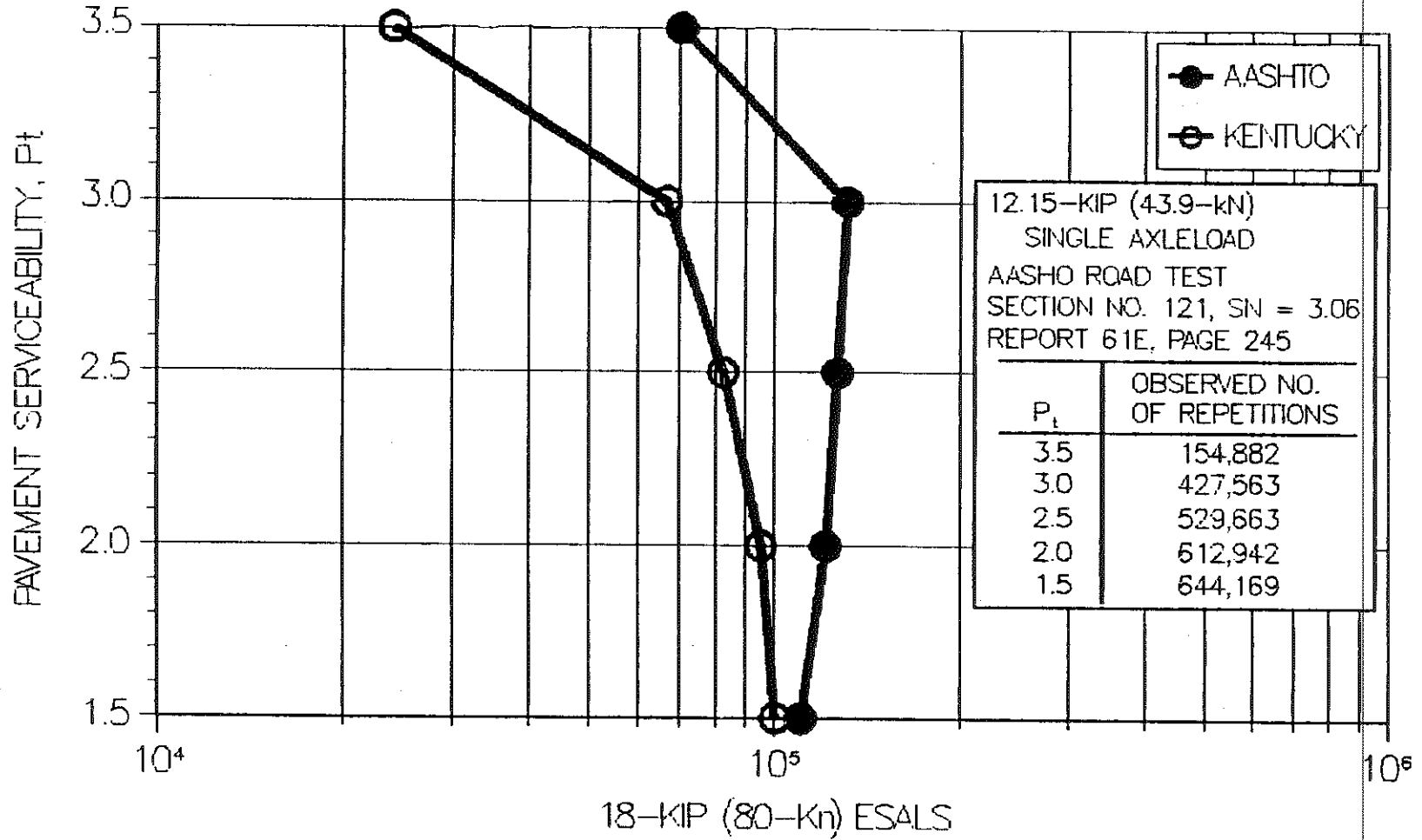
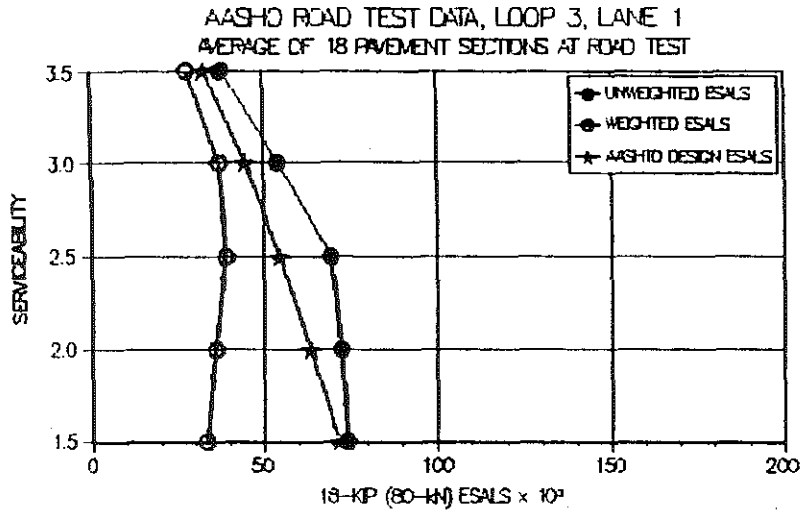
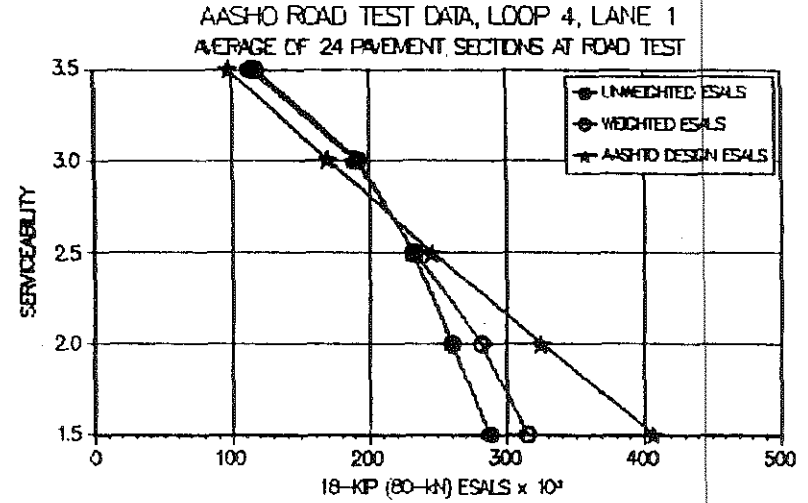


FIGURE 15. COMPARISON OF KENTUCKY AND AASHTO ESALS VS SERVICEABILITY FOR PAVEMENT SECTION 121 AT AASHTO ROAD TEST.

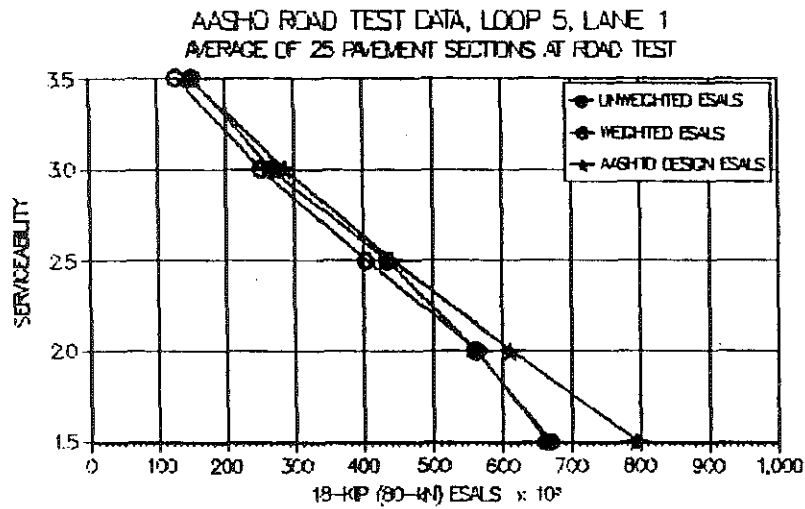
SINGLE AXLES



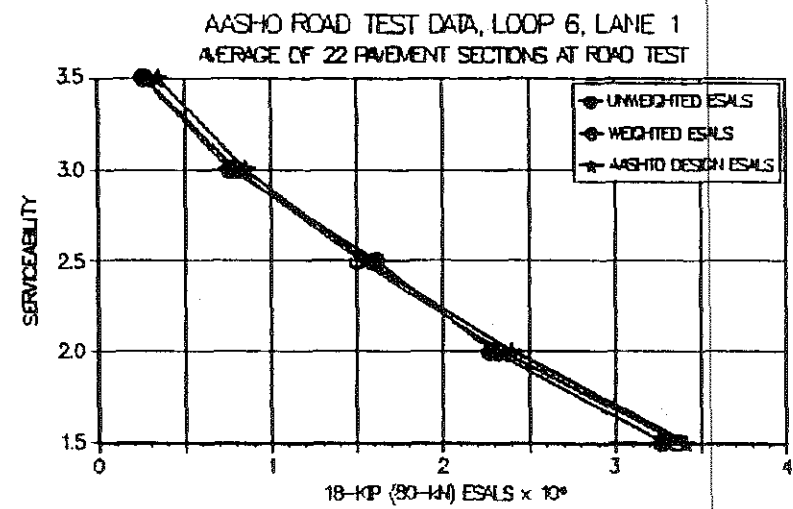
(a)



(b)



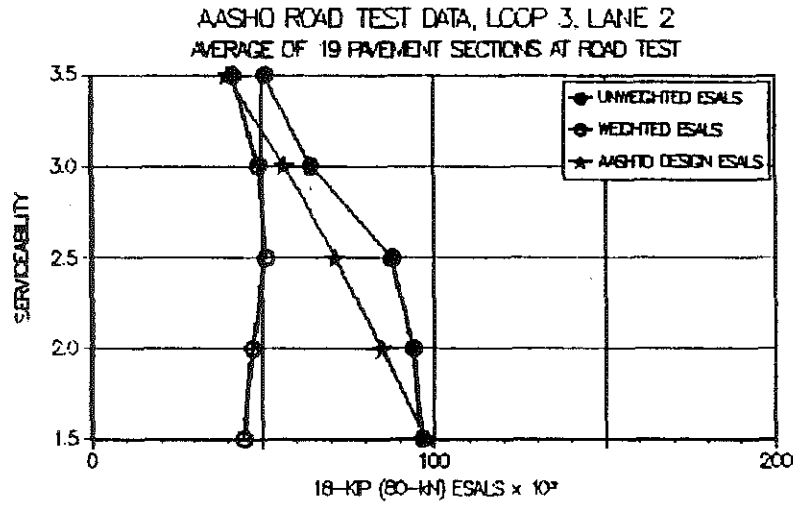
(c)



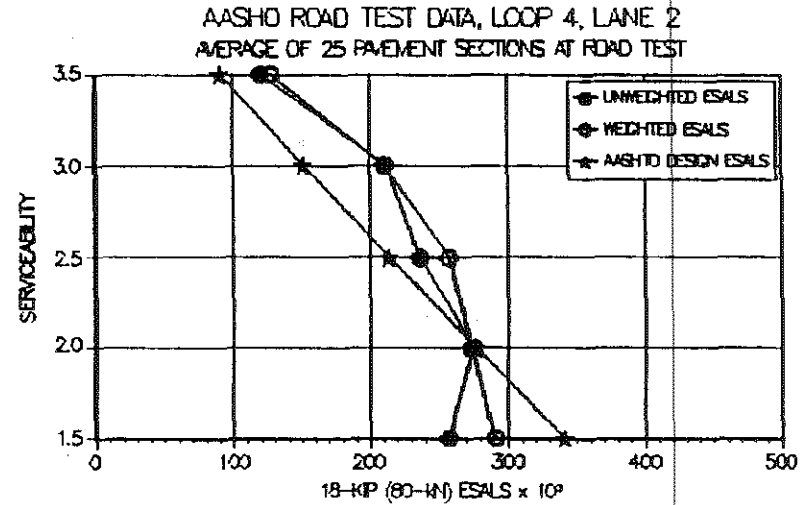
(d)

FIGURE 16. COMPARISON OF SERVICEABILITY AND RATIO OF AASHTO ESALS FOR UNWEIGHTED, WEIGHTED AASHO ROAD TEST DATA, AND FOR AASHTO DESIGN EQUATION CALCULATIONS FOR SINGLE AXLELOADS AND SN USED AT AASHO ROAD TEST.

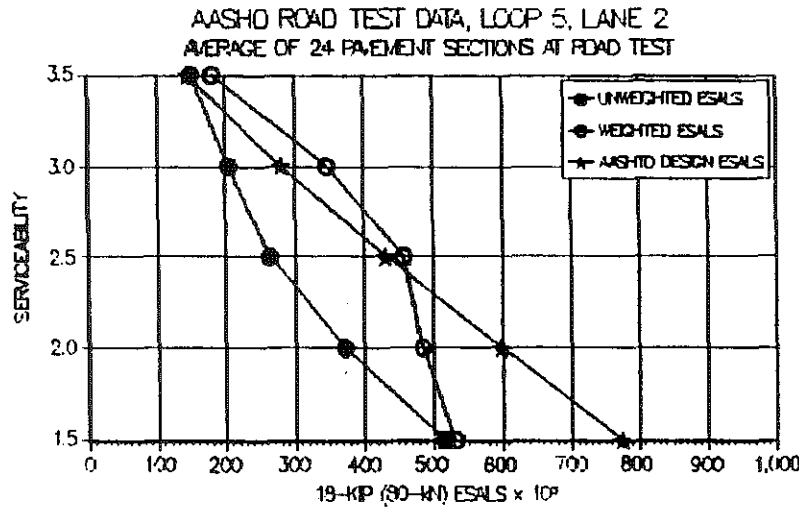
TANDEM AXLES



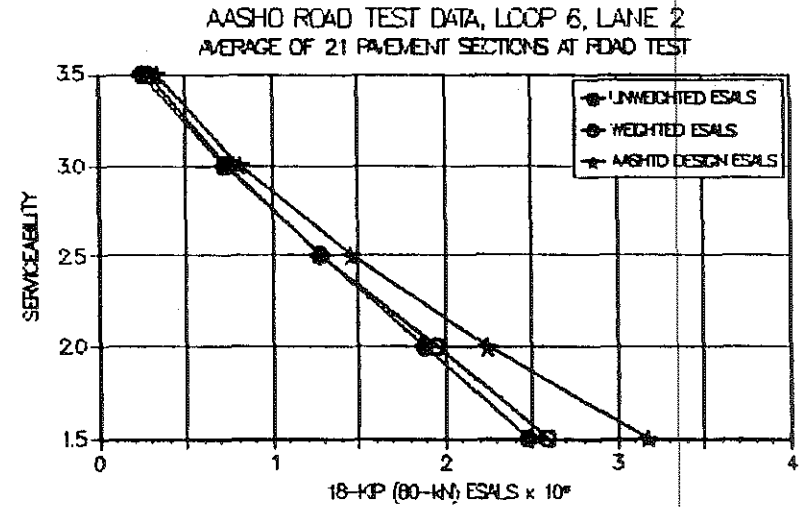
(a)



(b)

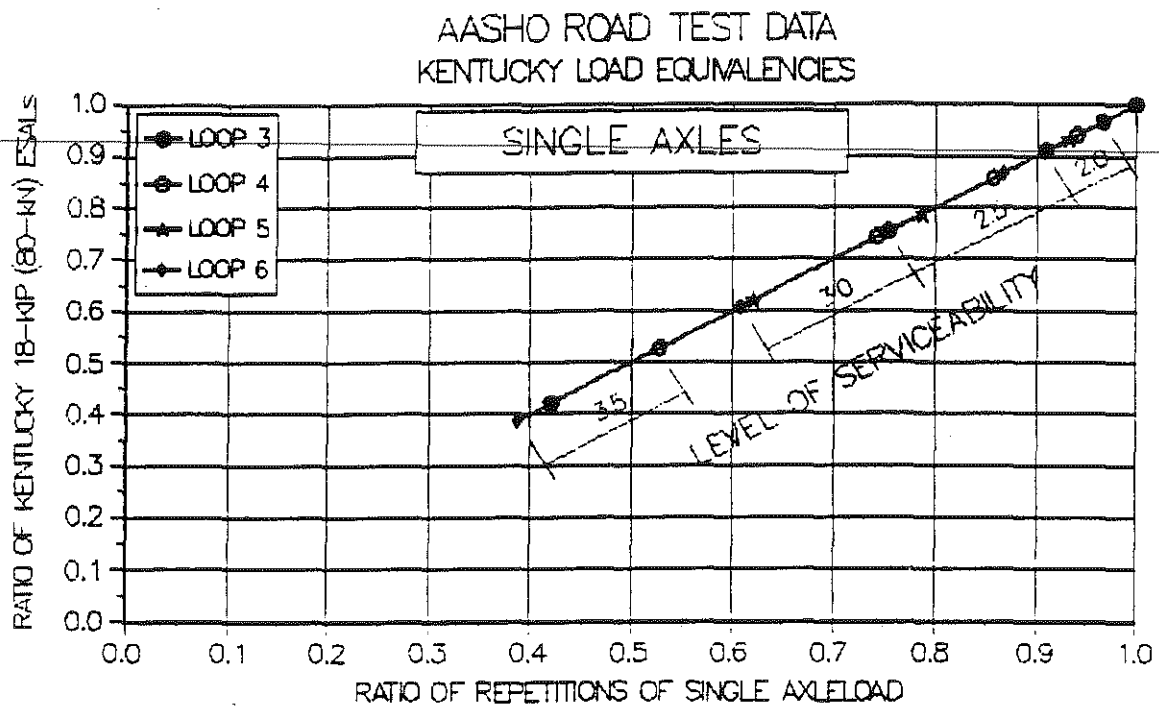


(c)

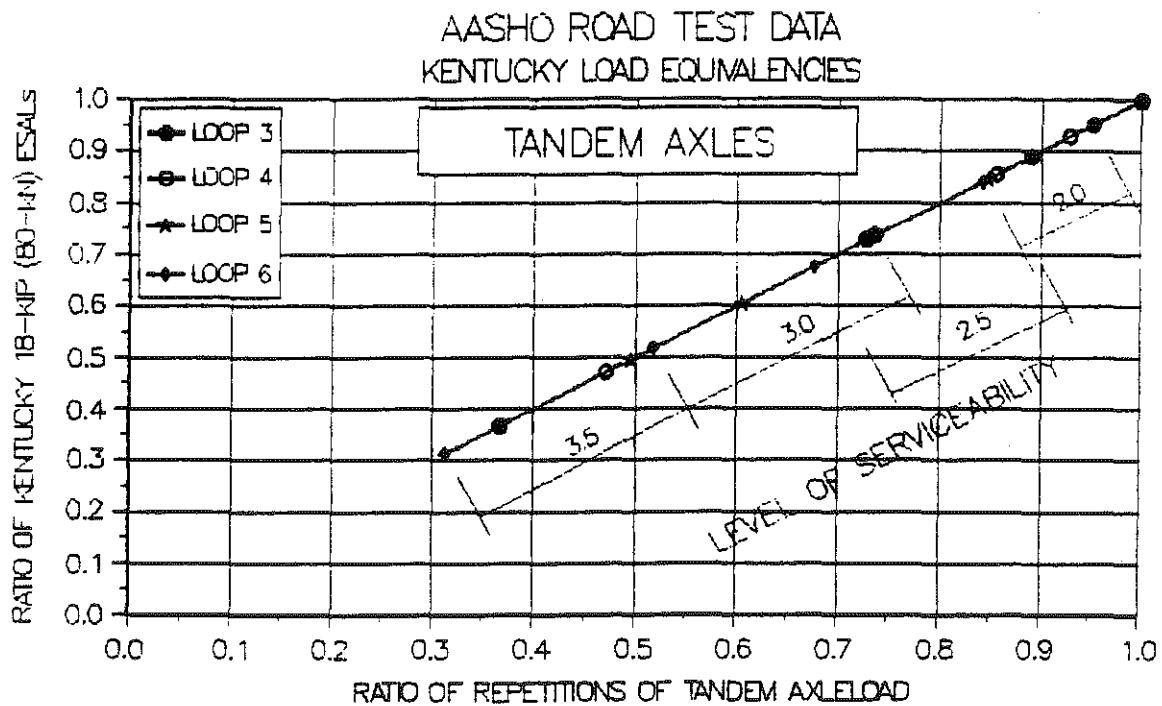


(d)

FIGURE 17. COMPARISON OF SERVICEABILITY AND RATIO OF AASHTO ESALS FOR UNWEIGHTED, WEIGHTED AASHO ROAD TEST DATA, AND FOR AASHTO DESIGN EQUATION CALCULATIONS FOR TANDEM AXLELOADS AND SN USED AT AASHO ROAD TEST.



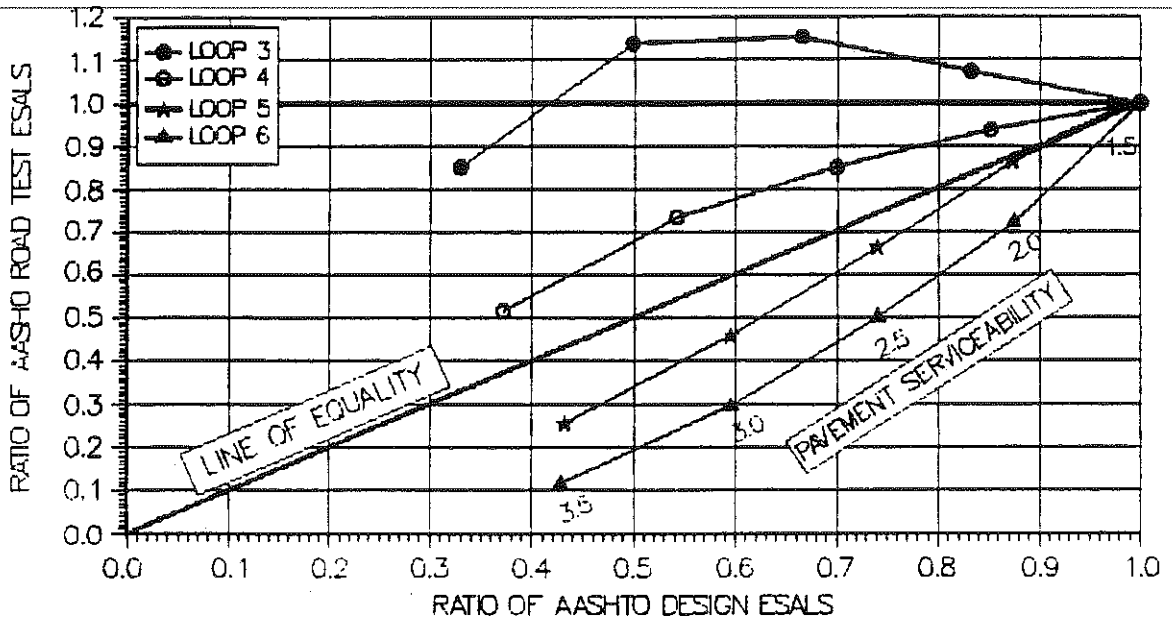
(a)



(b)

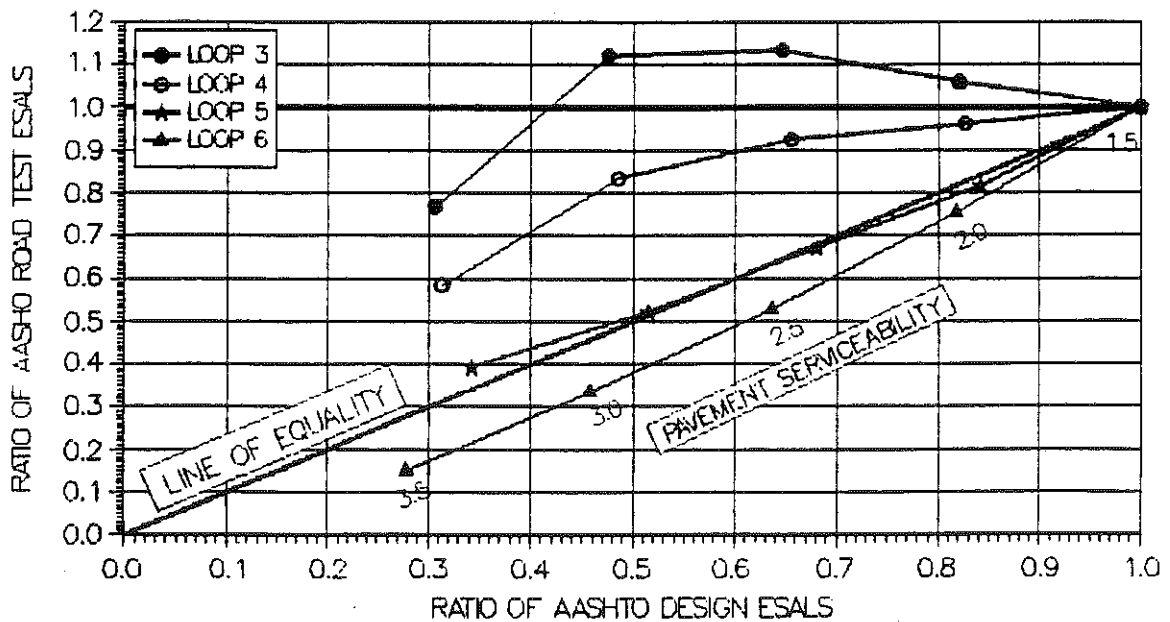
FIGURE 18. AVERAGE RATIO OF KENTUCKY ESALS TO AVERAGE RATIO OF REPETITIONS OF LOAD FOR AASHO ROAD TEST DATA AS A FUNCTION OF LOOP AND SERVICEABILITY.

RATIO OF AASHTO DESIGN ESALS VS AASHTO ROAD TEST ESALS FOR SINGLE AXLE DATA



(c)

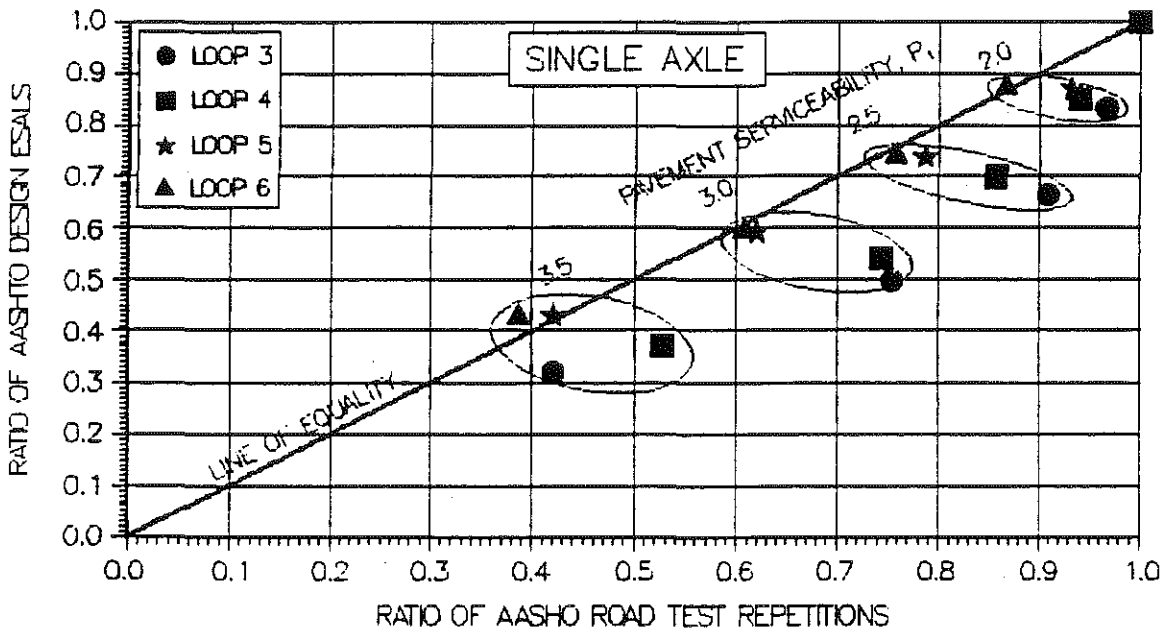
RATIO OF AASHTO DESIGN ESALS VS AASHTO ROAD TEST ESALS FOR TANDEM AXLE DATA



(b)

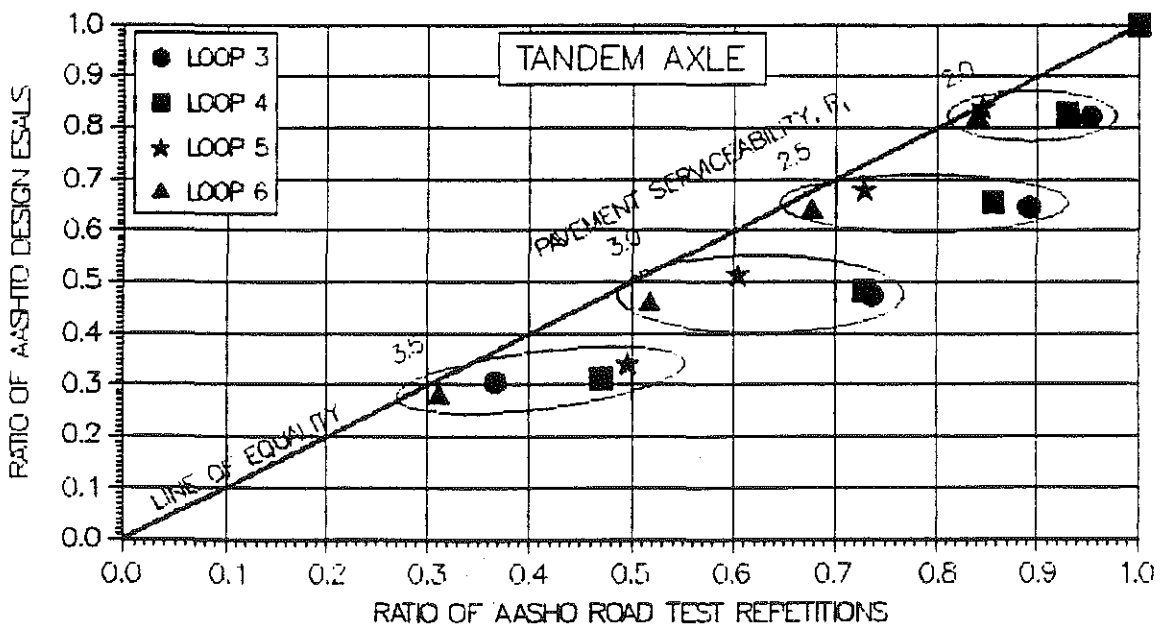
FIGURE 19. RATIO OF AASHTO ROAD TEST ESALS TO RATIO OF ESALS CALCULATED USING AASHTO EQUATION C-13 FOR EQUAL SERVICEABILITY LEVEL.

COMPARISON BETWEEN RATIO OF AASHO ROAD TEST REPETITIONS AND RATIO OF AASHTO DESIGN ESALS



(c)

COMPARISON BETWEEN RATIO OF AASHO ROAD TEST REPETITIONS AND RATIO OF AASHTO DESIGN ESALS



(b)

FIGURE 20. COMPARISON OF RATIO OF AASHTO DESIGN ESALS TO RATIO OF AASHO ROAD TEST REPETITIONS.

AASHTO VS KY ESALS

599 5-AXLE SEMI-TRAILER TRUCKS

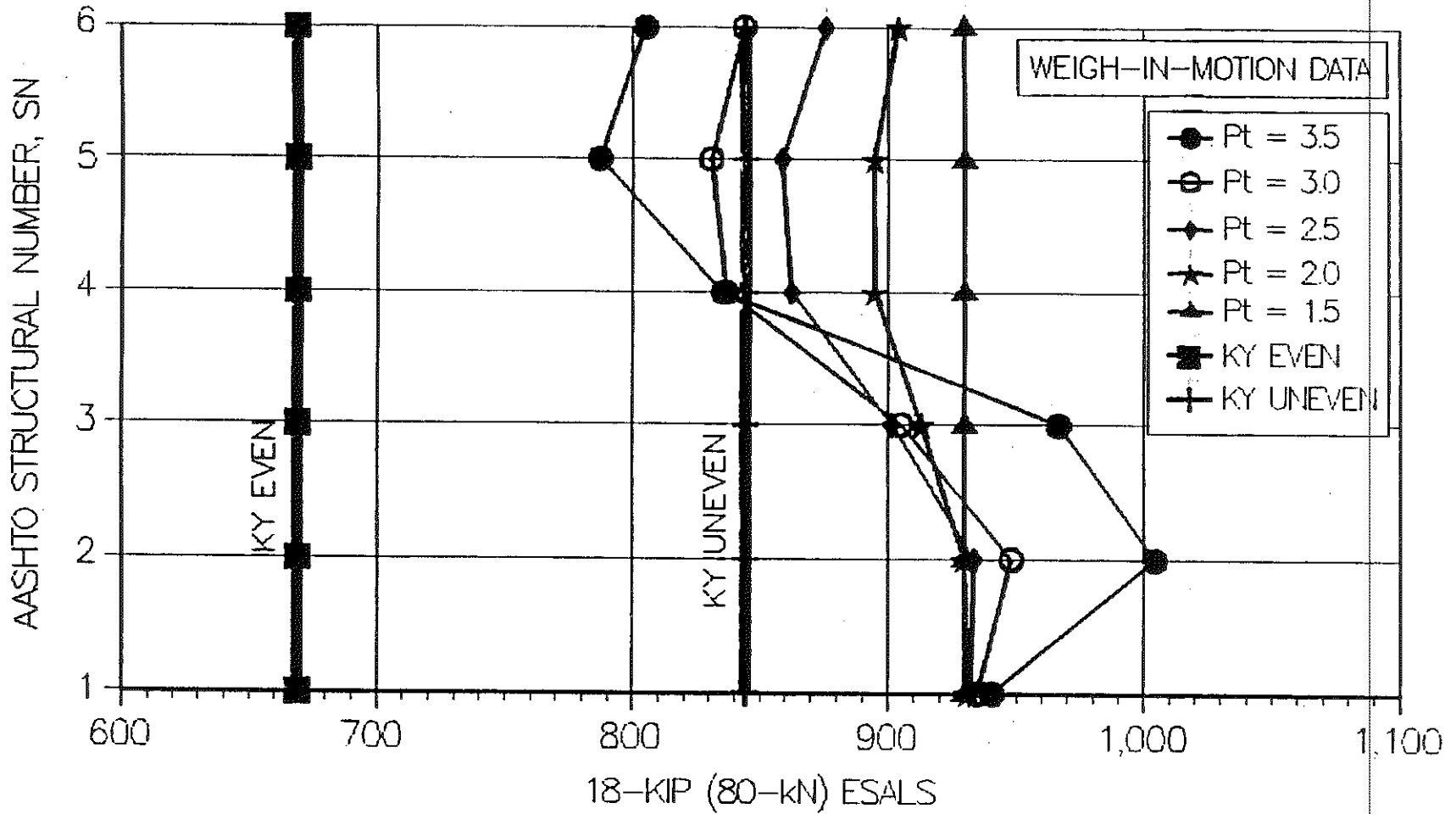
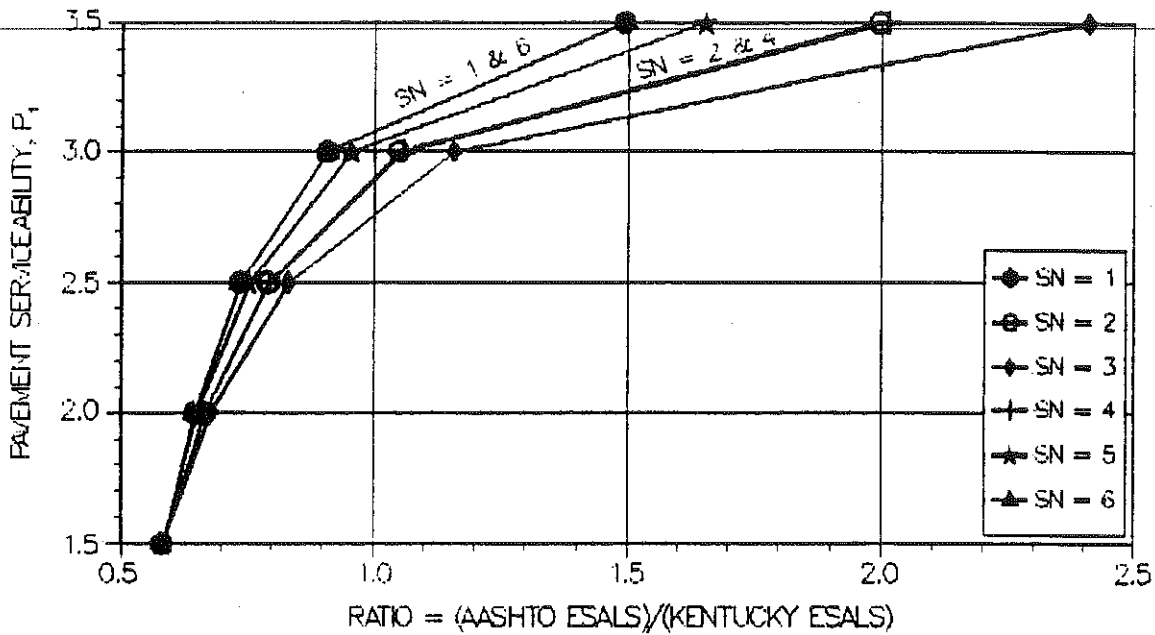


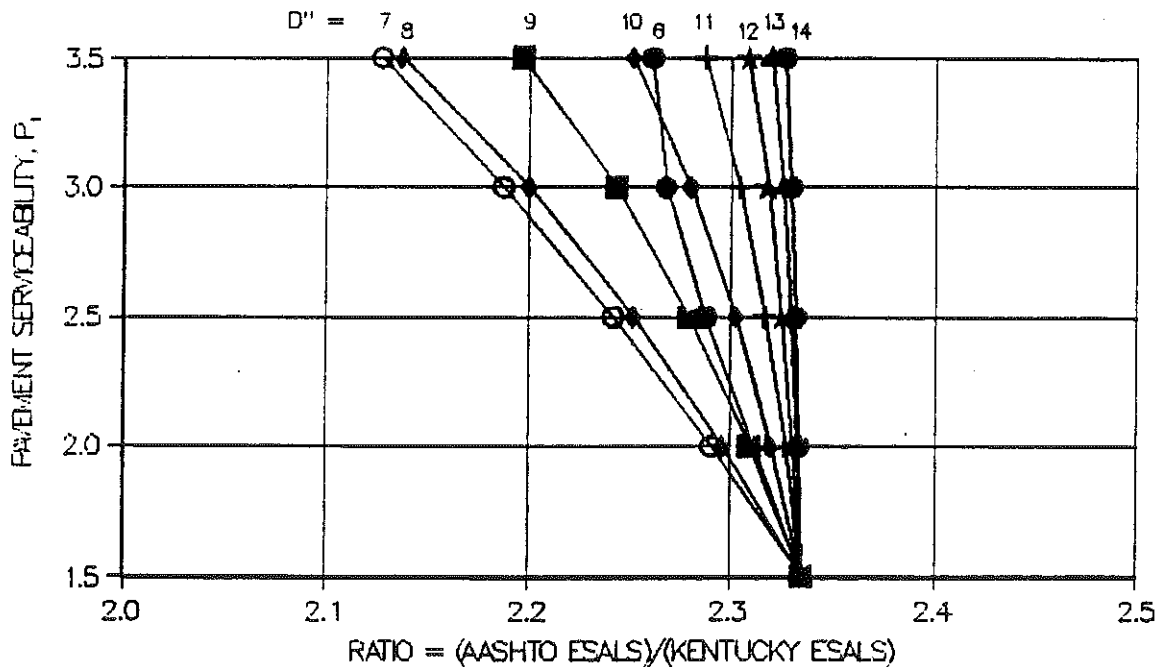
FIGURE 21. KENTUCKY WIM DATA ANALYZED USING AASHTO LOAD EQUIVALENCY EQUATION.

COMPARISON OF KENTUCKY AND AASHTO FLEXIBLE PAVEMENT LOAD EQUIVALENCIES FOR KENTUCKY TRAFFIC



(c)

COMPARISON OF KENTUCKY AND AASHTO RIGID PAVEMENT LOAD EQUIVALENCIES FOR KENTUCKY TRAFFIC



(b)

FIGURE 22. PAVEMENT SERVICEABILITY VERSUS RATIO OF KENTUCKY ESALS TO AASHTO ESALS FOR KENTUCKY TRAFFIC DATA FOR BOTH FLEXIBLE AND RIGID PAVEMENTS.

COMBINATIONS OF SN AND P_t WITH AASHTO
ESALS EQUAL TO KENTUCKY ESALS

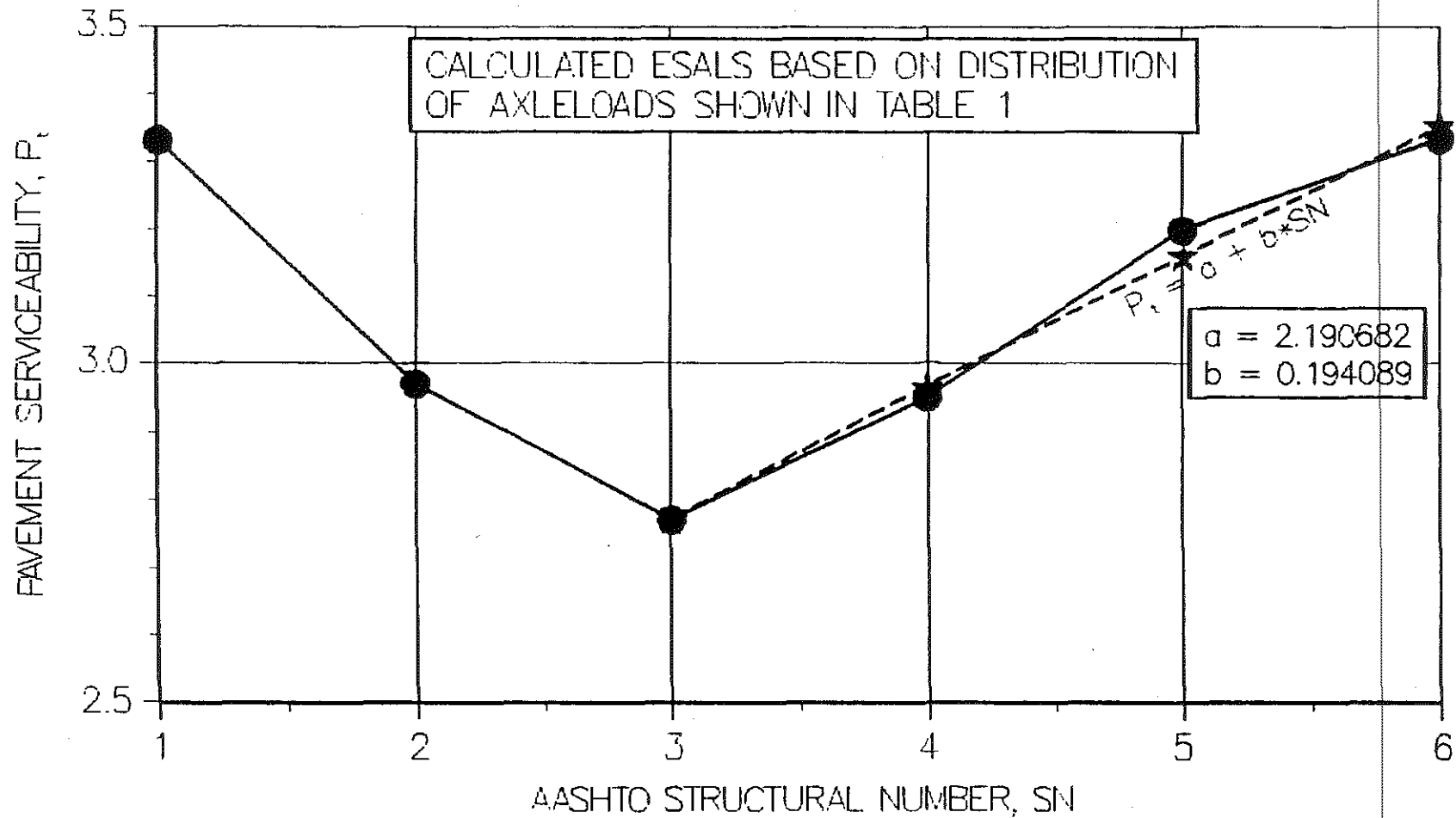
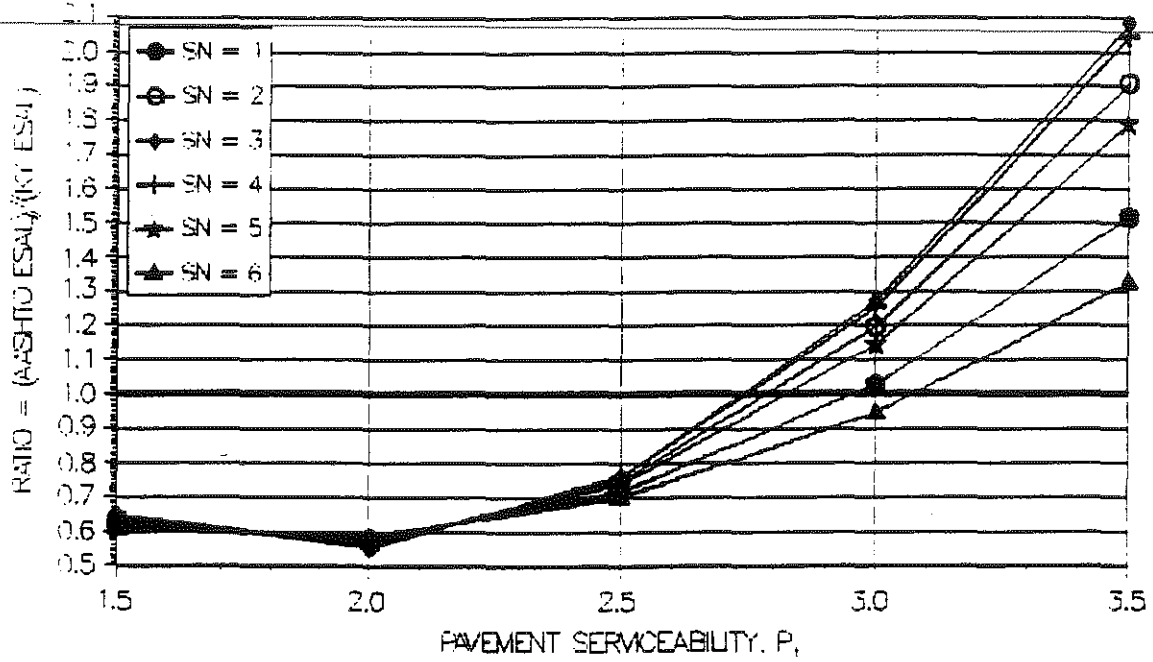


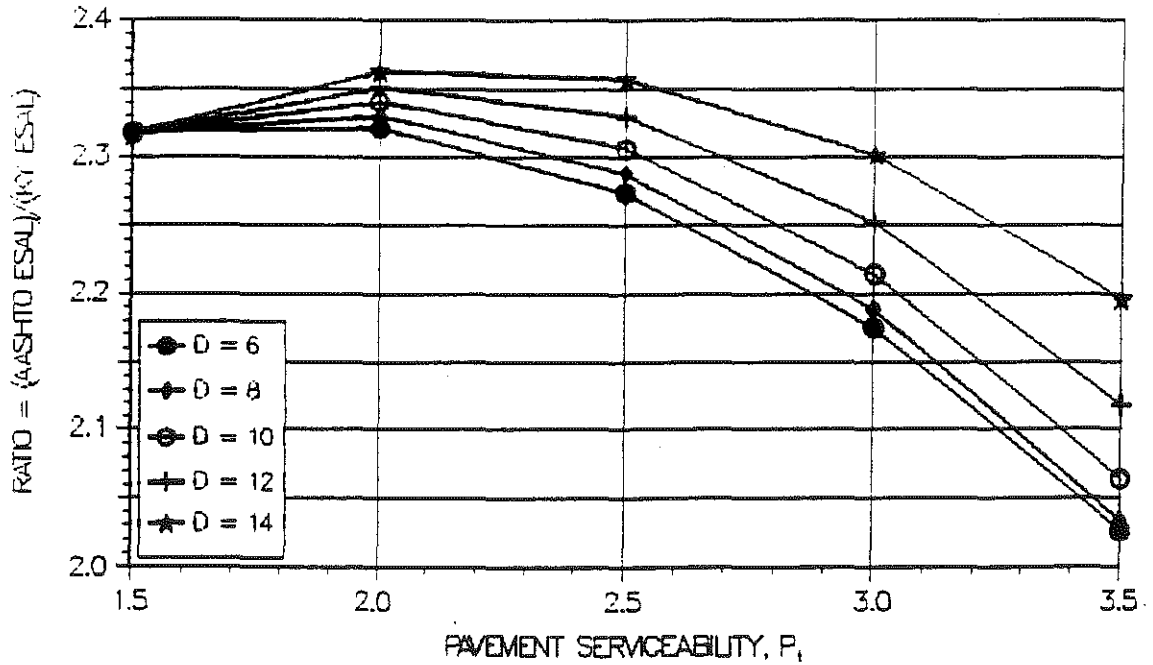
FIGURE 23. COMBINATION OF AASHTO STRUCTURAL NUMBERS AND SERVICEABILITIES EQUIVALENT TO KENTUCKY ESALS.

AASHTO AND KENTUCKY FLEXIBLE ESALS



(a)

AASHTO AND KENTUCKY RIGID ESALS



(b)

FIGURE 24. RATIOS OF AASHTO TO KENTUCKY ESALS FOR FLEXIBLE AND RIGID PAVEMENTS.

TABLE 1. KENTUCKY W-4 TABLE DATA PROPORTIONED FOR SERVICEABILITY LEVEL USING AVERAGE RATIO OF REPETITIONS OF APPLIED LOADS AT AASHO ROAD TEST.

AXLELOAD KIPS	TOTAL NO. OF AXLES	SERVICEABILITY, Pt				
		3.5	3	2.5	2	1.5
		PROPORTIONAL NUMBER OF AXLES DISTRIBUTION COEFFICIENTS				
	SINGLE	0.413418	0.661171	0.803602	0.907418	1
2	521719	215687.9	344945.5	419254.4	473417.1	521719
5	313514	129612.3	207286.4	251940.5	284488.2	313514
7.5	56626	23410.2	37439.47	45504.76	51383.43	56626
10	406723	168146.5	268913.5	326843.4	369067.6	406723
14	48447	20028.85	32031.75	38932.1	43961.67	48447
17	16145	6674.63	10674.61	12974.15	14650.26	16145
18.25	2342	968.2245	1548.463	1882.036	2125.172	2342
19.25	4778	1975.31	3159.075	3839.61	4335.642	4778
21	2658	1098.865	1757.393	2135.974	2411.916	2658
23	1306	539.9236	863.4894	1049.504	1185.088	1306
25	460	190.1722	304.1387	369.6569	417.4121	460
28	605	250.1178	400.0085	486.1792	548.9877	605
32	350	144.6962	231.4099	281.2607	317.5962	350
TOTAL SINGLES	1375673	568727.7	909555.1	1105493	1248310	1375673
	TANDEM					
5	5350	2211.785	3537.265	4299.27	4854.685	5350
9	139466	57657.73	92210.88	112075.1	126553.9	139466
15	160246	66248.55	105950	128774	145410.1	160246
21	108006	44651.6	71410.44	86793.83	98006.56	108006
27	158133	65375	104553	127076	143492.7	158133
31	76366	31571.06	50490.99	61367.86	69295.86	76366
32.25	14939	6176.049	9877.234	12005.01	13555.91	14939
33.25	34428	14233.15	22762.8	27666.41	31240.58	34428
35	28820	11914.7	19054.95	23159.81	26151.78	28820
37	11310	4675.755	7477.844	9088.738	10262.89	11310
39	4406	1821.519	2913.12	3540.67	3998.082	4406
41	2131	880.9933	1408.955	1712.476	1933.707	2131
43	922	381.1712	609.5997	740.921	836.6391	922
45	697	288.1522	460.8362	560.1105	632.4701	697
48	607	250.9446	401.3308	487.7864	550.8025	607
52	2184	902.9045	1443.998	1755.067	1981.8	2184
TOTAL TANDEMS	748011	309241.1	494563.2	601103.1	678758.4	748011

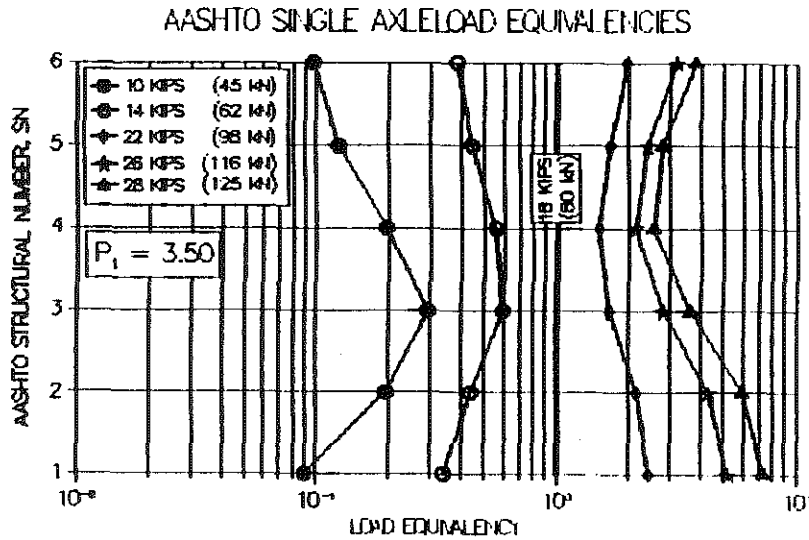
TABLE 2. KENTUCKY LOAD EQUIVALENCY EQUATIONS

KENTUCKY LOAD EQUIVALENCY FACTORS (LEF) BASED ON ELASTIC THEORY AND AASHO ROAD TEST PAVEMENT THICKNESSES			
LOG(DAMAGE FACTOR) = A + B*LOG(LOAD) + C*(LOG(LOAD) ^2)			
NOTE: (LOAD EXPRESSED IN KIPS)			
DESCRIPTION	COEFFICIENTS		
	A	B	C
TWO-TIRED STEERING	-3.540112	2.72886	0.289133
FOUR-TIRED SINGLE REAR	-3.439501	0.423747	1.846657
FOUR-TIRED TANDEM	-7.47681392	7.31958101	-1.5377459
SIX-TIRED TANDEM	-7.04251553	5.64606809	-0.51945722
EIGHT-TIRED TANDEM AXLES	-2.979479	-1.265144	2.007989
SIX-TIRED TRIDEM	-8.98760945	8.115983411	-1.650684632
TEN-TIRED TRIDEM	-8.3649958	5.94259543	-0.56377024
TWELVE-TIRED TRIDEM AXLES	-2.740987	-1.873428	1.964442
SIXTEEN TIRE QUAD AXLES	-2.589482	-2.224981	1.923512
MULTIPLYING FACTORS, MF:			
UNEVEN LOAD			
TANDEM	0.0018635439	0.0242188935	-9.069960E-05
TRIDEM	-0.198429071	1.20191282	-0.1746353238
NOTE: TOTAL LEF = (LEF)x(MF)			

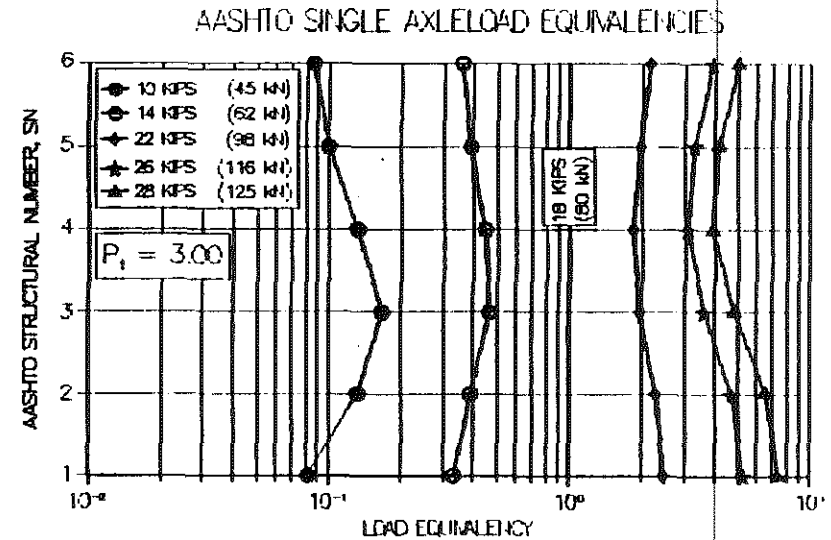
TABLE 3. PROPORTIONAL DISTRIBUTION OF KENTUCKY W-4 DATA.

SINGLE AXLELOAD KIPS	TOTAL NO. OF AXLES	PROPORTIONAL DISTRIBUTION
2	521719	0.379246
5	313514	0.227899
7.5	56626	0.041162
10	406723	0.295654
14	48447	0.035217
17	16145	0.011736
18.25	2342	0.001702
19.25	4778	0.003473
21	2658	0.001932
23	1306	0.000949
25	460	0.000334
28	605	0.00044
32	350	0.000254
TOTAL SINGLES	1375673	1
TANDEM AXLELOAD KIPS		
5	5350	0.007152
9	139466	0.186449
15	160246	0.214229
21	108006	0.144391
27	158133	0.211405
31	76366	0.102092
32.25	14939	0.019972
33.25	34428	0.046026
35	28820	0.038529
37	11310	0.01512
39	4406	0.00589
41	2131	0.002849
43	922	0.001233
45	697	0.000932
48	607	0.000811
52	2184	0.00292
TOTAL TANDEM	748011	1

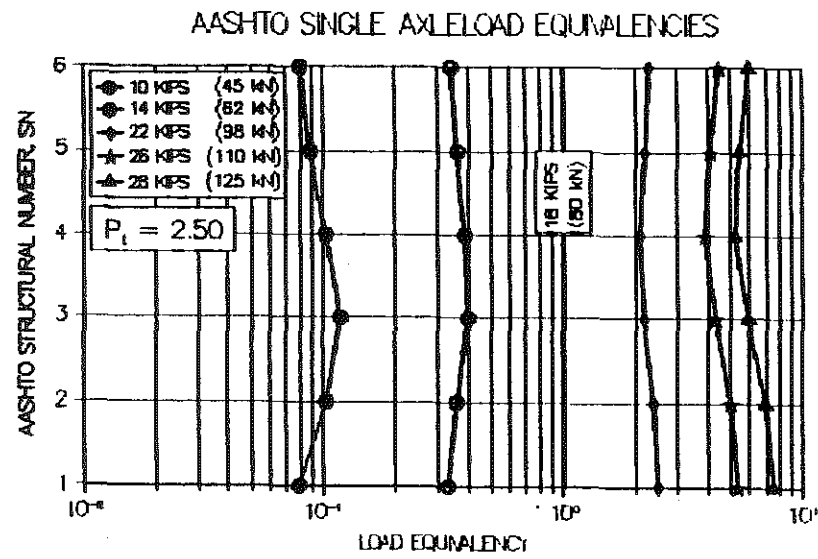
APPENDIX A



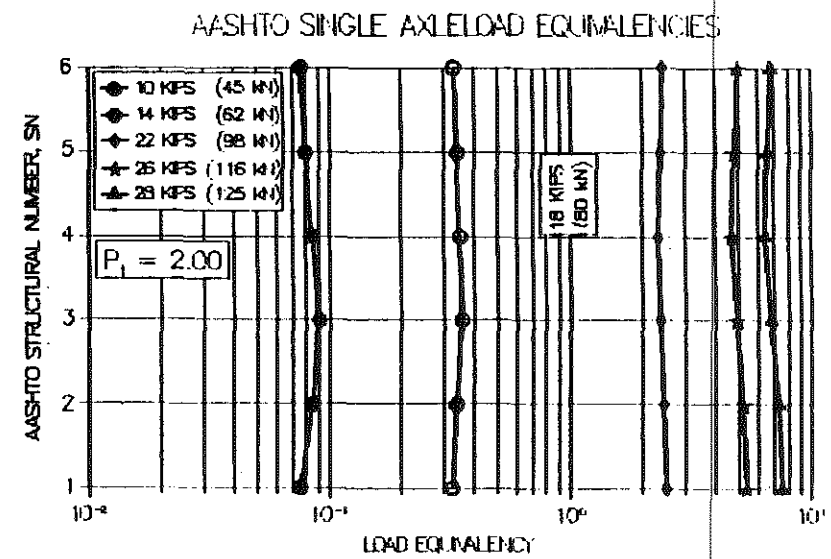
(a)



(b)



(c)



(d)

FIGURE A1. RELATIONSHIP BETWEEN LOAD EQUIVALENCIES FOR SINGLE AXLELOADS OF 10, 14, 18, 22, 26, AND 28 KIPS (45, 62, 98, 116, AND 125 kN, RESPECTIVELY) AND AASHTO STRUCTURAL NUMBER FOR $P_t = 3.5, 3.0, 2.5, \text{ AND } 2.0$.

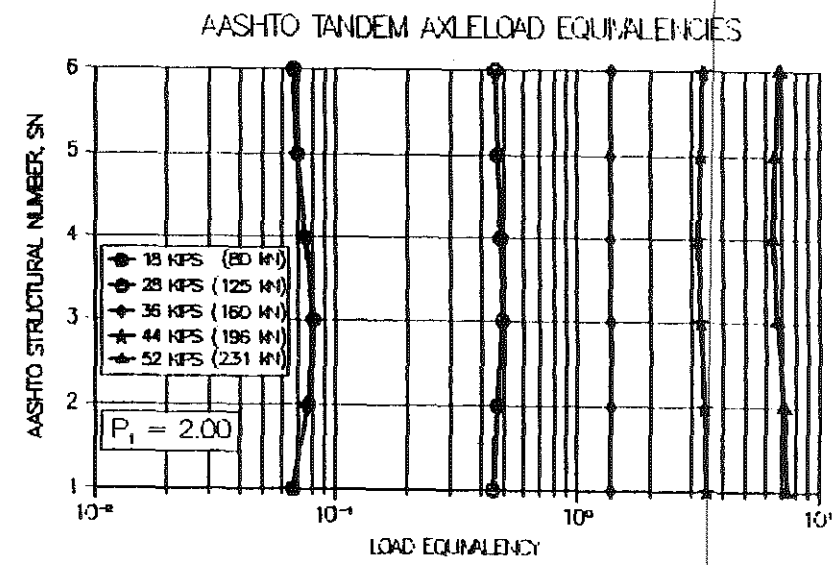
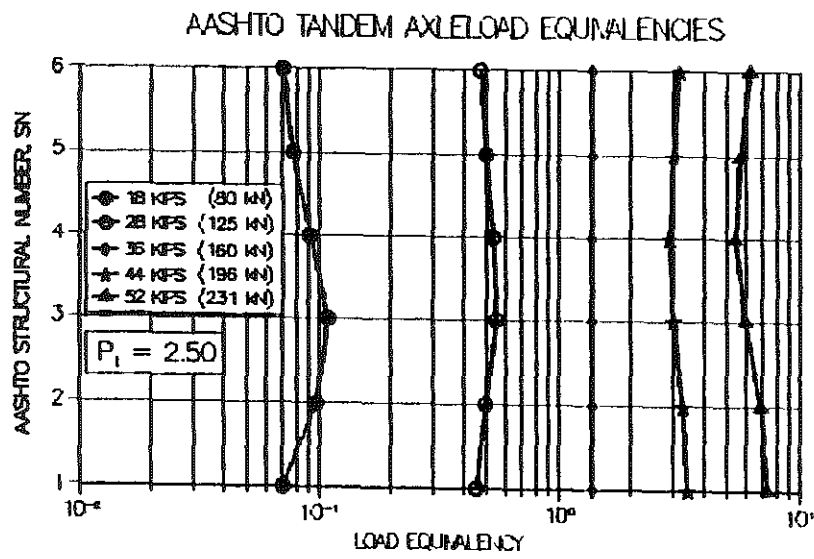
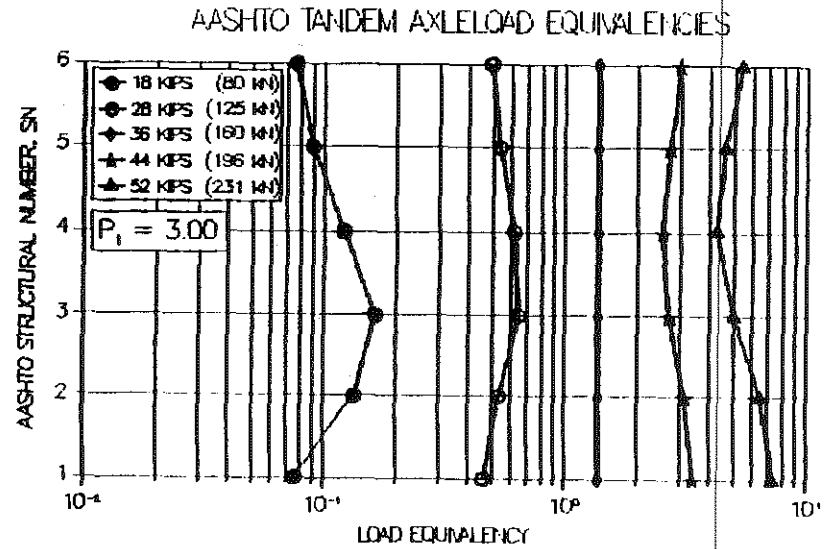
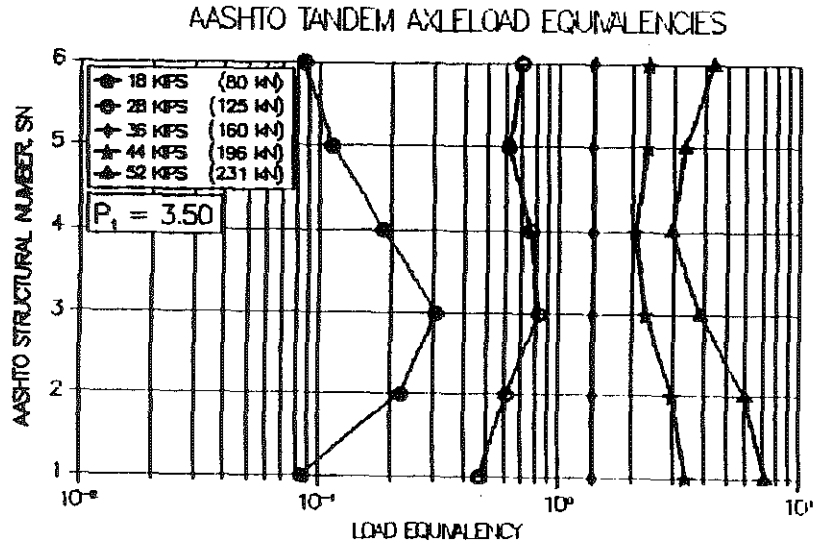


FIGURE A2. RELATIONSHIP BETWEEN LOAD EQUIVALENCIES FOR TANDEM AXLELOADS OF 18, 28, 36, 44, AND 52 KIPS (80, 125, 160, 196, AND 231 kN, RESPECTIVELY) AND AASHTO STRUCTURAL NUMBER FOR $P_t = 3.5, 3.0, 2.5, \text{ AND } 2.0$.

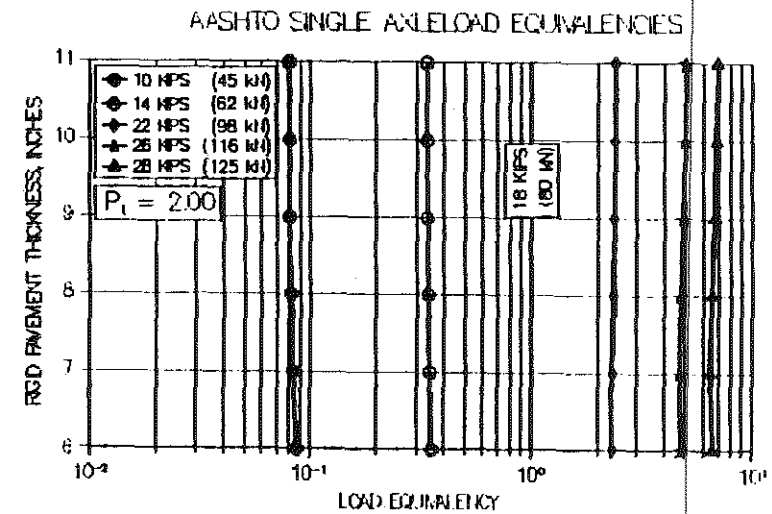
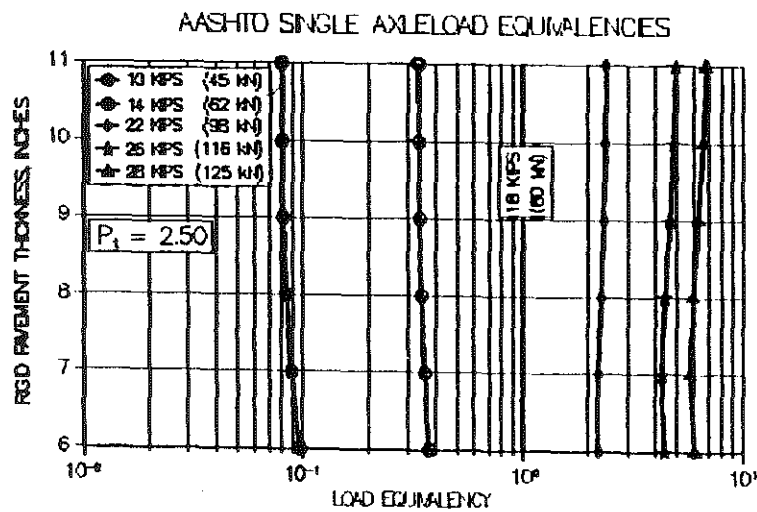
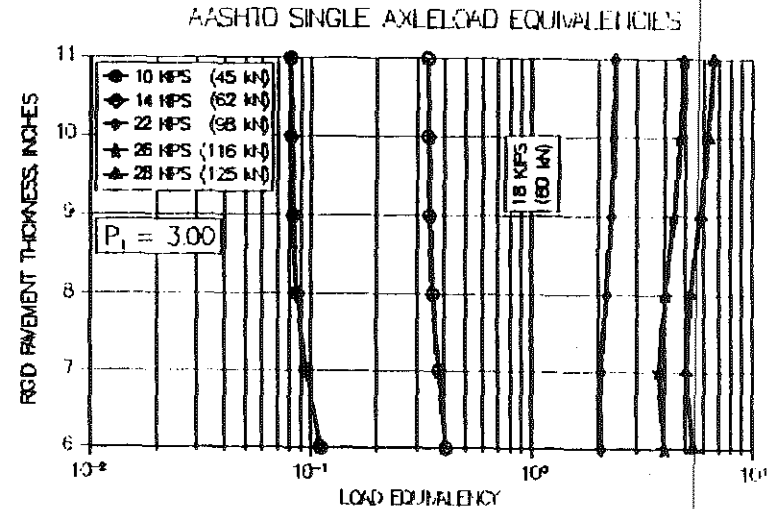
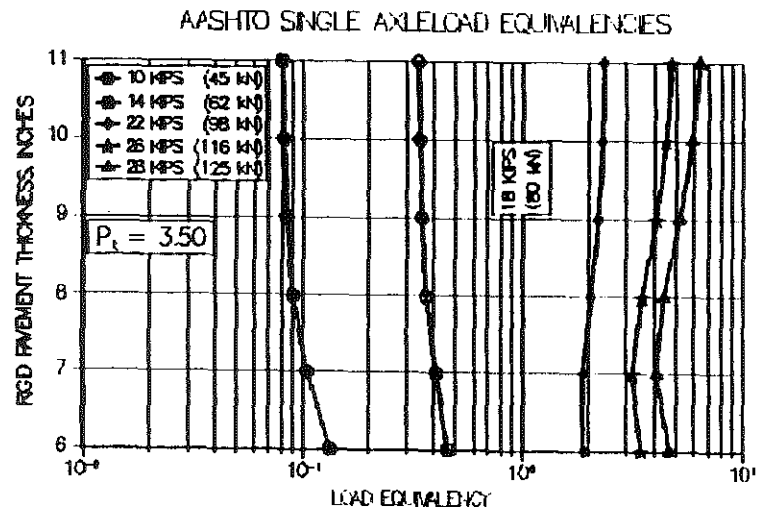
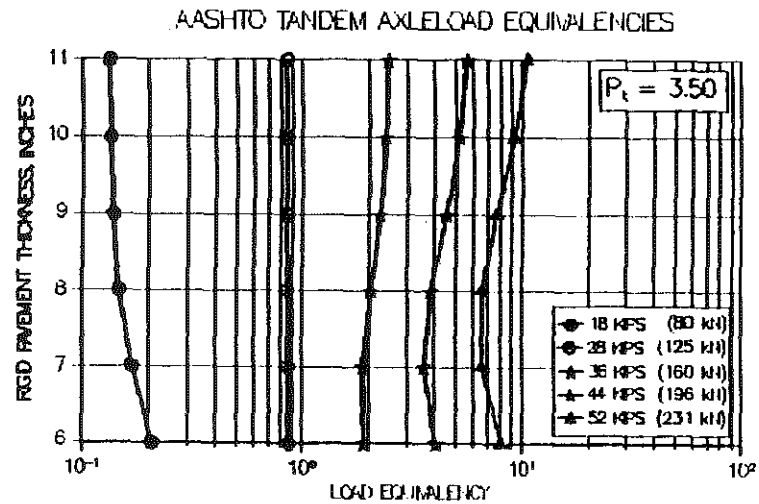
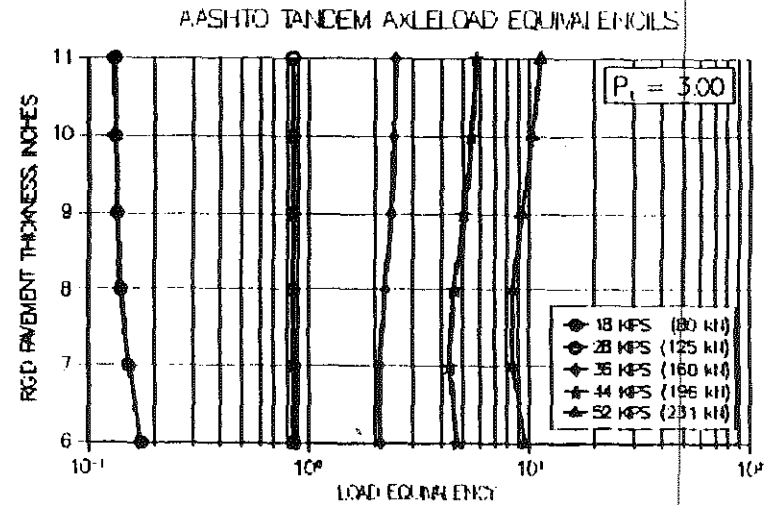


FIGURE A3.

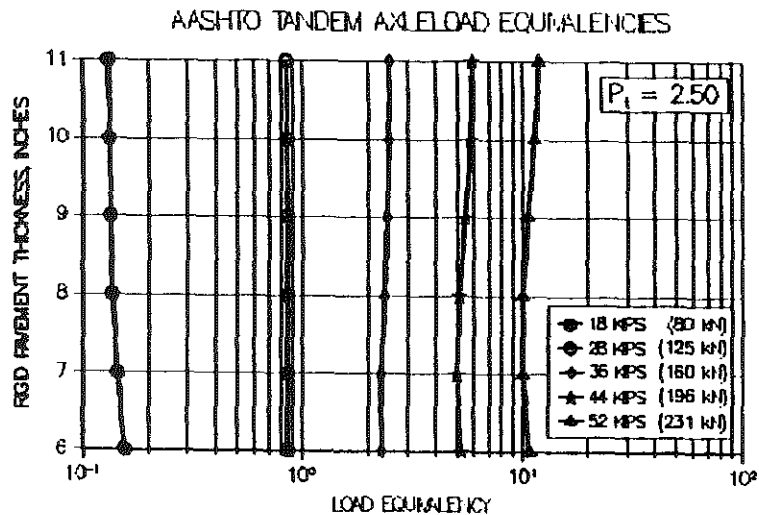
RELATIONSHIP BETWEEN LOAD EQUIVALENCIES FOR SINGLE AXLELOADS OF 10, 14, 18, 22, 26, AND 28 KIPS (45, 62, 98, 116, AND 125 kN, RESPECTIVELY) AND AASHTO RIGID PAVEMENT THICKNESSES FOR $P_t = 3.5$, 3.0, 2.5, AND 2.0.



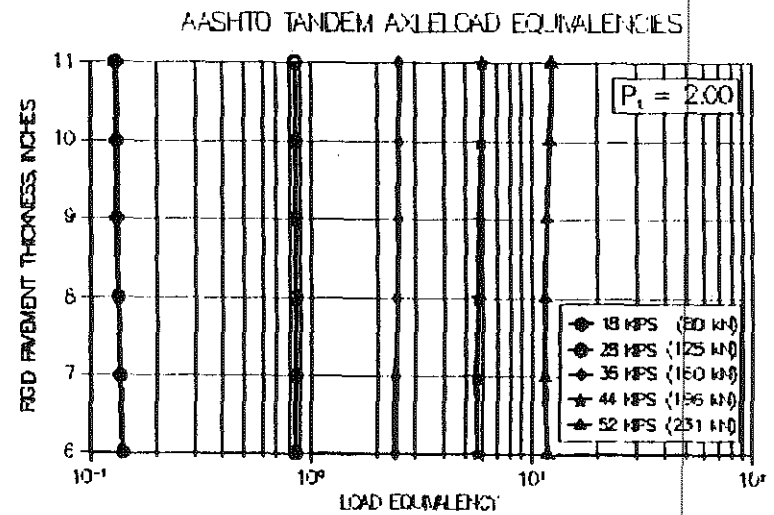
(a)



(b)



(c)

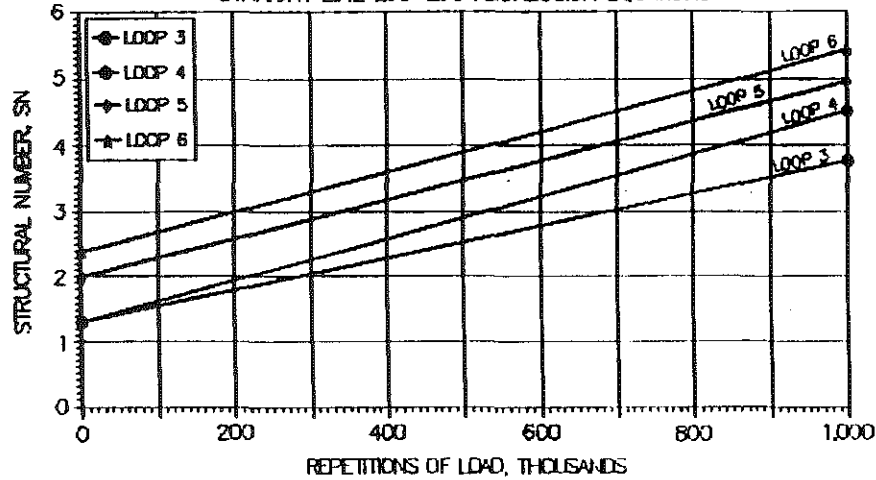


(d)

FIGURE A4. RELATIONSHIP BETWEEN LOAD EQUIVALENCIES FOR TANDEM AXLELOADS OF 18, 28, 36, 44, AND 52 KIPS (80, 125, 160, 196, AND 231 kN, RESPECTIVELY) AND AASHTO RIGID PAVEMENT THICKNESSES FOR $P_t = 3.5, 3.0, 2.5,$ AND 2.0 .

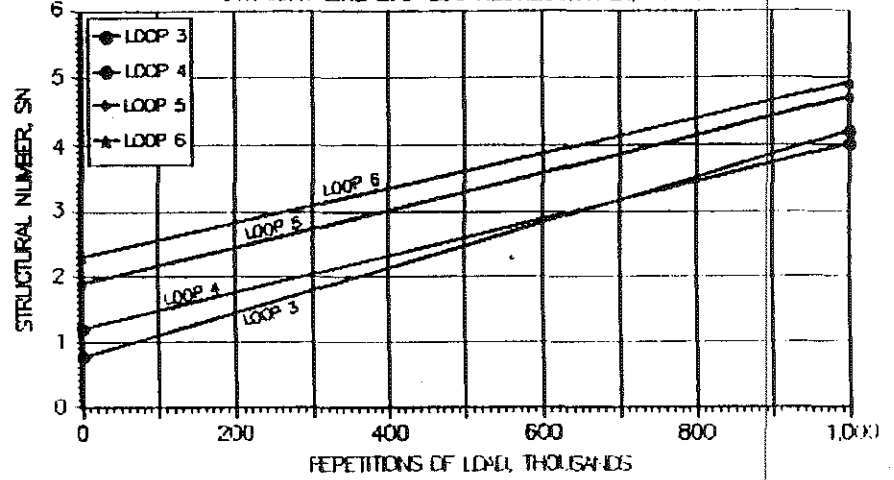
APPENDIX B

AASHTO ROAD TEST DATA, REPETITIONS OF LOAD
TANDEM AXLELOADS, $P_t = 3.5$
STRAIGHT LINE LOG-LOG REGRESSION EQUATIONS



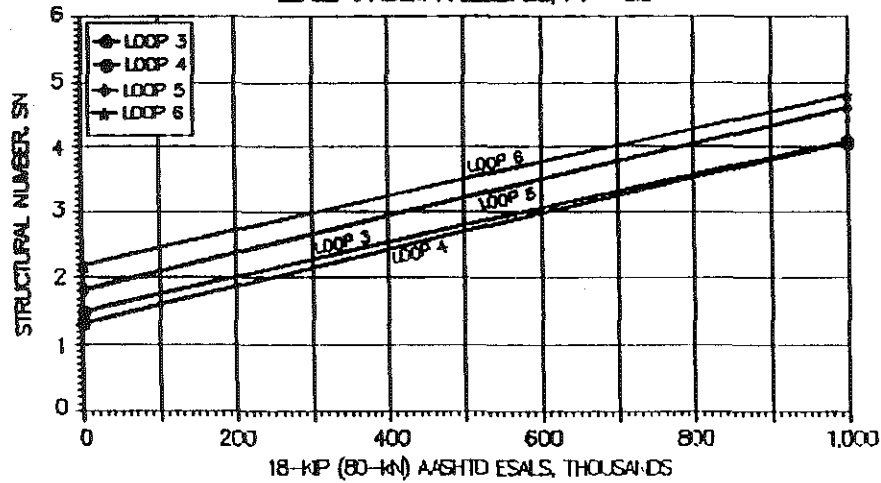
(a)

AASHTO ROAD TEST DATA, REPETITIONS OF LOAD
TANDEM AXLELOADS, $P_t = 3.0$
STRAIGHT LINE LOG-LOG REGRESSION EQUATIONS



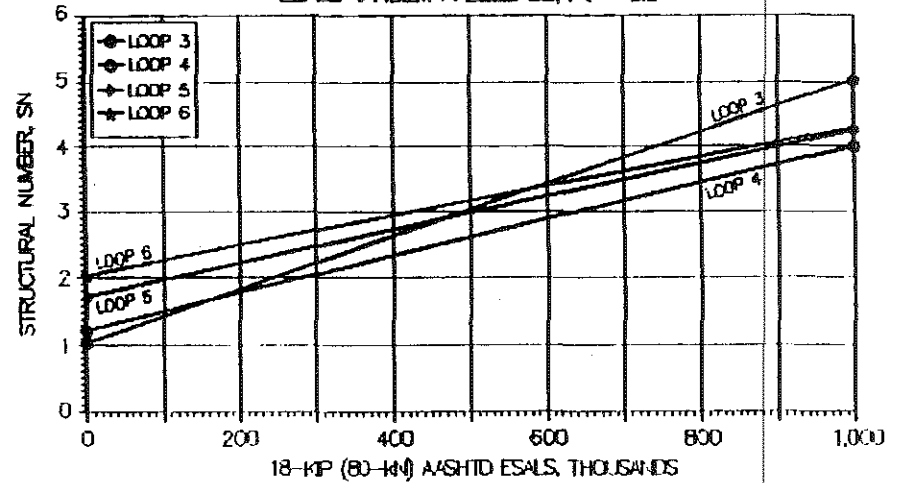
(b)

AASHTO ROAD TEST, 18-KIP (80-kN)
ESALS TANDEM AXLELOADS, $P_t = 3.5$



(c)

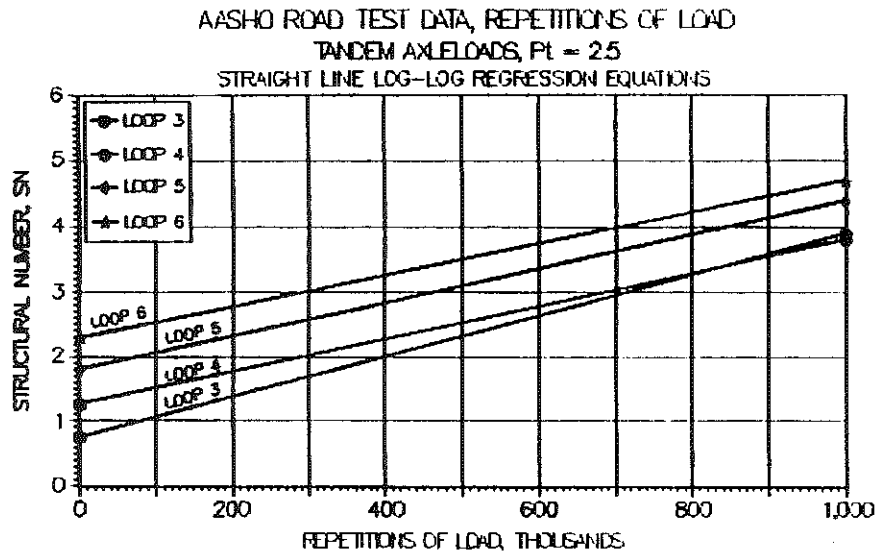
AASHTO ROAD TEST DATA, 18-KIP (80-kN)
ESALS TANDEM AXLELOADS, $P_t = 3.0$



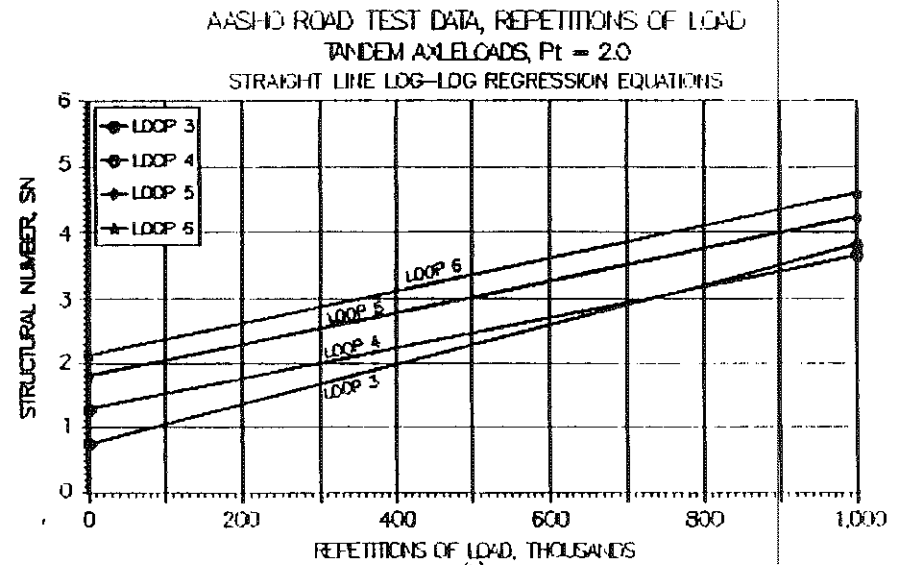
(d)

FIGURE B1.

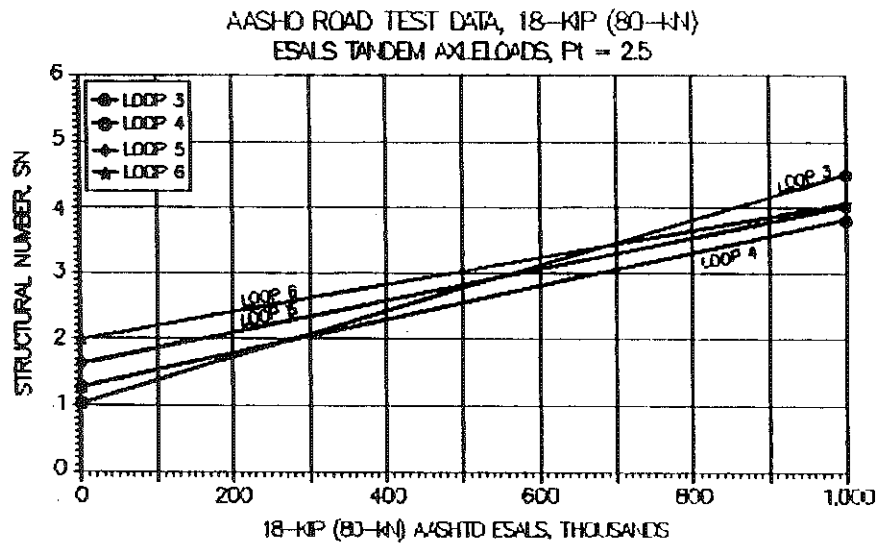
RELATIONSHIP BETWEEN AASHTO STRUCTURAL NUMBER AND REPETITIONS OF TANDEM AXLELOADS OR 18-KIP (80-kN) ESALS FOR AASHTO ROAD TEST DATA AT P_t VALUES OF 3.5 AND 3.0.



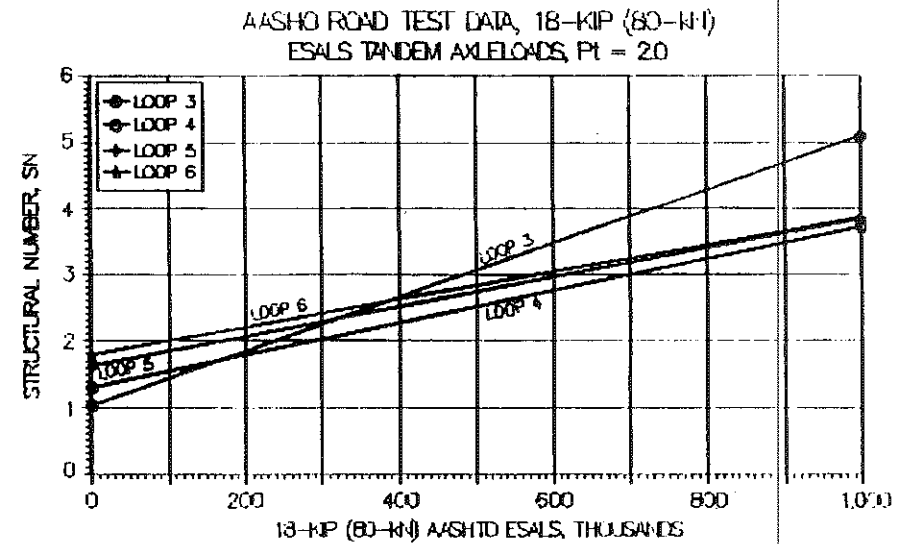
(a)



(b)



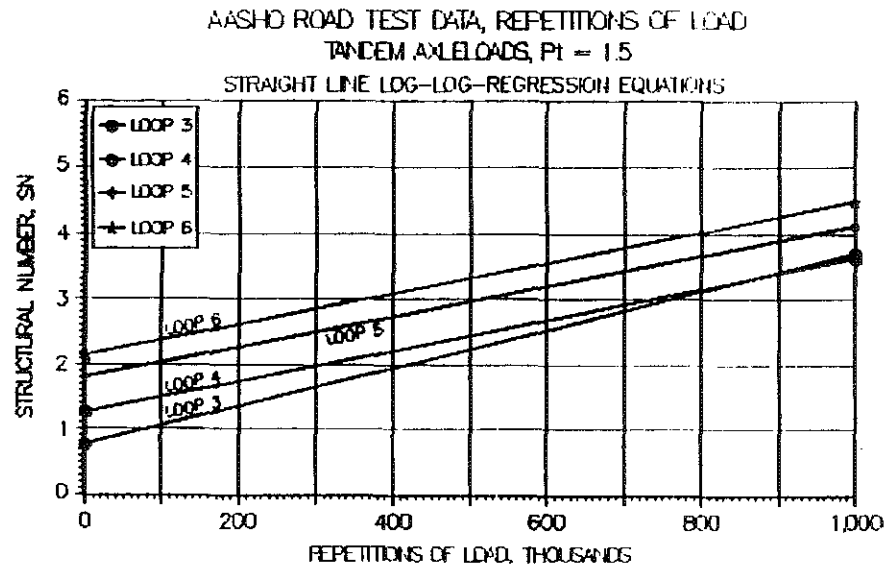
(c)



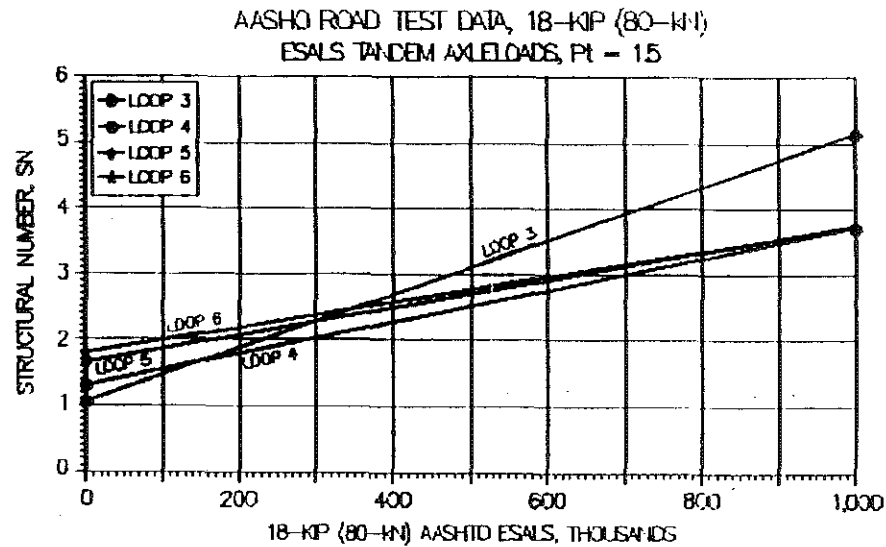
(d)

FIGURE B2.

RELATIONSHIP BETWEEN AASHTO STRUCTURAL NUMBER AND REPETITIONS OF TANDEM AXLELOADS OR 18-KIP (80-kN) ESALS FOR AASHTO ROAD TEST DATA AT P_t VALUES OF 2.5 AND 2.0.



(a)



(b)

FIGURE B3.

RELATIONSHIP BETWEEN AASHO STRUCTURAL NUMBER AND REPETITIONS OF TANDEM AXLELOADS OR 18-KIP (80-kN) ESALS FOR AASHO ROAD TEST DATA AT A P_t VALUE OF 1.5.

APPENDIX C

DEVELOPMENT OF FIGURE 10

Under the section "Normalizing AASHO Road Test Data", the ratio of ESALs at each P_i to ESALs at failure ($P_i = 1.5$) was calculated for each of the 176 pavement sections having values of observed repetitions for all five levels of P_i . Use of Equation C-16 produced irrational results for Loop 3 and the ratio of ESALs was abandoned.

Ratios of repetitions were calculated for each P_i to repetitions at failure ($P_i = 1.5$) for all 176 pavement sections. The average of all 176 pavement sections (Lanes 1 and 2) was obtained for each of the five levels of P_i . Figure 10a displays the results and includes a polynomial regression equation fitted to the averages.

APPENDIX D

DEVELOPMENT OF KENTUCKY LOAD EQUIVALENCY RELATIONSHIPS

Between 1972 and 1976, large 3-axle and 4-axle single frame dump trucks (vehicle class 6 and 7) were introduced into eastern Kentucky to haul coal. Tires on the steering axle increased from an 8-inch (203-mm) width to 14- to 16-inch (356- to 406- mm, respectively) widths. In-pavement, Weigh-In-Motion (WIM) scales recorded steering axleloads of 8 to 22 kips (36 to 98 kN, respectively). It was decided that load equivalency factors (LEF) should be developed for 2-tired axles and for other tire-axle configurations using the same methodology to obtain LEF for the steering axle in order to assure compatibility between LEF relationships. WIM data indicated loads were not equally distributed on the dual-tire assemblies of tandems and tridemms and adjustment factors were required to account for additional fatigue caused by uneven loading.

If factors are to be developed, the relationships should be compared to AASHTO load equivalency factors and the pavement structures tested at the AASHTO Road Test should be analyzed to obtain the new LEF. The following conditions and criteria were used to develop the Kentucky LEF.

- o The original Chevron n-Layer computer program was modified to include superposition principles and to include the equation necessary to calculate strain energy density, SED.
- o AASHTO Road Test Pavement Sections constructed on Loops 3-6:

AC: 2 to 6 inches on 1-inch increments (51 to 152 mm on 25-mm increments)

Base: 0 to 9 inches on 3-inch increments (0 to 229 mm on 76-mm increments)

Subbase: 0 to 16 inches on 4-inch increments (0 to 406 mm on 102-mm increments).

These combinations resulted in the construction and testing of 120 sections of which 12 were duplicates. The 120 sections consisted of 100 possible combinations of layer thicknesses but not all combinations were constructed on each Loop. Earlier Kentucky analyses of typical Kentucky pavement structures using the Chevron n-Layer computer program indicated that peculiar and unreliable results were obtained for asphaltic concrete thicknesses less than 3 inches (76 mm). For development of KY LEF, the 2-inch (51-mm) AC sections at the AASHO Road Test were eliminated from the matrix leaving 80 possible combinations of layer thicknesses.

- o AASHO Road Test soil samples were sent to a number of research and testing laboratories and one of these was the Division of Research, Kentucky Department of Highways. Soils were tested using the Kentucky CBR test procedure. Test results indicated that the soil corresponded to a Kentucky CBR of 5.3, or a modulus of 7,950 psi (55 kPa).
- o Results of Kentucky research indicated that the mean annual temperature for Kentucky was approximately 70 degrees F (21 C) corresponding to a modulus of elasticity of 480 ksi (3.3 kPa). Similarly, average temperature at the AASHO Road Test was

approximately 60 degrees F (16 C) corresponding to a modulus of elasticity of 600 ksi (4.1 kPa).

- o Each tire within a fixed tire-axle configuration was loaded equally for the range of 2,000 pounds to 8,000 pounds (0.9 to 3.6 kg, respectively) in increments of 500 pounds (0.23 kg).
- o Strains, stresses, and strain energy densities (SED) were computed at the bottom of the asphaltic concrete and at the top of the subgrade.
- o Tensile strains computed at the bottom of the asphaltic concrete were converted to "work strain" by the procedure given in reference 12 in the main body of this report.
- o With these computed strains, ESALs were computed using a strain-ESAL relationship appropriate to 600 ksi (4.1 kPa) and based upon laboratory fatigue test results (reference 4 in the main portion of this report).
- o LEF were computed for each load on each tire-axle configuration and for each pavement structure by:

$$LEF = N_{18} / N_L$$

where N_{18} = ESALs due to the calculated strain for an 18-kip (80-kN), 4-tired single axle, and
 N_L = ESALs due to the calculated strain for load, L in kips, for the tire-axle configuration.

- o After the LEF values were calculated for the complete matrix of load and pavement structures, a regression analysis was performed for all LEF values for all pavement structures for a particular tire-axle configuration. The best regression

equation was determined to be:

$$\log(\text{LEF}) = a + b \log(L) + c (\log(L))^2$$

where a, b, and c are constants given in Table 2 of main text.

- o Considering the diversified pavement structure thicknesses and combinations of layer thicknesses, the scatter of tandem loads at an LEF = 1 was approximately +/- 1 kip (4.45-kN). For tridem, the scatter at LEF = 1 was approximately +/- 1.5 kips (6.7 kN).
- o Rationale for pavement thickness design assumed for the Kentucky method is to protect the subgrade from any detrimental effects beyond normal consolidation for thicknesses appropriate to Interstate traffic to letting the subgrade rut or shear but the asphaltic concrete to remain intact for farm-to-market roads. Farm-to-market roads in Kentucky traverse generally hilly, and/or curvy terrain that should prevent speeds approaching hydroplaning conditions. Thus, rutting is not considered a dangerous attribute for low volume, low speed roads. Subgrades deform but do not have any significant fatigue characteristics. However, true fatigue of asphaltic concrete is a bending phenomenon. Thus, strains at the bottom of the asphaltic concrete should have a relationship with repetitions of loading as has been determined by laboratory testing. Analyses indicate that while the magnitude of tensile strain and the associated number of repetitions differs significantly with structure thickness and subgrade support, the ratio of repetitions for

other loads on the same pavement and subgrade varies very little. For thin pavements, the strains are relatively high for thin pavements, and relatively low for thick pavements but the ratio of the associated ESALs from the fatigue criterion line are nearly the same. Therefore, Kentucky LEF relationships inherently include structure but the equations are not affected specifically by structure.