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*].

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

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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 his 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*]

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

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

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

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

$f_3 = 0.894$ 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*]

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

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*]:

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

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:

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

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*]:

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

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

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

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 = $W/((8^{0.5})*\ell)$;
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, ℓ = 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 = 0.754 * 0.528 = 0.398; and

(b) For a tandem axle (dual wheels): R_1 = 0.754 * 0.528 * 0.452 = 0.180.

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 71.4% of cumulative fatigue damage calculated by the TKUPAV program is very close to that determined by the PCAPAV program (63.4%). 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 /°F (9.9E-06 /°C), ΔT= 20 °F (11.1°C).

Thus, $\alpha\Delta T$ = 0.00011, W/ℓ = 3.873, L/ℓ = 4.648, a/ℓ = 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 64.2% fatigue damage was caused by 90% of load repetitions, whereas a total 138.84% 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 203.0% to an acceptable level of 41.3% 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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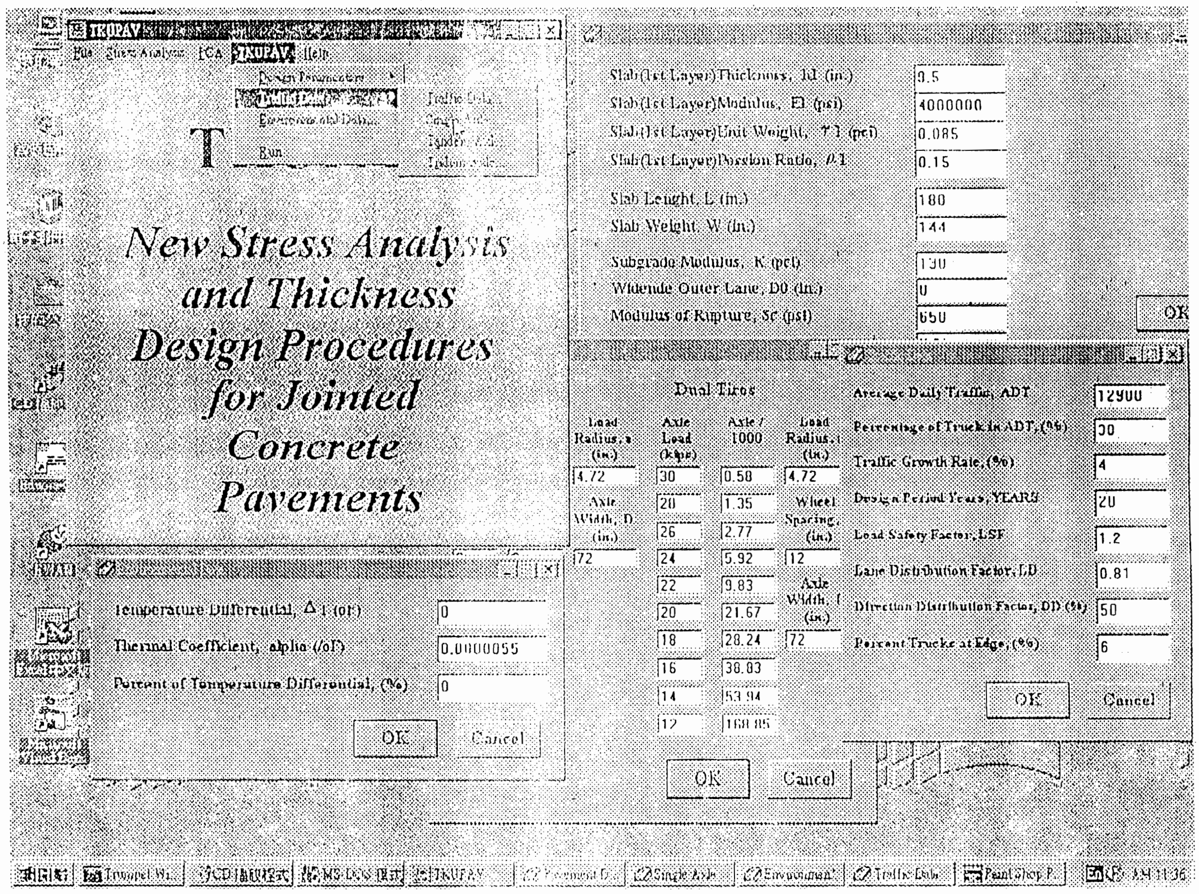

Figure 1 - Sample Input Screens of the TKUPAV Program

Table 1 -- Proposed Prediction Models for Stress Adjustments

Dual Wheel (Single Axle)	$R_1=0.56197+0.09313\Phi_1+0.0065\Phi_2$ $\Phi_1=\begin{cases}-0.043+0.452(A1)+0.075(A1)^2 & if\ A1\le -2\\ 2.997+6.278(A1)+4.122(A1)^2+0.964(A1)^3 & if\ A1>-2\end{cases}$ $\Phi_2=\begin{cases}-1.461-4.460(A2)+392.524(A2)^2+2955.995(A2)^3+4914.455(A2)^4 & if\ A2\le 0\\ -1.425+45.240(A2)-309.329(A2)^2+832.054(A2)^3-765.888(A2)^4 & if\ A2>0\end{cases}$ $A1=-0.7919x1+0.60762x2+0.06072x3$ $A2=0.01799x1-0.88168x2+0.4715x3$ $X=[x1,x2,x3]=\left[\frac{s}{\ell},\frac{a}{\ell},\frac{s\times a}{\ell^2}\right]$	$0.05\le\frac{a}{\ell}\le 0.4$ $0\le\frac{s}{\ell}\le 4.0$
Tandem Axle (Single Wheel)	$R_1=0.58306+0.19316\Phi_1+0.06236\Phi_2$ $\Phi_1=\begin{cases}0.159+1.604(A1)+0.820(A1)^2+0.135(A1)^3 & if\ A1\le -1\\ 1.319+4.509(A1)+1.760(A1)^2-0.914(A1)^3 & if\ A1>-1\end{cases}$ $\Phi_2=\begin{cases}2.151+11.020(A2)-2.894(A2)^2 & if\ A2\le -0.2\\ 2.210+11.770(A2)-16.209(A2)^2-70.589(A2) & if\ A2>-0.2\end{cases}$ $A1=-0.51308x1+0.85264x2+0.08604x3-0.04849x4$ $A2=-0.07313x1-0.93937x2+0.33502x3+0.00055x4$ $X=[x1,x2,x3,x4]=\left[\frac{t}{\ell},\frac{a}{\ell},\frac{t\times a}{\ell^2},\frac{t}{a}\right]$	$0.1\le\frac{a}{\ell}\le 0.4$ $0\le\frac{t}{\ell}\le 1.6$
Tridem Axle (Single Wheel)	$R_1=0.44485+0.17726\Phi_1+0.02072\Phi_2$ $\Phi_1=\begin{cases}0.230+1.078(A1)+0.177(A1)^2 & if\ A1\le -1\\ 2.480+6.329(A1)+3.363(A1)^2 & if\ A1>-1\end{cases}$ $\Phi_2=\begin{cases}-1.754+11.049(A2)+8.611(A2)^2 & if\ A2\le 0.12\\ -2.398+20.152(A2)-15.813(A2)^2 & if\ A2>0.12\end{cases}$ $A1=-0.54456x1+0.83346x2-0.09349x3-0.00724x4$ $A2=0.05007x1+0.87037x2-0.48983x3+0.00362x4$ $X=[x1,x2,x3,x4]=\left[\frac{t}{\ell},\frac{a}{\ell},\frac{t\times a}{\ell^2},\frac{t}{a}\right]$	$0.05\le\frac{a}{\ell}\le 0.4$ $0\le\frac{t}{\ell}\le 3$
Finite Slab Length	$R_2=0.9399+0.07986\Phi_1$ $\Phi_1=-4.0308+\frac{1}{0.2029+0.0345(A1)^{-3.3043}}$ $A1=-0.9436\frac{a}{\ell}+0.3310\frac{L}{\ell}$	$2\le\frac{L}{\ell}\le 7$ $0.05\le\frac{a}{\ell}\le 0.3$
Finite Slab Width	$R_2=1.00477+0.01214\Phi_1$ $\Phi_1=-0.5344+1.654(1-A1)^{-10.7412}$ $A1=0.9951\frac{a}{\ell}-0.09856\frac{W}{\ell}$	$2\le\frac{W}{\ell}\le 7$ $0.05\le\frac{a}{\ell}\le 0.3$
Tied Concrete Shoulder [6]	$R_3=\begin{cases}0.99864-0.51237(x1)-0.0672*\ln(x2)+0.00315*\ln^2(x2)\\ +0.015936(x1)^2*\ln^2(x2) & if\ x1\le 5\\ 1.04284-0.84692(x1)-0.0009299*\ln(x2)+0.06837(x1)*\ln(x2)\\ +0.63417(x1)^2+0.0042*\ln^2(x2)-0.000629(x1)*\ln(x2)^3 & if\ x1>5\end{cases}$ $X=[x1,x2]=\left[\frac{a}{\ell},\frac{AGG}{k\ell}\right]$	$0.05\le\frac{a}{\ell}\le 0.3$ $5\le\frac{AGG}{k\ell}$

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

Widened Outer Lane	$R_4 = 0.61711 + 0.15373\Phi_1 + 0.02504\Phi_2$ $\Phi_1 = \begin{cases} 0.693 + 1.279(A1) + 0.369(A1)^2 + 0.037(A1)^3 & \text{if } A1 \le -2.5 \\ 2.839 + 8.234(A1) + 8.158(A1)^2 + 3.608(A1)^3 + 0.576(A1)^4 & \text{if } A1 > -2.5 \end{cases}$ $\Phi_2 = \begin{cases} -2.285 + 5.921(A2) - 6.001(A2)^2 + 7.743(A2)^3 & \text{if } A2 \le 0.5 \\ -3.008 + 4.693(A2) + 4.334(A2)^2 - 2.167(A2)^3 & \text{if } A2 > 0.5 \end{cases}$ $A1 = -0.98868x1 - 0.12214x2 - 0.08717x3$ $A2 = 0.19802x1 + 0.98019x2 + 0.00305x3$ $X = [x1\ ,\ x2\ ,\ x3] = \left[\frac{D_0}{\ell}\ ,\ \frac{a}{\ell}\ ,\ \frac{D_0}{a}\right]$	$0.1 \le \frac{a}{\ell} \le 0.4$ $0 \le \frac{D_0}{\ell} \le 2$
Unbonded Second Layer	$R_5 = 0.72692 + 0.14272\Phi_1 + 0.00933\Phi_2$ $\Phi_1 = \begin{cases} 3.31765 + 2.4036(A1) & \text{if } A1 \le -1.4 \\ 5.72684 + 4.10244(A1) & \text{if } A1 > -1.4 \end{cases}$ $\Phi_2 = \begin{cases} 14.535 - 20.351(A2) + 5.986(A2)^2 & \text{if } A2 \le 1.2 \\ 1.619 - 8.367(A2) + 4.877(A2)^2 & \text{if } A2 > 1.2 \end{cases}$ $A1 = 0.11914x1 - 0.99288x2$ $A2 = 0.65518x1 + 0.75547x2$ $h_{eff} = \sqrt{h_1^2 + \frac{E_2 h_2}{E_1 h_1} h_2^2}\ ,\ X = [x1\ ,\ x2] = \left[\frac{a}{\ell}\ ,\ \left(\frac{h_{eff}}{h1}\right)^2\right]$	$0.05 \le \frac{a}{\ell} \le 0.4$ $1 \le (\frac{h_{efft}}{h_1})^2 \le 2$
Bonded Second Layer	$\alpha = \frac{(1/2)h_1(h_1 + h_2)}{h_1 + h_2(E_1/E_2)}\ ,\ \beta = (1/2)(h_1 + h_2) - \alpha$ $h_{1f} = \sqrt[3]{h_1^3 + 12h_1\beta^2}\ ,\ h_{2f} = \sqrt[3]{h_2^3 + 12h_2\beta^2}$ $h_{eff} = \sqrt{h_{1f}^2 + \left(\frac{h_{2f}}{h_{1f}}\right) h_{2f}^2}\ ,\ X = [x1\ ,\ x2] = \left[\frac{a}{\ell}\ ,\ \left(\frac{h_{eff}}{h_{1f}}\right)^2\right]$ Use the above unbonded prediction model to calculate R_5	(same as above)
Load plus Day-time Curling	$R_T = 0.94825 + 0.15054\Phi_1 + 0.03724\Phi_2 + 0.03395\Phi_3$ $\Phi_1 = \begin{cases} -2.5575 + 0.8003(A1) - 0.8003(A1)^2 & \text{if } A1 \le 3 \\ -2.6338 + 1.1038(A1) - 0.0914(A1)^2 & \text{if } 3 < A1 \le 7 \\ 0.7564 - 0.0155(A1) & \text{if } A1 > 7 \end{cases}$ $\Phi_2 = \begin{cases} -0.6788 + 0.0.8003(A2) - 0.8003(A2)^2 & \text{if } A2 \le 3 \\ 3.7674 - 2.297(A2) + 0.2963(A2)^2 & \text{if } 3 < A2 \le 7 \\ -7.0337 + 1.2945(A2) & \text{if } A2 > 7 \end{cases}$ $\Phi_3 = \begin{cases} 4.0843 + 4.8241(A3) & \text{if } A3 \le 3 \\ 0.1815 + 0.0541(A3) - 1.0899(A3)^2 & \text{if } -1 < A3 \le 0.5 \\ 0.0453 + 0.0383(A3) & \text{if } A3 > 0.5 \end{cases}$ $A1 = -0.04724X1 + 0.56954X2 - 0.08408X3 + 0.20033X4 - 0.26647X5 + 0.00375X6 + 0.73881X7 - 0.01142X8 + 0.0953X9 + 0.01121X10$ $A2 = 0.03869X1 + 0.35781X2 + 0.09078X3 - 0.04054X4 + 0.86388X5 + 0.01635X6 - 0.31246X7 + 0.00552X8 - 0.12677X9 - 0.01765X10$ $A3 = 0.58567X1 + 0.25804X2 + 0.14784X3 + 0.14984X4 + 0.12743X5 - 0.05012X6 + 0.72295X7 - 0.0131X8 - 0.01304X9 - 0.06591X10$ $X = [x1\ ,\ x2\ ,\ x3\ ,\ \ldots\ ,\ x10]$ $= \left[\frac{W}{\ell}\ ,\ \frac{L}{\ell}\ ,\ AT\ ,\ \frac{a}{\ell}\ ,\ DG\ ,\ DP\ ,\ \frac{L}{\ell} * \frac{a}{\ell}\ ,\ \frac{L}{\ell} * AT\ ,\ DG * \frac{L}{\ell}\ ,\ DG * \frac{W}{\ell}\right]$	$0.05 \le \frac{a}{\ell} \le 0.3$ $3 \le \frac{W}{\ell} \le 11$ $\frac{W}{\ell} = \frac{L}{\ell}$ $1.06 \le DG \le 9.93$ $2.61 \le DP \le 140.74$ $5.5 \le AT \le 22$ $DG = d\gamma \times 10^5$ $DP = dp \times 10^5$ $AT = \alpha \times \Delta T \times 10^5$

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

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

h	k	ℓ	6*Me/h^2	σ_w	Dual	D	R_1	R_2	σ_w*R_1*R_2	B/A
in.	pci	in.	psi (A)	psi					psi (B)	Ratio
4	100	21.6	897.5	2489.0	0.702	0.501	0.352	1.007	881.8	0.98
6	100	29.3	499.0	1303.1	0.732	0.511	0.374	1.003	489.2	0.98
8	100	36.4	327.9	812.9	0.749	0.526	0.394	0.995	318.8	0.97
10	100	43.0	237.0	560.4	0.761	0.531	0.404	0.985	222.7	0.94
12	100	49.3	182.2	412.1	0.769	0.536	0.412	0.971	165.1	0.91
4	300	16.4	721.9	2099.5	0.670	0.500	0.335	1.009	709.2	0.98
6	300	22.3	407.9	1125.1	0.705	0.502	0.354	1.007	401.0	0.98
8	300	27.6	269.0	711.3	0.727	0.502	0.365	1.004	260.6	0.97
10	300	32.7	194.2	494.7	0.741	0.521	0.386	0.999	191.1	0.98
12	300	37.4	148.9	366.2	0.752	0.527	0.396	0.994	144.0	0.97
4	500	14.5	646.7	1922.6	0.654	0.500	0.327	1.009	634.0	0.98
6	500	19.6	369.9	1043.7	0.691	0.499	0.345	1.008	362.6	0.98
8	500	24.3	245.0	664.7	0.715	0.505	0.361	1.006	241.1	0.98
10	500	28.7	177.2	464.6	0.730	0.509	0.372	1.003	173.2	0.98
12	500	32.9	135.8	345.1	0.742	0.522	0.387	0.999	133.5	0.98

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

h	k	ℓ	6*Me/h^2	σ_w	Dual	D	Tandem	R_1	R_2	σ_w*R_1*R_2	B/A
in.	pci	in.	psi, (A)	psi						psi, (B)	Ratio
4	100	21.6	723.4	4978.1	0.702	0.501	0.404	0.142	1.007	712.5	0.98
6	100	29.3	423.3	2606.1	0.732	0.511	0.424	0.159	1.003	414.6	0.98
8	100	36.4	297.7	1625.9	0.749	0.526	0.445	0.175	0.995	283.8	0.95
10	100	43.0	228.7	1120.8	0.761	0.531	0.463	0.187	0.985	206.5	0.90
12	100	49.3	185.0	824.1	0.769	0.536	0.505	0.208	0.971	166.9	0.90
4	300	16.4	600.6	4199.0	0.670	0.500	0.407	0.136	1.009	576.8	0.96
6	300	22.3	329.3	2250.2	0.705	0.502	0.405	0.143	1.007	324.9	0.99
8	300	27.6	224.8	1422.7	0.727	0.502	0.419	0.153	1.004	218.2	0.97
10	300	32.7	170.1	989.5	0.741	0.521	0.434	0.168	0.999	165.8	0.97
12	300	37.4	136.6	732.4	0.752	0.527	0.448	0.177	0.994	129.1	0.95
4	500	14.5	565.0	3845.2	0.654	0.500	0.420	0.137	1.009	532.4	0.94
6	500	19.6	298.4	2087.5	0.691	0.499	0.405	0.140	1.008	294.1	0.99
8	500	24.3	199.7	1329.5	0.715	0.505	0.410	0.148	1.006	197.5	0.99
10	500	28.7	149.5	929.1	0.730	0.509	0.422	0.157	1.003	146.2	0.98
12	500	32.9	119.3	690.1	0.742	0.522	0.435	0.168	0.999	116.1	0.97

(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	ℓ	6*Me/h^2	σ_w	Dual	D	R_1	R_2	R3	$\sigma_w*R_1*R_2*R_3$	B/A
in.	pci	in.	psi (A)	psi						psi (B)	Ratio
4	100	21.6	897.5	2489.0	0.702	0.501	0.352	1.007	0.764	638.101	0.989
6	100	29.3	499.0	1303.1	0.732	0.511	0.374	1.003	0.769	376.296	0.996
8	100	36.4	327.9	812.9	0.749	0.526	0.394	0.995	0.798	254.361	0.991
10	100	43.0	237.0	560.4	0.761	0.531	0.404	0.985	0.819	182.325	0.961
12	100	49.3	182.2	412.1	0.769	0.536	0.412	0.971	0.834	137.761	0.930
4	300	16.4	721.9	2099.5	0.670	0.500	0.335	1.009	0.739	524.445	1.006
6	300	22.3	407.9	1125.1	0.705	0.502	0.354	1.007	0.796	319.262	1.026
8	300	27.6	269.0	711.3	0.727	0.502	0.365	1.004	0.831	216.621	1.016
10	300	32.7	194.2	494.7	0.741	0.521	0.386	0.999	0.856	163.608	1.035
12	300	37.4	148.9	366.2	0.752	0.527	0.396	0.994	0.875	126.060	1.020
4	500	14.5	646.7	1922.6	0.654	0.500	0.327	1.009	0.744	471.896	1.000
6	500	19.6	369.9	1043.7	0.691	0.499	0.345	1.008	0.807	292.767	1.025
8	500	24.3	245.0	664.7	0.715	0.505	0.361	1.006	0.846	204.007	1.038
10	500	28.7	177.2	464.6	0.730	0.509	0.372	1.003	0.873	151.263	1.034
12	500	32.9	135.8	345.1	0.742	0.522	0.387	0.999	0.894	119.347	1.042

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

h	k	ℓ	6*Me/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	723.4	4978.1	0.702	0.501	0.404	0.142	1.007	0.724	515.605	0.955
6	100	29.3	423.3	2606.1	0.732	0.511	0.424	0.159	1.003	0.769	318.857	0.997
8	100	36.4	297.7	1625.9	0.749	0.526	0.445	0.175	0.995	0.798	226.409	1.002
10	100	43.0	228.7	1120.8	0.761	0.531	0.463	0.187	0.985	0.819	168.995	0.971
12	100	49.3	185.0	824.1	0.769	0.536	0.505	0.208	0.971	0.834	139.260	0.987
4	300	16.4	600.6	4199.0	0.670	0.500	0.407	0.136	1.009	0.739	426.540	0.917
6	300	22.3	329.3	2250.2	0.705	0.502	0.405	0.143	1.007	0.796	258.680	0.994
8	300	27.6	224.8	1422.7	0.727	0.502	0.419	0.153	1.004	0.831	181.385	1.013
10	300	32.7	170.1	989.5	0.741	0.521	0.434	0.168	0.999	0.856	141.992	1.043
12	300	37.4	136.6	732.4	0.752	0.527	0.448	0.177	0.994	0.875	113.006	1.031
4	500	14.5	565.0	3845.2	0.654	0.500	0.420	0.137	1.009	0.744	396.251	0.884
6	500	19.6	298.4	2087.5	0.691	0.499	0.405	0.140	1.008	0.807	237.428	0.980
8	500	24.3	199.7	1329.5	0.715	0.505	0.410	0.148	1.006	0.846	167.120	1.019
10	500	28.7	149.5	929.1	0.730	0.509	0.422	0.157	1.003	0.873	127.664	1.034
12	500	32.9	119.3	690.1	0.742	0.522	0.435	0.168	0.999	0.894	103.794	1.050

(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 (f2=0.973, f3=0.894, f4=0.953)						TKUPAV (R1=0.398, R2=0.992, f3=0.894, f4=0.953)					σ_{eq} Ratio
Load	Load*1.2	n_i	6*Me/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	1.952	393.6	0.606	26536	23.8	1186.5	398.6	0.613	21414	29.5	1.01
28	33.6	14690	243.4	1.829	368.9	0.568	76395	19.2	1107.4	372.0	0.572	66751	22.0	1.01
26	31.2	30140	243.4	1.706	344.1	0.529	234343	12.9	1028.3	345.5	0.531	218058	13.8	1.00
24	28.8	64410	243.4	1.583	319.1	0.491	1218769	5.3	949.2	318.9	0.491	1243647	5.2	1.00
22	26.4	106900	243.4	1.458	294.1	0.452	41207557	0.3	870.1	292.3	0.450	Unlimited	0.0	0.99
20	24.0	235800	243.4	1.333	268.9	0.414	Unlimited	0.0	791.0	265.7	0.409	Unlimited	0.0	0.99
18	21.6	307200	243.4	1.208	243.5	0.375	Unlimited	0.0	711.9	239.2	0.368	Unlimited	0.0	0.98
16	19.2	422500	243.4	1.081	218.0	0.335	Unlimited	0.0	632.8	212.6	0.327	Unlimited	0.0	0.98
14	16.8	586900	243.4	0.954	192.3	0.296	Unlimited	0.0	553.7	186.0	0.286	Unlimited	0.0	0.97
12	14.4	1837000	243.4	0.825	166.3	0.256	Unlimited	0.0	474.6	159.4	0.245	Unlimited	0.0	0.96
							Subtotal =	61.4%				Subtotal =	70.5%	
(B)Tandem Axle (kips)			PCAPAV (f2=0.973, f3=0.894, f4=0.953)						TKUPAV (R1=0.180, R2=0.992, f3=0.894, f4=0.953)					
52	62.4	21320	226.0	1.706	319.5	0.492	1177998	0.018	2056.6	312.2	0.480	2342697	0.9	0.98
48	57.6	42870	226.0	1.583	296.4	0.456	24134471	0.002	1898.4	288.2	0.443	Unlimited	0.0	0.97
44	52.8	124900	226.0	1.458	273.1	0.42	Unlimited	0.000	1740.2	264.2	0.406	Unlimited	0.0	0.97
40	48.0	372900	226.0	1.333	249.7	0.384	Unlimited	0.000	1582.0	240.2	0.370	Unlimited	0.0	0.96
36	43.2	885800	226.0	1.208	226.1	0.348	Unlimited	0.000	1423.8	216.2	0.333	Unlimited	0.0	0.96
32	38.4	930200	226.0	1.081	202.4	0.311	Unlimited	0.000	1265.6	192.1	0.296	Unlimited	0.0	0.95
28	33.6	1656000	226.0	0.954	178.6	0.275	Unlimited	0.000	1107.4	168.1	0.259	Unlimited	0.0	0.94
24	28.8	984900	226.0	0.825	154.5	0.238	Unlimited	0.000	949.2	144.1	0.222	Unlimited	0.0	0.93
20	24.0	1227000	226.0	0.695	130.1	0.2	Unlimited	0.000	791.0	120.1	0.185	Unlimited	0.0	0.92
16	19.2	1356000	226.0	0.563	105.5	0.162	Unlimited	0.000	632.8	96.1	0.148	Unlimited	0.0	0.91
							Subtotal =	2.0%				Subtotal =	0.9%	
(Note: 1 psi = 0.07 kg/cm^2, 1 kip = 454 kg)							Σ n_i/N_i =	63.4%				Σ n_i/N_i =	71.4%	

Table 4 -- Adjustment Factors for Loading Only

Dual		Tandem		Axle Width		Slab Length		Slab Width	
s/ℓ=	0.310	t/ℓ=	1.291	s/ℓ =	1.859	a/ℓ=	0.122	a/ℓ=	0.122
a/ℓ=	0.122	a/ℓ=	0.122	a/ℓ=	0.122	L/ℓ=	4.648	W/ℓ=	3.873
s*a/ℓ^2=	0.038	t*a/ℓ^2=	0.157	s*a/ℓ^2=	0.227	A1=	1.424	A1=	-0.260
A1=	-0.169	t/a=	10.593	A1=	-1.385	Φ1=	0.650	Φ1=	-0.397
A2=	-0.084	A1=	-1.059	A2=	0.033	R2=	0.992	R2=	1.000
Φ1=	2.049	A2=	-0.150	Φ1=	-0.352				
Φ2=	0.177	Φ1=	-0.780	Φ2=	-0.245				
R1=	0.754	Φ2=	0.314	R1=	0.528				
		R1=	0.452						

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

(A) Single Axle									
1.2 *Axle Load	P, lb.	DP	A1	A2	A3	Φ1	Φ2	Φ3	R_T
36000	18000	58.49	2.504	4.699	1.162	-0.554	-0.484	0.090	0.850
33600	16800	54.59	2.489	4.635	1.356	-0.565	-0.514	0.097	0.847
31200	15600	50.69	2.475	4.571	1.551	-0.577	-0.541	0.105	0.845
28800	14400	46.79	2.460	4.508	1.747	-0.589	-0.566	0.112	0.842
26400	13200	42.89	2.446	4.444	1.942	-0.600	-0.589	0.120	0.840
24000	12000	38.99	2.431	4.380	2.138	-0.612	-0.609	0.127	0.838
21600	10800	35.09	2.416	4.316	2.333	-0.624	-0.627	0.135	0.836
19200	9600	31.19	2.402	4.253	2.529	-0.635	-0.642	0.142	0.833
16800	8400	27.29	2.387	4.189	2.724	-0.647	-0.655	0.150	0.831
14400	7200	23.40	2.372	4.125	2.919	-0.659	-0.666	0.157	0.830
18000	9000	29.24	2.394	4.221	2.626	-0.641	-0.649	0.146	0.832
(B) Tandem Axle									
62400	31200	101.38	2.665	5.400	-0.989	-0.425	0.004	-0.938	0.853
57600	28800	93.58	2.636	5.273	-0.598	-0.448	-0.106	-0.241	0.869
52800	26400	85.78	2.606	5.145	-0.207	-0.472	-0.207	0.123	0.874
48000	24000	77.98	2.577	5.018	0.183	-0.495	-0.298	0.155	0.868
43200	21600	70.19	2.548	4.890	0.574	-0.518	-0.380	0.067	0.858
38400	19200	62.39	2.519	4.763	0.965	-0.542	-0.451	0.082	0.853
33600	16800	54.59	2.489	4.635	1.356	-0.565	-0.514	0.097	0.847
28800	14400	46.79	2.460	4.508	1.747	-0.589	-0.566	0.112	0.842
24000	12000	38.99	2.431	4.380	2.138	-0.612	-0.609	0.127	0.838
19200	9600	31.19	2.402	4.253	2.529	-0.635	-0.642	0.142	0.833
36000	18000	58.49	2.504	4.699	1.161	-0.554	-0.484	0.090	0.850

(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)	ni*90%	N_i	Damage (%)	RT	σ_{eq}, psi	σ_{eq}/S_c	ni*10%	N_i	Damage (%)	Damage (%)
30	36.0	6310	398.6	5679	21414	26.5	0.850	462.7	0.712	631	1382	45.7	72.2
28	33.6	14690	372.0	13221	66751	19.8	0.847	435.9	0.671	1469	4345	33.8	53.6
26	31.2	30140	345.5	27126	218058	12.4	0.845	409.1	0.629	3014	13654	22.1	34.5
24	28.8	64410	318.9	57969	1243647	4.7	0.842	382.4	0.588	6441	42899	15.0	19.7
22	26.4	106900	292.3	96210	Unlimited	0.0	0.840	355.6	0.547	10690	135064	7.9	7.9
20	24.0	235800	265.7	212220	Unlimited	0.0	0.838	328.9	0.506	23580	577713	4.1	4.1
18	21.6	307200	239.2	276480	Unlimited	0.0	0.836	302.1	0.465	30720	8444924	0.4	0.4
16	19.2	422500	212.6	380250	Unlimited	0.0	0.833	275.4	0.424	42250	Unlimited	0.0	0.0
14	16.8	586900	186.0	528210	Unlimited	0.0	0.831	248.7	0.383	58690	Unlimited	0.0	0.0
12	14.4	1837000	159.4	1653300	Unlimited	0.0	0.830	222.0	0.341	183700	Unlimited	0.0	0.0
					Subtotal =	63.4%					Subtotal =	128.9%	192.3%
(B)Tandem Axle (kips)													
52	62.4	21320	312.2	19188	2342697	0.8	0.853	376.5	0.579	2132	55171	3.9	4.7
48	57.6	42870	288.2	38583	Unlimited	0.0	0.869	353.7	0.544	4287	147221	2.9	2.9
44	52.8	124900	264.2	112410	Unlimited	0.0	0.874	330.1	0.508	12490	533733	2.3	2.3
40	48.0	372900	240.2	335610	Unlimited	0.0	0.868	305.6	0.470	37290	5139145	0.7	0.7
36	43.2	885800	216.2	797220	Unlimited	0.0	0.858	280.9	0.432	88580	Unlimited	0.0	0.0
32	38.4	930200	192.1	837180	Unlimited	0.0	0.853	256.4	0.394	93020	Unlimited	0.0	0.0
28	33.6	1656000	168.1	1490400	Unlimited	0.0	0.847	232.0	0.357	165600	Unlimited	0.0	0.0
24	28.8	984900	144.1	886410	Unlimited	0.0	0.842	207.6	0.319	98490	Unlimited	0.0	0.0
20	24.0	1227000	120.1	1104300	Unlimited	0.0	0.838	183.2	0.282	122700	Unlimited	0.0	0.0
16	19.2	1356000	96.1	1220400	Unlimited	0.0	0.833	158.9	0.244	135600	Unlimited	0.0	0.0
					Subtotal =	0.8%					Subtotal =	9.8%	10.7%
					$\Sigma n_i/N_i$ =	64.2%					$\Sigma n_i/N_i$ =	138.84%	203.0%

(Note: 1 psi = 0.07 kg/cm^2, 1 kip = 454 kg)