MODIFIED PCA STRESS ANALYSIS AND THICKNESS DESIGN PROCEDURES

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ABSTRACT

This study focused on the development of a new stress analysis and thickness design procedure for jointed concrete pavements. Based on Westergaard's edge stress solution and several prediction models for stress adjustments for a variety of loading and environmental (i.e., thermal curling) conditions, a modified PCA equivalent stress analysis and thickness design procedure was proposed and implemented in a highly user-friendly, window-based TKUPAV program for practical trial applications. The proposed approach has been further verified by reproducing very close results to the PCA's equivalent stresses and fatigue damages using a spreadsheet program and the TKUPAV program. The possible detrimental effect of loading plus day-time curling has also been illustrated in a case study, which also indicated that the effect of thermal curling should be considered in the thickness design of concrete pavements.

INTRODUCTION

The Portland Cement Association's thickness design procedure (or PCA method) is the most well-known, widely-adopted, and mechanically-based procedure for the thickness design of jointed concrete pavements [*1*]. Since PCA's equivalent stress was determined based on a fixed slab modulus, a fixed slab length and width, a constant contact area, wheel spacing, axle spacing, and aggregate interlock factor in order to simplify the calculations, the required minimum slab thickness will be the same using the PCA method despite the fact that a shorter or longer joint spacing, a better or worse load transfer mechanism, different wheel spacing and axle spacing, and environmental effects are often considered in reality. Therefore, the main objective of this study was to develop a new stress analysis and thickness design procedure for jointed concrete pavements through proposed modifications to the PCA's equivalent stress calculations and fatigue analysis [*2*].

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REVIEW OF PCA THICKNESS DESIGN PROCEDURE

The PCA method is the most widely-adopted thickness design procedure for jointed concrete pavements based on mechanical principles. Based on the results of J-SLAB [*3*] finite element (F.E.) analysis, the PCA method uses design tables and charts and a PCAPAV personal computer program to determine the minimum slab thickness required to satisfy the following design factors: design period, the flexural strength of concrete (or the concrete modulus of rupture), the modulus of subbase-subgrade reaction, design traffic (including load safety factor, axle load distribution), with or without doweled joints and a tied concrete shoulder [*4*].

The PCA thickness design criteria are to limit the number of load repetitions based on both fatigue analysis and erosion analysis. Cumulative damage concept is used for the fatigue analysis to prevent the first crack initiation due to critical edge stresses, whereas the principal consideration of erosion analysis is to prevent pavement failures such as pumping, erosion of foundation, and joint faulting due to critical corner deflections during the design period. Since the main focus of this study was to develop alternative stress analysis procedures for thickness design of concrete pavements, the erosion analysis was not within the scope of this study.

Equivalent Stress Calculations

In the PCA thickness design procedure, the determination of equivalent stress is based on the resulting maximum edge bending stress of J-SLAB F.E. analysis under a single axle (SA) load and a tandem axle (TA) load for different levels of slab thickness and modulus of subgrade reaction. The basic input parameters were assumed as: slab modulus E = 4E+06 psi (2.8E+5 kg/cm^2), Poisson's ratio μ = 0.15, finite slab length L = 180 in. (4.57 m), finite slab width W = 144 in. (3.66 m). A standard 18-kip (8,165 kg) single axle load (dual wheels) with each wheel load equal to 4,500 pounds (2,041 kg), wheel contact area = 7*10 in.^{2} (17.8*25.4 cm^2) or an equivalent load radius a = 4.72 in. (12.0 cm), wheel spacing s = 12 in. (30.5 cm), axle width (distance between the center of dual wheels) D = 72 in. (183 cm) was used for the analysis, whereas a standard 36-kip (16,330 kg) tandem axle load (dual wheels) with axle spacing t = 50 in. (127 cm) and remaining gear configurations same as the standard single axle was also used. If a tied concrete shoulder (WS) was present, the aggregate interlock factor was assumed as AGG = 25000 psi (1,750 kg/cm^2). PCA also incorporated “the results of computer program MATS [*5*], developed for analysis and design of mat foundations, combined footings and slabs-on-grade” to account for the support provided by the subgrade extending beyond the slab edges for a slab with no concrete shoulder (NS). Together with several other adjustment factors, the equivalent stress was defined as follows: [*6*]

$$\sigma_{eq} = \frac{6 * M_e}{h^2} * f_1 * f_2 * f_3 * f_4 \qquad \text{(E.1)}$$

$$M_e = \begin{cases} -1600 + 2525 * \log(\ell) + 24.42 * \ell + 0.204 * \ell^2 & \text{for SA / NS} \\ 3029 - 2966.8 * \log(\ell) + 133.69 * \ell - 0.0632 * \ell^2 & \text{for TA / NS} \\ (-970.4 + 1202.6 * \log(\ell) + 53.587 * \ell) * (0.8742 + 0.01088 * k^{0.447}) & \text{for SA / WS} \\ (2005.4 - 1980.9 * \log(\ell) + 99.008 * \ell) * (0.8742 + 0.01088 * k^{0.447}) & \text{for TA / WS} \end{cases}$$

$$f_1 = \begin{cases} (24 / SAL)^{0.06} * (SAL / 18) & \text{for SA} \\ (48 / TAL)^{0.06} * (TAL / 36) & \text{for TA} \end{cases}$$

$$f_2 = \begin{cases} 0.892 + h / 85.71 - h^2 / 3000 & \text{for NS} \\ 1 & \text{for WS} \end{cases}$$

$$f_3 = 0.894 \quad \text{for 6\% Truck at the Slab Edge}$$

$$f_4 = 1 / (1.235 * (1 - CV))$$

where:

σ_{eq} = equivalent stress, psi;

h = thickness of the slab, in.;

$\ell = [Eh^3 / (12 * (1 - \mu^2) * k)]^{0.25}$, radius of relative stiffness of the slab-subgrade system, in.;

k = modulus of subgrade reaction, pci;

f_1 = adjustment factor for the effect of axle loads and contact areas;

f_2 = adjustment factor for a slab with no concrete shoulder based on the results of MATS computer program;

f_3 = adjustment factor to account for the effect of truck placement on the edge stress (PCA recommended a 6% truck encroachment, f_3=0.894);

edge truck placement, %	1	2	3	4	5	6	7
adjustment factor, f_3	0.825	0.855	0.870	0.880	0.890	0.894	0.901

f_4 = adjustment factor to account for the increase in concrete strength with age after the 28*th* day, along with a reduction in concrete strength by one coefficient of variation (CV); (PCA used CV=15%, f_4=0.953); and

SAL, TAL = actual single axle or tandem axle load, kips.

It was also noted that the above equivalent stress equation (E.1) is only applicable to U.S. customary system (English system). Until proper adjustments to the coefficients in the equation, it cannot be directly used with pertinent input variables in metric unit (SI system).

Fatigue Analysis

PCA's fatigue analysis concept was to avoid pavement failures (or first initiation of crack) by fatigue of concrete due to critical stress repetitions. Based on Miner's cumulative fatigue damage assumption, the PCA thickness design procedures first let the users select a trial slab thickness, calculate the ratio of equivalent stress (σ_{eq}) versus the concrete modulus of rupture (S_c) for each axle load and axle type, then determine the maximum allowable load repetitions (N_f) based on the following σ_{eq}/S_c - N_f relationship : [4]

$$\begin{cases} \log N_f = 11.737 - 12.077 * (\sigma_{eq} / S_c) & \text{for } \sigma_{eq} / S_c \geq 0.55 \\ N_f = \left[\dfrac{4.2577}{\sigma_{eq} / S_C - 0.4325} \right]^{3.268} & \text{for } 0.45 < \sigma_{eq} / S_c < 0.55 \\ N_f = \text{Unlimited} & \text{for } \sigma_{eq} / S_c \leq 0.45 \end{cases} \qquad \text{(E.2)}$$

The PCA thickness design procedures then use the expected number of load repetitions dividing by N_f to calculate the percentage of fatigue damage for each axle load and axle type. The total cumulative fatigue damage has to be within the specified 100% limiting design criterion, or a different trial slab thickness has to be used and repeat previous calculations again. Thus, in the PCAPAV program, an iterative process was utilized to help the users automatically determine the minimum required slab thickness.

Identical equivalent stresses and fatigue damages were obtained, after comparing the results of a spreadsheet using the aforementioned equations (E.1) and (E.2) with the PCAPAV program outputs. A more detailed example was described later in a case study.

EFFECTS OF THERMAL CURLING AND MOISTURE WARPING

Whether curling and warping stresses should be considered in concrete pavement thickness design is quite controversial. The temperature differential through the slab thickness and the self-weight of the slab induces additional thermal curling stresses. For day-time curling condition, compressive curling stresses are induced at the top of the slab whereas tensile stresses occur at the bottom; or vice versa for night-time curling condition. The moisture gradient in concrete slabs also results in additional warping stresses. Since higher moisture content is generally at the bottom of the slab, compressive and tensile stresses will occur at the bottom and at the top of the slab, respectively. A totally different situation will happen if the moisture content at the top of the slab is higher than that at the bottom right after raining.

Even though the effects of thermal curling and moisture warping have been discussed in the PCA design guide, curling stresses were not considered in the fatigue analysis due to the possible beneficial effect of most heavy trucks driving at night and only quite limited number of day-time curling combined with load repetitions. Furthermore, since moisture gradient highly depends on a variety of factors such as the ambient relative humidity at the slab surface, free water in the slab, and the moisture content of the subbase or subgrade, which are very difficult to measure accurately, thus it was also ignored in the PCA's fatigue analysis [*4*].

On the other hand, many others have repetitively indicated that curling stress should be considered in pavement thickness design, because curling stress may be quite large and cause the slab to crack when combined with only very few number of load repetitions. Darter and Barenberg [*7*] surveyed the non-traffic loop of the AASHO Road Test and have found after 16 years most of the long slabs (40 ft or 12.2 m) had cracks, but not in the 15-foot (4.57 m) slabs, probably because longer slabs have much greater curling stress than shorter slabs. In consideration of zero-maintenance design, Darter and Barenberg have suggested the inclusion of curling stress for pavement thickness design. More detailed descriptions and similar suggestions to include curling stress in the fatigue analysis may also be found in the NCHRP 1-26 report [*8*].

MODIFIED PCA STRESS ANALYSIS AND THICKNESS DESIGN PROCEDURES

PCA's equivalent stress was determined based on the assumptions of a fixed slab modulus, a fixed slab length and width, a constant contact area, wheel spacing, axle spacing, and aggregate interlock factor, which may influence the stress occurrence, in order to simplify the calculations. Thus, the required minimum slab thickness will be the same based on the PCA thickness design procedure disregard the fact that a shorter or longer joint spacing, a better or worse load transfer mechanism, different wheel spacing and axle spacing, and environmental effects are considered.

Therefore, this study strives to revise PCA's equivalent stress calculation process and to develop a new thickness design procedure by including the effect of thermal curling. A well-known slab-on-grade finite element program (ILLI-SLAB) was used for the analysis. Based on Westergaard's closed-form edge stress solution and several prediction models for stress adjustments for a variety of loading and environmental conditions, a modified PCA equivalent stress calculation procedure was developed. Thus, the required minimum slab thickness may be determined using the original PCA's fatigue analysis concept.

ILLI-SLAB Finite Element Solutions

The basic tool for this analysis is the ILLI-SLAB F.E. computer program which was originally developed in 1977 and has been continuously revised and expanded at the University of Illinois over the years. The ILLI-SLAB model is based on classical medium-thick plate theory, and employs the 4-noded 12-degree-of-freedom plate bending elements. The Winkler foundation assumed by Westergaard is modeled as a uniform, distributed subgrade through an equivalent mass foundation. Curling analysis was not implemented until versions after June 15, 1987. The present version (March 15, 1989) [*9*] was successfully compiled on available Unix-based workstations of the Civil Engineering Department at Tamkang University. With some modifications to the original codes, a micro-computer version of the program was also developed using Microsoft FORTRAN PowerStation [*10*].

Identification of Mechanistic Variables (Dimensionless)

To account for the effects of a finite slab, dual-wheel, tandem axle, or tridem axle, a widened outer lane, a tied concrete shoulder, a second bonded or unbonded layer under loading only condition, the following relationship has been identified through many intensive F.E. studies for a constant Poisson's ratio (usually $\mu \approx 0.15$) [*2, 11*]:

$$\frac{\sigma h^2}{P}, \frac{\delta k \ell^2}{P}, \frac{q \ell^2}{P} = f\left\{ \frac{a}{\ell}, \frac{L}{\ell}, \frac{W}{\ell}, \frac{s}{\ell}, \frac{t}{\ell}, \frac{D_0}{\ell}, \frac{AGG}{k\ell}, \left(\frac{h_{efft}}{h_1} \right)^2 \right\} \quad \text{(E.3)}$$

Where σ, q are slab bending stress and vertical subgrade stress, respectively, [FL^{-2}]; δ is the slab deflection, [L]; P = wheel load, [F]; a = the radius of the applied load, [L]; $\ell = (E*h^3/(12*(1-\mu^2)*K))^{0.25}$ is the radius of relative stiffness of the slab-subgrade system [L]; k = modulus of subgrade reaction, [FL^{-3}]; L, W = length and width of the finite slab, [L]; s = transverse wheel spacing, [L]; t = longitudinal axle spacing, [L]; D_0 = offset distance between the outer face of the wheel and the slab edge, [L]; AGG = aggregate interlock factor, [FL^{-2}]; $h_{efft} = (h_1^2 + h_2^2 * (E_2*h_2)/(E_1*h_1))^{0.5}$ is the effective thickness of two unbonded layers, [L]; h_1, h_2 = thickness of the top slab, and the bottom slab, [L]; and E_1, E_2 = concrete modulus of the top slab, and the bottom slab, [FL^{-2}]. Note that variables in both sides of the expression are all dimensionless and primary dimensions are represented by [F] for force and [L] for length.

Furthermore, the following concise relationship has been identified by Lee and Darter [*12*] for the effects of loading plus thermal curling:

$$\frac{\sigma}{E}, \frac{\delta h}{\ell^2}, \frac{qh}{k\ell^2} = f\left(\frac{a}{\ell}, \alpha\Delta T, \frac{L}{\ell}, \frac{W}{\ell}, \frac{\gamma h^2}{k\ell^2}, \frac{ph}{k\ell^4}\right) \quad \text{(E.4)}$$

Where α is the thermal expansion coefficient, $[T^{-1}]$; ΔT is the temperature differential through the slab thickness, [T]; γ is the unit weight of the concrete slab, $[FL^{-3}]$; $D_\gamma=\gamma*h^2/(k*\ell^2)$; and $D_P=P*h/(k*\ell^4)$. Also note that D_γ was defined as the relative deflection stiffness due to self-weight of the concrete slab and the possible loss of subgrade support, whereas D_p was the relative deflection stiffness due to the external wheel load and the loss of subgrade support. The primary dimension for temperature is represented by [T].

Development of Stress Prediction Models

A series of F. E. factorial runs were performed based on the dominating mechanistic variables identified. Several BASIC programs were written to automatically generate the F. E. input files and summarize the desired outputs. The F. E. mesh was generated according to the guidelines established in earlier studies [*13*]. As proposed by Lee and Darter [*14*], a two-step modeling approach using the projection pursuit regression (PPR) technique introduced by Friedman and Stuetzle [*15*] was utilized for the development of prediction models. Through the use of local smoothing techniques, the PPR attempts to model a multi-dimensional response surface as a sum of several nonparametric functions of projections of the explanatory variables. The projected terms are essentially two-dimensional curves which can be graphically represented, easily visualized, and properly formulated. Piece-wise linear or nonlinear regression techniques were then used to obtain the parameter estimates for the specified functional forms of the predictive models. This algorithm is available in the S-PLUS statistical package [*16*]. The proposed prediction models for the stress adjustments are given in Table 1. More detailed descriptions of the development process can be found in Reference [*2*].

Modified Equivalent Stress Calculations

To expand the applicability of the PCA's equivalent stress for different material properties, finite slab sizes, gear configurations, and environmental effects (e.g., temperature differentials), the following equation was proposed [*2, 17, 18*]:

$$\sigma_{eq} = \left[\sigma_w * R_1 * R_2 * R_3 * R_4 * R_5 + R_T * \sigma_c\right] * f_3 * f_4 \quad \text{(E.5)}$$

$$\sigma_w = \frac{3(1+\mu)P}{\pi(3+\mu)h^2}\left[\log_e \frac{Eh^3}{100ka^4} + 1.84 - \frac{4}{3}\mu + \frac{1-\mu}{2} + 1.18(1+2\mu)\frac{a}{\ell}\right]$$

$$\sigma_c = \frac{CE\alpha\Delta T}{2} = \frac{E\alpha\Delta T}{2}\left[1 - \frac{2\cos\lambda\cosh\lambda}{\sin 2\lambda + \sinh 2\lambda}\left(\tan\lambda + \tanh\lambda\right)\right]$$

where:

σ_{eq} = modified equivalent stress, [FL^{-2}];
σ_w = Westergaard's closed-form edge stress solution, [FL^{-2}];
σ_c = Westergaard/Bradbury's curling stress, [FL^{-2}];
E = elastic modulus of the slab, [FL^{-2}];
h = slab thickness, [L];
λ = $W/((8^{0.5})*a)$;
C = the curling stress coefficient;
R_1= adjustment factor for different gear configurations including dual-wheel, tandem axle, and tridem axle;
R_2 = adjustment factor for finite slab length and width;
R_3 = adjustment factor for a tied concrete shoulder;
R_4 = adjustment factor for a widened outer lane;
R_5 = adjustment factor for a bonded/unbonded second layer; and
R_T = adjustment factor for the combined effect of loading plus day-time curling.

Based on the principles of superposition, the effects of other different variations of gear configurations such as dual wheel / tridem axle, and dual wheel / tandem axle may also be obtained by a simple matter of multiplication. Also note that the last column of Table 1 indicates the applicable ranges of the predictive model; the upper or the lower bound may be used if the input data exceeds these limits.

For the case of a bonded or unbonded second layer, the pertinent variables are defined as: h_{efft} = effective thickness of two unbonded layers converted to a single slab, [L]; α = a distance from the middle surface of the bottom layer to the location of the neutral axis of an equivalent system, [L]; β = a distance from the neutral axis to the middle surface of the top layer, [L]; h_{1f}, h_{2f} = the equivalent thickness of top layer and bottom layer when converting a bonded layer to an unbonded layer, [L].

Modified Thickness Design Procedure

A new thickness design procedure was developed based on the above "modified equivalent stresses," and the PCA's cumulative fatigue damage concept. The NCHRP 1-26 report [*8*] has suggested the inclusion of thermal curling by separating traffic repetitions into three parts:

loading with no curling, loading combined with day-time curling, and loading combined with night-time curling. Nevertheless, based on practical considerations of the difficulty and variability in determining temperature differentials, a more conservative design approach was proposed by neglecting possible beneficial effects due to night-time curling. Thus, only the conditions of loading with no curling, and loading combined with day-time curling were considered under this study. Separated fatigue damages are then calculated and accumulated. The 100% limiting criterion of the cumulative fatigue damage is also applied to determine the minimum required slab thickness. A brief description of the proposed thickness design procedures is as follows:

1. Data input: assume a trial slab thickness; input other pertinent design factors, material properties, load distributions, and environmental factors (i.e., temperature differentials).
2. Expected repetitions (n_i): calculate the expected repetitions for the case of loading with no curling and for the case of loading with day-time curling during the design period.
3. Modified equivalent stress (σ_{eq}): calculate the "modified equivalent stresses" using equation (E.5) for each case.
4. Stress Ratio(σ_{eq} /S_C): calculate the ratio of the modified equivalent stress versus the concrete modulus of rupture (S_C) for each case.
5. Maximum allowable load repetitions (N_i): determine the maximum allowable load repetitions for different stress ratios based on the fatigue equation (E.2).
6. Calculate the percentage of each individual fatigue damage (n_i/N_i).
7. Check if the cumulative fatigue damage $\Sigma(n_i/N_i)<100\%$.
8. If not, assume a different slab thickness and repeat steps (1) - (7) again to obtain the minimum required slab thickness.

DEVELOPMENT OF THE TKUPAV PROGRAM

To facilitate practical trial applications of the proposed stress analysis and thickness design procedures, a window-based computer program (TKUPAV) was developed using the Microsoft Visual Basic software package [*19*]. The TKUPAV program was designed to be highly user-friendly and thus came with many well-organized graphical interfaces, selection menus, and command buttons for easy use. Both English version and Chinese version of the program are available. Furthermore, since all the mechanistic variables used in the proposed models are dimensionally correct, both English and metric (SI) systems can be used by the program. Several example input screens of the TKUPAV program are shown in Figure 1.

VERIFICATION OF THE TKUPAV PROGRAM

The proposed stress analysis and thickness design procedures have been further verified by reproducing very close results to the PCA's equivalent stresses and fatigue damages in the following case study using a spreadsheet program and the TKUPAV program. Furthermore, the possible detrimental effect of loading plus day-time curling has been clearly observed even when a very small percentage of loading plus curling repetitions was considered in the case study. Thus, it also illustrated the importance of incorporating the effect of thermal curling in the thickness design of concrete pavements.

Suppose a four-lane divided highway with the following design factors: design period = 20 years, load safety factor LSF = 1.2, average daily traffic ADT = 12,900, lane distribution LD = 81%, directional distribution = 50%, percentage of heavy trucks = 19%, annual traffic growth rate = 4% (compounded), the modulus of subbase/subgrade reaction k = 130 pci (3.64 kg/cm^3), the concrete modulus of rupture S_C = 650 psi (45.5 kg/cm^2), and the coefficient of variation = 15%. The expected axle load distributions are listed in the following table [*1, 4*]: (Note: 1 in. = 2.54 cm, 1 psi = 0.07 kg/cm^2, 1 pci = 0.028 kg/cm^3, 1 kip = 454 kg)

Single Axle		Tandem Axle	
Load, kips	Axles / 1000 Trucks	Load, kips	Axles / 1000 Trucks
30	0.58	52	1.96
28	1.35	48	3.94
26	2.77	44	11.48
24	5.92	40	34.27
22	9.83	36	81.42
20	21.67	32	85.54
18	28.24	28	152.23
16	38.83	24	90.52
14	53.94	20	112.81
12	168.85	16	124.69

(1) Comparison of Equivalent Stress Calculations (TKUPAV / PCA):

Note that many important factors were implicitly selected by the PCA method: t = 50 in. (127 cm), s = 12 in. (30.5 cm), D = 72 in. (183 cm), a = 4.72 in. (12.0 cm), L = 180 in. (4.57 m), W=144 in. (3.66 m), AGG = 25000 psi (1,750 kg/cm^2), E = 4E+06 psi (2.8E+5 kg/cm^2), μ = 0.15. The results of this comparison are summarized in Table 2 (a) - (b) for the case with no concrete shoulder, and Table 2 (c) - (d) when a concrete shoulder was considered. The effect of the four

PCA adjustments (f_i) may be excluded in such a comparison. The last column (Column (B) / Column (A)) represent the ratio of equivalent stresses determined by the proposed approach (TKUPAV) and by the PCA method. Apparently, adequate precision to the PCA method can be obtained if the proposed stress analysis procedures are adopted.

(2) Fatigue Analysis Example for Loading Only (TKUPAV / PCAPAV):

Assume a trial slab thickness h = 9.5 in. (24.1 cm) with no concrete shoulder, the results of this fatigue analysis example for loading only are summarized in Table 3. In the PCAPAV analysis, ª = 38.73 in. (98.37 cm), f_2 = 0.973, f_3 = 0.894, and f_4 = 0.953. The detailed calculations of stress adjustment factors are given in Table 4; thus,

(a) For a single axle (dual wheels): R_1 = 0.750 * 0.526 = 0.395; and

(b) For a tandem axle (dual wheels): R_1 =0.459 * 0.750 * 0.526 = 0.181

Note that the adjustment factor for "axle width" was to account for the effect of other wheels in the far side of the axle using the prediction equation for dual wheels. And the effect of finite slab length and width is R_2 = 0.992 * 1.000 = 0.992.

Apparently, the resulting 62.3% of cumulative fatigue damage calculated by the TKUPAV program is very close to that determined by the PCAPAV program (63.5%). Very good agreement to the equivalent stress calculations was also observed.

(3) TKUPAV Fatigue Analysis Example (with Curling):

Assume a trial slab thickness h = 9.5 in. (24.1 cm) with no concrete shoulder and only a very small portion (10%) of load repetitions was combined with day-time curling. Other pertinent variables are: γ = 0.087 pci (2,436 kg/m^3), α = 5.5E-06 /^{o}F (9.9E-06 /^{o}C), ΔT= 20 ^{o}F (11.1^{o}C). Thus, $\alpha\Delta$T = 0.00011, W/ª = 3.718, L/ª = 4.648, a/ª = 0.1219, DG = 4.0274, λ = 1.370, and σ_c= 88.5 psi (6.20 kg/cm^2). More detailed calculations of the adjustment factors for loading plus curling are given in Table 5.

The results of this TKUPAV fatigue analysis example are summarized in Table 6. Thus, a total of 56.0% fatigue damage was caused by 90% of load repetitions, whereas a total 91.0% of fatigue damage could be induced by only 10% of load repetitions plus day-time curling. In this case, an additional 1/2 inch (1.27 cm) of slab thickness which may reduce the total cumulative fatigue damage from 147.0% to an acceptable level of 33.0% is required.

CONCLUSIONS AND RECOMMENDATIONS

This study focused on the development of a new stress analysis and thickness design procedure for jointed concrete pavements through proposed modifications to the PCA's equivalent stress calculations and fatigue analysis. The proposed approach has been further verified by reproducing very close results to the PCA's equivalent stresses and fatigue damages using Microsoft Excel spreadsheets and the window-based TKUPAV program.

Furthermore, this study also enhanced the applicability of the PCA method by the fact that any different material properties, finite slab sizes, gear configurations (such as additional effects of a single axle / single wheel, and a tridem axle / dual wheels), and environmental effects (e.g., temperature differentials) could be analyzed by the proposed approach. In addition, the proposed approach and prediction models are all applicable to the U. S. customary system or SI unit system because all the mechanistic variables involved are dimensionally correct.

The possible detrimental effect of loading plus day-time curling has also been illustrated in a case study, which also indicated that the effect of thermal curling should be considered in the thickness design of concrete pavements. In addition, a relatively small increase in slab thickness (e.g., 1/2 in.) will result in a very significant reduction in cumulative fatigue damage. The possible beneficial effect of night-time curling was ignored in the proposed approach, however it may be easily incorporated into the proposed approach using an additional prediction model for night-time curling developed by Lee and Darter [*12*]. With some proper adjustments to the TKUPAV program, it may also be applicable to the stress analysis and thickness design of airport concrete pavements.

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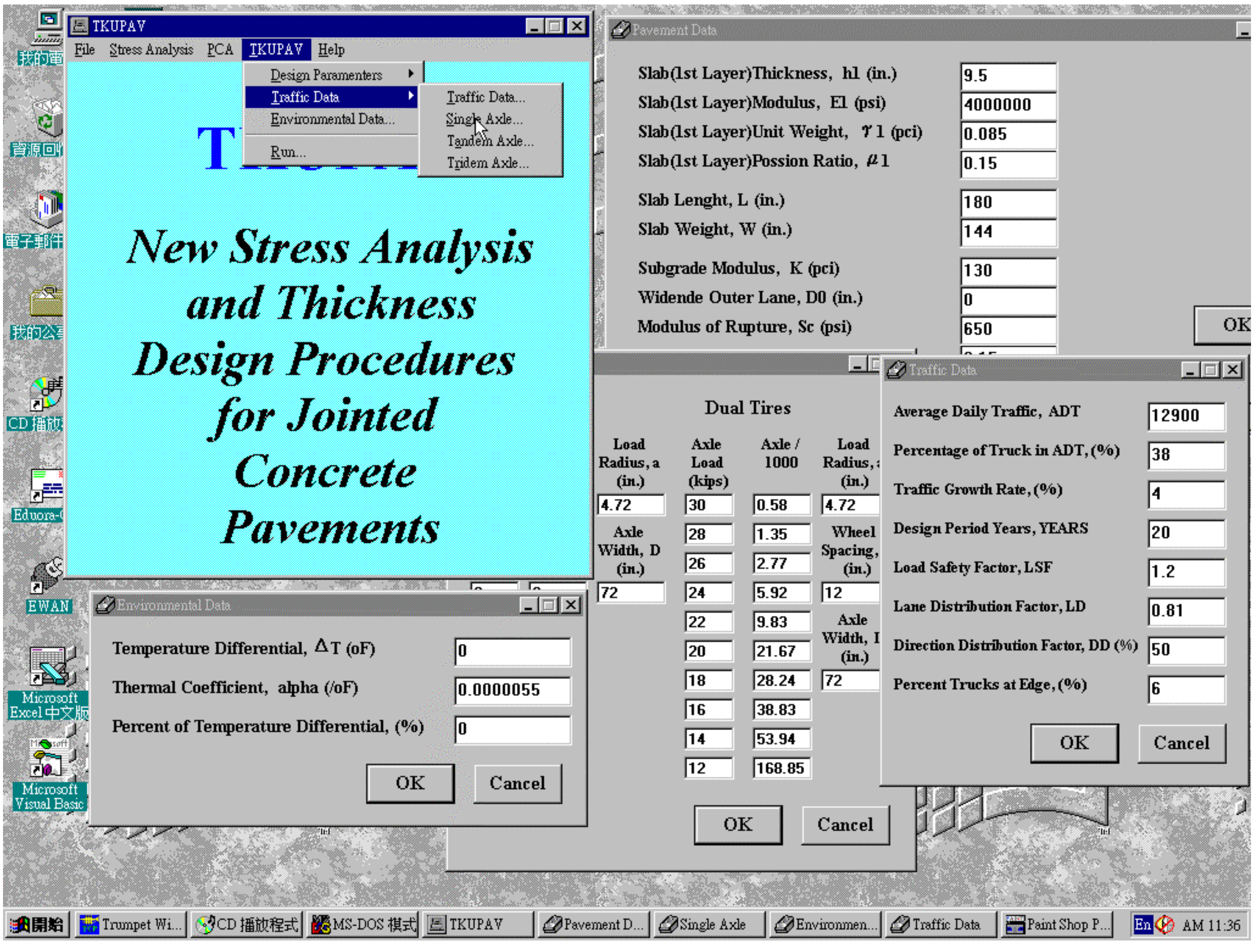

Figure 1 - Sample Input Screens of the TKUPAV Program

Table 1 -- Proposed Prediction Models for Stress Adjustments

Dual Wheel (Single Axle)	$R = 0.56197 + 0.09005\,\Phi_1 + 0.00597\,\Phi_2$ $\Phi_1 = \begin{cases} 0.32375 + 0.73128\,A_1 + 0.12928\,A_1^2 & A_1 \le -1.5 \\ 3.03815 + 7.24759\,A_1 + 5.80453\,A_1^2 + 1.70083\,A_1^3 & A_1 > -1.5 \end{cases}$ $\Phi_2 = \begin{cases} 1.01832 + 108.7979\,A_2 + 2079.976A_2^2 + 11522.38\,A_2^3 + 18645.37\,A_2^4 & A_2 \le 0 \\ 0.1775 - 0.93117\,A_2 + 9.31273\,A_2^2 - 28.6173\,A_2^3 + 28.57623\,A_2^4 & A_2 > 0 \end{cases}$ $A_1 = -0.75995\,x_1 + 0.64713\,x_2 - 0.06082\,x_3$ $A_2 = -0.03466\,x_1 - 0.82967\,x_2 + 0.55718\,x_3$ $X = [\,x_1, x_2, x_3\,] = \left[\frac{s}{a}, \frac{a}{a}, \frac{s \times a}{a^2}\right]$	$0.05 \le \frac{a}{a} \le 0.4$ $0.2 \le \frac{s}{a} \le 4.0$
Tandem Axle (Single Wheel)	$R = 051721 + 0.17298\,\Phi_1 + 0.02722\,\Phi_2$ $\Phi_1 = \begin{cases} -0.079 + 0.839\,A_1 + 0.368\,A_1^2 & A_1 \le -0.3 \\ 1.632 + 8.353\,A_1 - 0.358\,A_1^2 - 30.793\,A_1^3 & A_1 > -0.3 \end{cases}$ $\Phi_2 = 2.553 + 14.880\,A_2$ $A_1 = -0.51020\,x_1 + 0.86005\,x_2 - 0.00114\,x_3$ $A_2 = -0.04868\,x_1 - 0.95280\,x_2 + 0.29966\,x_3$ $X = [\,x_1, x_2, x_3\,] = \left[\frac{t}{a}, \frac{a}{a}, \frac{t \times a}{a^2}\right]$	$0.05 \le \frac{a}{a} \le 0.4$ $0 \le \frac{t}{a} \le 0.4$
Tridem Axle (Single Wheel)	$R = 0.44084 + 0.24238\,\Phi_1 + 0.02310\,\Phi_2$ $\Phi_1 = \begin{cases} -0.019 + 1.060\,A_1 + 0.371\,A_1^2 & A_1 \le -0.4 \\ 1.594 + 6.322\,A_1 - 3.323\,A_1^2 - 21.337\,A_1^3 & A_1 > -0.4 \end{cases}$ $\Phi_2 = \begin{cases} 3.792 + 17.087\,A_2 - 0.712\,A_2^2 & A_2 \le -0.2 \\ 1.313 + 6.666\,A_2 + 38.682\,A_2^2 + 154.194\,A_2^3 & A_2 > -0.2 \end{cases}$ $A_1 = -0.74449\,x_1 + 0.63504\,x_2 + 0.20606\,x_3$ $A_2 = -0.06053\,x_1 - 0.95139\,x_2 + 0.30198\,x_3$ $X = [\,x_1, x_2, x_3\,] = \left[\frac{t}{a}, \frac{a}{a}, \frac{t \times a}{a^2}\right]$	$0.05 \le \frac{a}{a} \le 0.4$ $0 \le \frac{t}{a} \le 3$
Finite Slab Length	$R_2 = 0.9399 + 0.07986\Phi_1$ $\Phi_1 = -4.0308 + \frac{1}{0.2029 + 0.0345(A_1)^{-3.3043}}$ $A_1 = -0.9436\frac{a}{a} + 0.3310\frac{L}{a}$	$2 \le \frac{L}{a} \le 7$ $0.05 \le \frac{a}{a} \le 0.3$
Finite Slab Width	$R_2 = 1.00477 + 0.01214\Phi_1$ $\Phi_1 = -0.5344 + 1.654(1 - A_1)^{-10.7412}$ $A_1 = 0.9951\frac{a}{a} - 0.09856\frac{W}{a}$	$2 \le \frac{W}{a} \le 7$ $0.05 \le \frac{a}{a} \le 0.3$
Tied Concrete Shoulder	$R = 0.60162 + 0.159676\,\Phi_1 + 0.01166\,\Phi_2$ $\Phi_1 = \begin{cases} -0.158 + 0.183\,A_1 + 0.015\,A_1^2 & A_1 \le -4.0 \\ 2.637 + 1.113\,A_1 - 0.106\,A_1^2 - 0.046\,A_1^3 & A_1 > -4.0 \end{cases}$ $\Phi_2 = \begin{cases} -1.229 + 1.776\,A_2 - 0.169\,A_2^2 & A_2 \le 1.0 \\ -1.565 + 2.328\,A_2 - 0.378\,A_2^2 & A_2 > 1.0 \end{cases}$ $A_1 = -0.96616\,x_1 - 0.14766\,x_2 + 0.09408\,x_3 + 0.02047\,x_4 - 0.18758\,x_5 - 0.01668\,x_6$ $A_2 = -0.36090\,x_1 + 0.91982\,x_2 + 0.05545\,x_3 - 0.13400\,x_4 + 0.03720\,x_5 - 0.03558\,x_6$ $X = [\,x_1, x_2, x_3, x_4, x_5, x_6\,] = \left[\log_{10}\left(1+\frac{AGG}{k^a}\right), 10\times\frac{a}{a}, \log_{10}\left(1+\frac{AGG}{k^a}\right)^2, \left(10\times\frac{a}{a}\right)^2, \log_{10}\left(1+\frac{AGG}{k^a}\right)*(10\times a/a), \log_{10}\left(1+\frac{AGG}{k^a}\right)/(10\times a/a) \right]$	$0.05 \le \frac{a}{a} \le 0.5$ $0.0 \le \frac{AGG}{k^a} \le 50000$

Table 1 -- Proposed Prediction Models for Stress Adjustments (Continue ...)

Widened Outer Lane	$R = 0.55063 + 0.11899\,\Phi_1 + 0.02401\,\Phi_2$ $\Phi_1 = \begin{cases} 0.343 + 0.574\,A_1 + 0.047\,A_1^2 & A_1 \le 0.4 \\ 3.925 + 21.088\,A_1 + 31.524\,A_1^2 & A_1 > 0.4 \end{cases}$ $\Phi_2 = \begin{cases} 0.577 - 27.355\,A_2 + 93.957\,A_2^2 & A_2 \le -0.25 \\ -1.843 + 2.884\,A_2 - 0.418\,A_2^2 & A_2 > -0.25 \end{cases}$ $A_1 = -0.56085\,x_1 - 0.09409\,x_2 + 0.82206\,x_3 - 0.02867x_4$ $A_2 = 0.25715\,x_1 - 0.21456\,x_2 + 0.94224\,x_3 - 0.00447x_4$ $X = [\,x_1, x_2, x_3, x_4\,] = \left[\frac{D_0}{a}, \frac{a}{a}, \frac{D_0 \times a}{a^2}, \frac{D_0}{a}\right]$	$0.05 \le \frac{a}{a} \le 4.0$ $0 \le \frac{D_0}{a} \le 4.0$
Unbonded Second Layer	$R_5 = 0.72692 + 0.14272\Phi_1 + 0.00933\Phi_2$ $\Phi_1 = \begin{cases} 3.31765 + 2.4036(A_1) & if\ A_1 \le -1.4 \\ 5.72684 + 4.10244(A_1) & if\ A_1 > -1.4 \end{cases}$ $\Phi_2 = \begin{cases} 14.535 - 20.351(A_2) + 5.986(A_2)^2 & if\ A_2 \le 1.2 \\ 1.619 - 8.367(A_2) + 4.877(A_2)^2 & if\ A_2 > 1.2 \end{cases}$ $A_1 = 0.11914x1 - 0.99288x2$ $A_2 = 0.65518x1 + 0.75547x2$ $h_{efft} = \sqrt{h_1^2 + \frac{E_2 h_2}{E_1 h_1} h_2^2}\ ,\ X = [x1\ ,\ x2] = \left[\frac{a}{a}\ ,\ \left(\frac{h_{efft}}{h1}\right)^2\right]$	$0.05 \le \frac{a}{a} \le 0.4$ $1 \le (\frac{h_{efft}}{h_1})^2 \le 2$
Bonded Second Layer	$\sim = \frac{(1/2)h_1(h_1 + h_2)}{h_1 + h_2(E_1/E_2)}\ ,\quad = (1/2)(h_1 + h_2)\ J\ \sim$ $h_{if} = \sqrt[3]{h_1^3 + 12h_1\ \ ^2}\ ,\ h_{2f} = \sqrt[3]{h_2^3 + 12h_2\ \ ^2}$ $h_{efft} = \sqrt{h_{1f}^2 + \left(\frac{h_{2f}}{h_{1f}}\right) h_{2f}^2}\ ,\ X = [x1\ ,\ x2] = \left[\frac{a}{a}\ ,\ \left(\frac{h_{efft}}{h_{1f}}\right)^2\right]$ Use the above unbonded prediction model to calculate R_5	(same as above)
Load plus Day-time Curling	$R_T = 0.94825 + 0.15054\Phi_1 + 0.03724\Phi_2 + 0.03395\Phi_3$ $\Phi_1 = \begin{cases} -2.5575+0.8003\,(A_1) & if\ A_1 \le 3 \\ -2.6338+1.1038(A_1)-0.0914(A_1)^2 & if\ 3 < A_1 \le 7 \\ 0.7564-0.0155(A_1) & if\ A_1 > 7 \end{cases}$ $\Phi_2 = \begin{cases} -0.6788+0.0107(A_2) & if\ A_2 \le 3 \\ 3.7674-2.297(A_2)+0.2963(A_2)^2 & if\ 3 < A_2 \le 7 \\ -7.0337+1.2945(A_2) & if\ A_2 > 7 \end{cases}$ $\Phi_3 = \begin{cases} 4.0843+4.8241\,(A_3) & if\ A_3 \le 3 \\ 0.1815+0.0541(A_3)-1.0899(A_3)^2 & if\ -1 < A_3 \le 0.5 \\ 0.0453+0.0383(A_3) & if\ A_3 > 0.5 \end{cases}$ $A_1 = -0.04724X_1+0.56954X_2-0.08408X_3+0.20033X_4-0.26647X_5$ $+0.00375X_6+0.73881X_7-0.01142X_8+0.0953X_9+0.01121X_{10}$ $A_2 = 0.03869X_1+0.35781X_2+0.09078X_3-0.04054X_4+0.86388X_5$ $+0.01635X_6-0.31246X_7+0.00552X_8-0.12677X_9-0.01765X_{10}$ $A_3 = 0.58567X_1+0.25804X_2+0.14784X_3+0.14984X_4+0.12743X_5$ $-0.05012X_6+0.72295X_7-0.0131X_8-0.01304X_9-0.06591X_{10}$ $X = [X_1, X_2, X_3, \ldots, X_{10}]$ $= \left[\frac{W}{a}, \frac{L}{a}, AT, \frac{a}{a}, DG, DP, \frac{L}{a} * \frac{a}{a}, \frac{L}{a} * AT, DG * \frac{L}{a}, DG * \frac{W}{a}\right]$	$0.05 \le \frac{a}{a} \le 0.3$ $3 \le \frac{W}{a} \le 11$ $\frac{W}{a} = \frac{L}{a}$ $1.06 \le DG \le 9.93$ $2.61 \le DP \le 140.74$ $5.5 \le AT \le 22$ $DG = D_{¥} \times 10^5$ $DP = D_P \times 10^5$ $AT = \sim \times \Delta T \times 10^5$

Table 2 -- Comparison of Equivalent Stress Calculations (TKUPAV / PCA)

(A) Equivalent Stress Calculations for Single Axle Load (No Shoulder)

h	k	a	$6*M_e/h^2$	σ_w	Dual	D	R_1	R_2	$\sigma_w*R_1*R_2$	B/A
in.	pci	in.	psi (A)	psi					psi (B)	Ratio
4	100	21.6	897.5	2487.8	0.700	0.501	0.350	1.007	877.8	0.98
6	100	29.3	499.0	1302.4	0.729	0.512	0.373	1.003	487.4	0.98
8	100	36.4	327.9	812.5	0.746	0.518	0.387	0.995	312.7	0.95
10	100	43.0	237.0	560.1	0.756	0.536	0.405	0.985	223.6	0.94
12	100	49.3	182.2	411.9	0.764	0.546	0.417	0.972	166.8	0.92
4	300	16.4	721.9	2098.4	0.666	0.501	0.334	1.009	706.7	0.98
6	300	22.3	407.9	1124.5	0.703	0.501	0.352	1.007	399.1	0.98
8	300	27.6	269.0	711.0	0.724	0.509	0.369	1.004	263.2	0.98
10	300	32.7	194.2	494.5	0.738	0.513	0.379	1.000	187.3	0.96
12	300	37.4	148.9	366.0	0.748	0.522	0.391	0.994	142.1	0.95
4	500	14.5	646.7	1921.6	0.650	0.508	0.330	1.009	639.8	0.99
6	500	19.6	369.9	1043.2	0.688	0.499	0.344	1.008	361.3	0.98
8	500	24.3	245.0	664.4	0.712	0.504	0.359	1.006	239.9	0.98
10	500	28.7	177.2	464.3	0.728	0.511	0.372	1.003	173.2	0.98
12	500	32.9	135.8	344.9	0.739	0.513	0.379	0.999	130.7	0.96

(B) Equivalent Stress Calculations for Tandem Axle Load (No Shoulder)

h	k	a	$6*M_e/h^2$	σ_w	Dual	D	Tandem	R_1	R_2	$\sigma_w*R_1*R_2$	B/A
in.	pci	in.	psi, (A)	psi						psi, (B)	Ratio
4	100	21.6	723.4	4975.6	0.700	0.501	0.423	0.148	1.007	742.9	1.03
6	100	29.3	423.3	2604.8	0.729	0.512	0.438	0.164	1.003	427.4	1.01
8	100	36.4	297.7	1625.0	0.746	0.518	0.454	0.176	0.995	283.9	0.95
10	100	43.0	228.7	1120.2	0.756	0.536	0.467	0.189	0.985	208.7	0.91
12	100	49.3	185.0	823.7	0.764	0.546	0.477	0.199	0.972	159.1	0.86
4	300	16.4	600.6	4196.9	0.666	0.501	0.427	0.143	1.009	604.0	1.01
6	300	22.3	329.3	2249.0	0.703	0.501	0.424	0.149	1.007	338.4	1.03
8	300	27.6	224.8	1421.9	0.724	0.509	0.435	0.160	1.004	228.8	1.02
10	300	32.7	170.1	989.0	0.738	0.513	0.446	0.169	1.000	167.1	0.98
12	300	37.4	136.6	732.0	0.748	0.522	0.456	0.178	0.994	129.6	0.95
4	500	14.5	565.0	3843.3	0.650	0.508	0.441	0.145	1.009	564.0	1.00
6	500	19.6	298.4	2086.4	0.688	0.499	0.422	0.145	1.008	304.8	1.02
8	500	24.3	199.7	1328.8	0.712	0.504	0.428	0.153	1.006	205.2	1.03
10	500	28.7	149.5	928.7	0.728	0.511	0.437	0.163	1.003	151.4	1.01
12	500	32.9	119.3	689.8	0.739	0.513	0.447	0.169	0.999	116.8	0.98

(Note: 1 in. = 2.54 cm, 1 psi = 0.07 kg/cm^2, 1 pci = 0.028 kg/cm^3, 1 kip = 454 kg)

Table 2 -- Comparison of Equivalent Stress Calculations (TKUPAV / PCA) (Continue ...)

(C) Equivalent Stress Calculations for Single Axle Load (With Shoulder)

h	k	a	$6*M_e/h^2$	σ_w	Dual	D	R_1	R_2	R_3	$\sigma_w*R_1*R_2*R_3$	B/A
in.	pci	in.	psi (A)	psi						psi (B)	Ratio
4	100	21.6	645.1	2487.8	0.700	0.501	0.350	1.007	0.724	635.2	0.985
6	100	29.3	377.9	1302.4	0.729	0.512	0.373	1.003	0.769	374.9	0.992
8	100	36.4	256.7	812.5	0.746	0.518	0.387	0.995	0.798	249.5	0.972
10	100	43.0	189.8	560.1	0.756	0.536	0.405	0.985	0.819	183.0	0.964
12	100	49.3	148.1	411.9	0.764	0.546	0.417	0.972	0.834	139.2	0.940
4	300	16.4	521.2	2098.4	0.666	0.501	0.334	1.009	0.739	522.5	1.003
6	300	22.3	311.3	1124.5	0.703	0.501	0.352	1.007	0.796	317.7	1.021
8	300	27.6	213.1	711.0	0.724	0.509	0.369	1.004	0.831	218.8	1.027
10	300	32.7	158.1	494.5	0.738	0.513	0.379	1.000	0.856	160.4	1.014
12	300	37.4	123.6	366.0	0.748	0.522	0.391	0.994	0.875	124.3	1.006
4	500	14.5	471.8	1921.6	0.650	0.508	0.330	1.009	0.744	476.1	1.009
6	500	19.6	285.6	1043.2	0.688	0.499	0.344	1.008	0.807	291.7	1.021
8	500	24.3	196.6	664.4	0.712	0.504	0.359	1.006	0.846	203.0	1.033
10	500	28.7	146.3	464.3	0.728	0.511	0.372	1.003	0.873	151.3	1.034
12	500	32.9	114.6	344.9	0.739	0.513	0.379	0.999	0.894	116.9	1.020

(D) Equivalent Stress Calculations for Tandem Axle Load (With Shoulder)

h	k	a	$6*M_e/h^2$	σ_w	Dual	D	Tandem	R_1	R_2	R_3	$\sigma_w*R_1*R_2*R_3$	B/A
in.	pci	in.	psi, (A)	psi							psi, (B)	Ratio
4	100	21.6	540.2	4975.6	0.700	0.501	0.423	0.148	1.007	0.724	537.6	0.995
6	100	29.3	319.9	2604.8	0.729	0.512	0.438	0.164	1.003	0.769	328.7	1.028
8	100	36.4	226.1	1625.0	0.746	0.518	0.454	0.176	0.995	0.798	226.5	1.002
10	100	43.0	174.1	1120.2	0.756	0.536	0.467	0.189	0.985	0.819	170.8	0.981
12	100	49.3	141.1	823.7	0.764	0.546	0.477	0.199	0.972	0.834	132.7	0.940
4	300	16.4	465.1	4196.9	0.666	0.501	0.427	0.143	1.009	0.739	446.6	0.960
6	300	22.3	260.1	2249.0	0.703	0.501	0.424	0.149	1.007	0.796	269.4	1.036
8	300	27.6	179.1	1421.9	0.724	0.509	0.435	0.160	1.004	0.831	190.2	1.062
10	300	32.7	136.2	989.0	0.738	0.513	0.446	0.169	1.000	0.856	143.1	1.051
12	300	37.4	109.6	732.0	0.748	0.522	0.456	0.178	0.994	0.875	113.5	1.035
4	500	14.5	448.0	3843.3	0.650	0.508	0.441	0.145	1.009	0.744	419.8	0.937
6	500	19.6	242.3	2086.4	0.688	0.499	0.422	0.145	1.008	0.807	246.1	1.016
8	500	24.3	164.0	1328.8	0.712	0.504	0.428	0.153	1.006	0.846	173.6	1.059
10	500	28.7	123.5	928.7	0.728	0.511	0.437	0.163	1.003	0.873	132.2	1.071
12	500	32.9	98.8	689.8	0.739	0.513	0.447	0.169	0.999	0.894	104.4	1.057

(Note: 1 in. = 2.54 cm, 1 psi = 0.07 kg/cm^2, 1 pci = 0.028 kg/cm^3, 1 kip = 454 kg)

Table 3 -- Fatigue Analysis Example for Loading Only (PCAPAV and TKUPAV)

(A)Single Axle (kips)			PCAPAV (f_2=0.973, f_3=0.894, f_4=0.953)						TKUPAV (R_1=0.395, R_2=0.992, f_3=0.894, f_4=0.953)					σ_{eq} Ratio
Load	Load*1.2	n_i	$6{*}M_e/h^2$	f1	σ_{eq} , psi (A)	σ_{eq}/S_c	N_i	n_i/N_i , (%)	σ_w, psi	σ_{eq} , psi (B)	σ_{eq}/S_c	N_i	n_i/N_i , (%)	(B/A)
30	36.0	6310	243.4	0.976	393.6	0.606	26536	23.8	1185.9	395.4	0.608	24552	25.7	1.00
28	33.6	14690	243.4	0.980	368.9	0.568	76395	19.2	1106.8	369.1	0.568	75838	19.4	1.00
26	31.2	30140	243.4	0.984	344.1	0.529	234343	12.9	1027.8	342.7	0.527	251786	12.0	1.00
24	28.8	64410	243.4	0.989	319.1	0.491	1218769	5.3	948.7	316.3	0.487	1563859	4.1	0.99
22	26.4	106900	243.4	0.994	294.1	0.452	4.1E+07	0.3	869.7	290.0	0.446	1E+15	0.0	0.99
20	24.0	235800	243.4	1.000	268.9	0.414	Unlimited	0.0	790.6	263.6	0.406	1E+15	0.0	0.98
18	21.6	307200	243.4	1.006	243.5	0.375	Unlimited	0.0	711.5	237.3	0.365	1E+15	0.0	0.97
16	19.2	422500	243.4	1.013	218.0	0.335	Unlimited	0.0	632.5	210.9	0.324	1E+15	0.0	0.97
14	16.8	586900	243.4	1.022	192.3	0.296	Unlimited	0.0	553.4	184.5	0.284	1E+15	0.0	0.96
12	14.4	1837000	243.4	1.031	166.3	0.256	Unlimited	0.0	474.4	158.2	0.243	1E+15	0.0	0.95
							Subtotal=	61.5%				Subtotal=	61.2%	
(B)Tandem Axle (kips)			PCAPAV (f_2=0.973, f_3=0.894, f_4=0.953)						TKUPAV (R_1=0.181, R_2=0.992, f_3=0.894, f_4=0.953)					
52	62.4	21320	226.0	0.984	319.5	0.492	1177998	1.8	2055.6	314.4	0.484	1873981	1.1	0.98
48	57.6	42870	226.0	0.989	296.4	0.456	2.4E+07	0.2	1897.4	290.3	0.447	1E+15	0.0	0.98
44	52.8	124900	226.0	0.994	273.1	0.420	Unlimited	0.0	1739.3	266.1	0.409	1E+15	0.0	0.97
40	48.0	372900	226.0	1.000	249.7	0.384	Unlimited	0.0	1581.2	241.9	0.372	1E+15	0.0	0.97
36	43.2	885800	226.0	1.006	226.1	0.348	Unlimited	0.0	1423.1	217.7	0.335	1E+15	0.0	0.96
32	38.4	930200	226.0	1.013	202.4	0.311	Unlimited	0.0	1265.0	193.5	0.298	1E+15	0.0	0.96
28	33.6	1656000	226.0	1.022	178.6	0.275	Unlimited	0.0	1106.8	169.3	0.260	1E+15	0.0	0.95
24	28.8	984900	226.0	1.031	154.5	0.238	Unlimited	0.0	948.7	145.1	0.223	1E+15	0.0	0.94
20	24.0	1227000	226.0	1.042	130.1	0.200	Unlimited	0.0	790.6	120.9	0.186	1E+15	0.0	0.93
16	19.2	1356000	226.0	1.057	105.5	0.162	Unlimited	0.0	632.5	96.8	0.149	1E+15	0.0	0.92
							Subtotal=	2.0				Subtotal=	1.1	

(Note: 1 psi = 0.07 kg/cm^2, 1 kip = 454 kg) $\Sigma\ n_i/N_i$ = 63.5% $\Sigma\ n_i/N_i$ = 62.3%

Table 4 -- Adjustment Factors for Loading Only

Dual		Tandem		Axle Width, D		Slab Length		Slab Width	
s/ª=	0.310	t/ª=	1.291	s/ª =	1.859	a/ª=	0.122	a/ª=	0.122
a/ª=	0.122	a/ª=	0.122	a/ª=	0.122	L/ª=	4.648	W/ª=	3.718
s*a/ª^2=	0.038	t*a/ª^2=	0.157	s*a/ª^2=	0.227	A_1=	1.424	A_1=	-0.245
A_1=	-0.159	A_1=	-0.554	A_1=	-1.348	Φ_1=	0.65	Φ_1=	-0.378
A_2=	-0.091	A_2=	-0.132	A_2=	-0.039	R_2=	0.992	R_2=	1.000
Φ_1=	2.026	Φ_1=	-0.431	Φ_1=	-0.350				
Φ_2=	0.930	Φ_2=	0.591	Φ_2=	-0.700				
R_1=	0.750	R_1=	0.459	R_1=	0.526				

Table 5 - Adjustment Factor (R_T) for Loading Plus Curling

(A) Single Axle									
1.2 *Axle Load	P, lb.	DP	A_1	A_2	A_3	Φ_1	Φ_2	Φ_3	R_T
36000	18000	58.488	2.504	4.704	1.112	-0.554	-0.481	0.088	0.850
33600	16800	54.588	2.489	4.640	1.306	-0.565	-0.511	0.095	0.847
31200	15600	50.689	2.475	4.576	1.502	-0.577	-0.539	0.103	0.845
28800	14400	46.790	2.460	4.513	1.697	-0.589	-0.564	0.110	0.842
26400	13200	42.891	2.445	4.449	1.893	-0.600	-0.587	0.118	0.840
24000	12000	38.992	2.431	4.385	2.088	-0.612	-0.608	0.125	0.838
21600	10800	35.093	2.416	4.321	2.284	-0.624	-0.626	0.133	0.836
19200	9600	31.193	2.401	4.258	2.479	-0.635	-0.641	0.140	0.833
16800	8400	27.294	2.387	4.194	2.674	-0.647	-0.654	0.148	0.831
14400	7200	23.395	2.372	4.130	2.870	-0.659	-0.665	0.155	0.830
(B) Tandem Axle									
62400	31200	101.378	2.665	5.405	-1.039	-0.425	0.008	-0.926	0.853
57600	28800	93.580	2.635	5.278	-0.648	-0.448	-0.102	-0.311	0.866
52800	26400	85.782	2.606	5.150	-0.257	-0.472	-0.203	0.096	0.873
48000	24000	77.983	2.577	5.023	0.134	-0.495	-0.295	0.169	0.868
43200	21600	70.185	2.548	4.895	0.525	-0.519	-0.377	0.065	0.858
38400	19200	62.387	2.518	4.768	0.916	-0.542	-0.449	0.080	0.853
33600	16800	54.588	2.489	4.640	1.306	-0.565	-0.511	0.095	0.847
28800	14400	46.790	2.460	4.513	1.697	-0.589	-0.564	0.110	0.842
24000	12000	38.992	2.431	4.385	2.088	-0.612	-0.608	0.125	0.838
19200	9600	31.193	2.401	4.258	2.479	-0.636	-0.641	0.140	0.833

(Note: Axle loads are in pounds (lb.), 1 lb. = 0.454 kg)

Table 6 -- TKUPAV Fatigue Analysis Example (with Curling)

(A)Single Axle (kips)			90% Load Only				10% Load plus Curling (σ_c = 88.5 psi)						Total
Load	Load*1.2	n_i	σ_{eq} , psi (A)	n_i*90%	N_i	Damage (%)	R_T	σ_{eq} , psi	σ_{eq}/S_c	n_i*10%	N_i	Damage (%)	Damage (%)
30	36.0	6310	395.420	5679	24552	23.1	0.850	452.5	0.696	631	2132	29.6	52.7
28	33.6	14690	369.059	13221	75838	17.4	0.847	426.0	0.655	1469	6636	22.1	39.6
26	31.2	30140	342.697	27126	251786	10.8	0.845	399.5	0.615	3014	20648	14.6	25.4
24	28.8	64410	316.336	57969	1563859	3.7	0.842	372.9	0.574	6441	64228	10.0	13.7
22	26.4	106900	289.975	96210	Unlimited	0.0	0.840	346.4	0.533	10690	207804	5.1	5.1
20	24.0	235800	263.613	212220	Unlimited	0.0	0.838	319.9	0.492	23580	1140310	2.1	2.1
18	21.6	307200	237.252	276480	Unlimited	0.0	0.836	293.4	0.451	30720	48939810	0.1	0.1
16	19.2	422500	210.891	380250	Unlimited	0.0	0.833	266.9	0.411	42250	Unlimited	0.0	0.0
14	16.8	586900	184.529	528210	Unlimited	0.0	0.831	240.4	0.370	58690	Unlimited	0.0	0.0
12	14.4	1837000	158.168	1653300	Unlimited	0.0	0.830	213.9	0.329	183700	Unlimited	0.0	0.0
					Subtotal=	55.0					Subtotal=	83.6	138.7
(B)Tandem Axle (kips)													
52	62.4	21320	314.440	19188	1873981	1.0	0.853	371.8	0.572	2132	67524	3.2	4.2
48	57.6	42870	290.252	38583	Unlimited	0.0	0.866	348.5	0.536	4287	187824	2.3	2.3
44	52.8	124900	266.064	112410	Unlimited	0.0	0.873	324.7	0.500	12490	777888	1.6	1.6
40	48.0	372900	241.877	335610	Unlimited	0.0	0.868	300.2	0.462	37290	11515303	0.3	0.3
36	43.2	885800	217.689	797220	Unlimited	0.0	0.858	275.4	0.424	88580	Unlimited	0.0	0.0
32	38.4	930200	193.501	837180	Unlimited	0.0	0.853	250.8	0.386	93020	Unlimited	0.0	0.0
28	33.6	1656000	169.314	1490400	Unlimited	0.0	0.847	226.3	0.348	165600	Unlimited	0.0	0.0
24	28.8	984900	145.126	886410	Unlimited	0.0	0.842	201.7	0.310	98490	Unlimited	0.0	0.0
20	24.0	1227000	120.938	1104300	Unlimited	0.0	0.838	177.2	0.273	122700	Unlimited	0.0	0.0
16	19.2	1356000	96.751	1220400	Unlimited	0.0	0.833	152.8	0.235	135600	Unlimited	0.0	0.0
					Subtotal=	1.0					Subtotal=	11.2	12.3
(Note: 1 psi = 0.07 kg/cm^2, 1 kip = 454 kg)					$\Sigma n_i/N_i$ =	56.0%					$\Sigma n_i/N_i$ =	91.0%	147.0%