Theoretical Analysis of the Effects of Wide-Base Tires on Flexible Pavements Using CIRCLY

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Many state highway agencies across the nation are concerned with the effects of wide-base tires on flexible pavements. This concern is supported, in many cases, by legislative regulations that try to limit the extent of damage caused by wide-base tires. A study was done by the California Department of Transportation to characterize and predict the effects of wide-base tires and to evaluate a tentative regulatory limit. The primary objectives were (a) to provide an extensive literature review summary about previous research in the area, including the wide range of regulatory limits, and (b) to perform an improved mechanistic analysis that includes effects of actual temperature gradients and nonuniform contract stress (normal and shear) distributions. The literature review summary indicates that the overall wide-base tire issue cannot be quantified reliably with a single regulatory limit. The reason for this lies in the various factors and assumptions involved in any experimental or theoretical evaluation (e.g., temperature and load conditions). Previous studies assume simple and incomplete loading conditions that are known to differ from actual circumstances. The mechanistic analysis, using a computer program called CIRCLY, shows that the effects of these simplifications significantly alter predicted pavement response. Future evaluations should continue to model the actual nonuniform vertical and shear forces that tires exert on pavement structures. The full influence of these factors should be verified by laboratory and field measurements.

By definition, wide-base (super-single or flotation) tires have rim widths of 356 mm (14 in.) or greater with nominal rim diameters between 560 and 610 mm (22 to 24 in.) (*1*). The most common rims are the 16R22.5 and the 18R22.5 (*2*).

Expected benefits from the use of wide-base tires include decreased fuel consumption and operating costs and increased payload. These larger tires are replacing conventional truck dual tires in all axle configurations (single, tandem, and tridem). This change is of great concern to the California Department of Transportation (Caltrans) because research during the past years, based on theoretical and experimental studies, suggests considerably more pavement deterioration from the use of wide-base tires (*3–15*).

Regulations based on limiting the weight per inch of tire width for steering and regular axles have been adopted in 28 states around the nation (as of 1990).

	Limit	
States (no.)	*Newtons per Millimeter*	*Pounds per Inch*
3	96	550
15	105	600
4	114	650
1	123	700
5	140	800

The scientific background behind these "pounds-per-inch" limits is uncertain.

In this paper, a literature review summary is first presented showing the wide range of factors involved in the analysis and comparison of the effects of wide-base tires versus conventional dual tires. Subsequently, the paper presents a mechanistic analysis for a typical California pavement structure. The analysis is based on layered elastic theory using a state-of-the-art computer program called CIRCLY (*16*). Capabilities of the program include modeling of nonuniform contact shear and vertical stresses as well as temperature gradients within the pavement structure.

LITERATURE REVIEW

An extensive literature review was done to collect and evaluate findings pertinent to the effects of wide-base tires and dual tires on flexible pavement structures. The following components were used to establish a basis for evaluation:

1. Primary response parameters: strains or deflections, or both.
2. Analytical methods: layered elastic or finite element analysis, or both.
3. Load equivalency: load equivalent factors based on either empirical or theoretical methods.
4. Available data bases based on measured primary responses.

Little information was found on actual testing to failure, influence of axle configuration (for wide-base tires), and effect of contact shear pressure.

Summary

General characteristics and findings from previous studies are summarized, respectively, in Tables 1 and 2. Figure 1 illus-

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TABLE 1 Literature Review Summary

AUTHOR(S)	RESPONSE PARAMETERS (Measured-M, Calculated-C)	AXLE CONFIGURATIONS		BASIS FOR ANALYSIS		ANALYTICAL METHOD OR THEORY	STRUCTURAL SECTIONS	SURFACE TEMPERATURES
		Type	Axle Load, Tire Size, Inflation Pressure	Single primary response	Load equivalent factors			
Zube, et al (*3*) (California, USA)	Surface TS[1] (M) TS at bottom of AC[2] (M) Surface Deflection (M)	SINGLE	WB[3] : 53 kN, 18x19.5, 515 kPa Duals : 80 kN, 10x20, 480 kPa	YES	NO	Elastic (Boussinesq) - used to estimate comparable WB load for field testing.	Wide range Surface layer : 50 to 95 mm	15 to 50 °C
Emery, et al (*4*) (Canada)	Surface Deflection (M) Deflection Bowl (M)	SINGLE	WB : 80 kN, 6.5x19.5, 580 kPa Duals : 80 kN, 9x20, 550 kPa	YES	NO	None	Wide range Surface layer : 50 to 115 mm	NF[4]
Terrel, et al (*5*) (Washington, USA)	TS at bottom of AC (C) CS[5] at top of Subgrade(C)	SINGLE	Several loads and tire widths were modelled	NO	YES	Chevron (CHEV5L) program - used to calculate strains for life predictions	Wide range Surface layer : 75 to 230 mm	Mean : 20 °C
Christison (*6*) (Canada)	TS at bottom of AC (M) Surface Deflection (M)	SINGLE	WB : several, 18x22.5, 600 kPa Duals : 80 kN, 10x20, 550 kPa	YES	NO	None	2 structures Surface layer : 195 and 280 mm	5 to 25 °C
Christison, et al (*7*) (Canada)	TS at bottom of AC (M) Surface Deflection (M)	SINGLE TANDEM	WB : several, 16.5x22.5 / 18x22.5 Duals : 80 kN, 10x20, 550 kPa	NO	YES	None	2 structures Surface layer : 195 and 280 mm	5 to 25 °C
Snelgrove (*8*) (Canada)	Surface Deflection (M)	SINGLE	WB : several, 18x22.5, 550 kPa Duals : 80 kN, 10x22.5, 550 kPa	YES	NO	None	2 structures	NF
Southgate, et al (*11*) (Kentucky, USA)	Strain Energy Density (C)	TANDEM TRIDEM	Tire loads : 25-45 kN at 515 kPa	NO	YES	Chevron (CHEV5L) - modified for calculation of strain energy	Wide range Surface layer: 50 to 150 mm	NF
Sharp, et al (*12*) (Australia)	Surface Deflection (M)	SINGLE TANDEM TRIDEM	WB : several, 18x22.5, 690 kPa Duals : 80 kN, 10x22.5, 690 kPa	YES	NO	None	1 structure Surface layer : 75 mm	Reference : 32 °C
Huhtala, et al (*13*) (Finland)	TS at bottom of AC (M) (both longitudinal and transversal)	SINGLE	Loads : 75-120 kN WB : 355, 380, and 445 mm wide Duals : 255 and 305 mm wide Pressures : 480-1050 kPa	NO	YES	None	2 structures Surface layer : 75 and 150 mm	5 to 10 °C
Bonaquist (*14*) (Virginia, USA)	TS at bottom of AC (M) CS in all layers (M)	SINGLE	Loads : 80-150 kN WB : 16.5x22.5 Duals : 11x22.5 Pressures : 515, 700, and 960 kPa	YES	NO	None	2 structures Surface layer : 89 and 178 mm	Mean : 14 °C and 23 °C

(1) Tensile Strain
(2) Asphalt Concrete
(3) Wide Base Tire
(4) Not Found
(5) Compressive Strain

TABLE 2 Wide-Base Tire Limits

AUTHOR(S)	AXLE TYPE	ESTIMATES FOR WIDE BASE LIMITS			OTHER SPECIFICS (tensile strain-TS or compressive strain-CS, thin or thick section, tire width)	BASIS FOR LIMITS
		AXLE LOAD (kN)	WIDTH LIMITS (N/mm)	WIDTH LIMITS (lbs\in)		
Zube, et al (*3*)	SINGLE	54	58	333	TS & Deflection	MEASURED primary response
Terrel, et al (*5*)	SINGLE	80	85	486	TS, thin, 470 mm	CALCULATED life using predictive equations for fatigue and rutting
		62	66	378	TS, thick, 470 mm	
		63	67	383	CS, thick, 470 mm	
		56	73	416	TS, thin, 380 mm	
		47	62	356	TS, thick, 380 mm	
		57	75	426	CS, thick, 380 mm	
Christison (*6*)	SINGLE	76	83	472	Bottom AC TS	MEASURED primary response
		64	70	397	Deflection	
Christison, et al (*7*)	SINGLE	72	79	450	TS & Defl, 457 mm	LEF's(1) from average of two MEASURED primary responses
		66	79	452	TS & Defl, 419 mm	
	TANDEM	120	66	375	TS & Deflection	
Snelgrove (*8*)	SINGLE	75	82	469	Deflection	MEASURED primary response
Southgate, et al (*11*)	TANDEM	115	63	361	Strain energy	CALCULATED LEF's using work strain
	TRIDEM	200	73	417	Strain energy	
Sharp, et al (*12*)	SINGLE	59	64	367	Deflection	MEASURED primary response
	TANDEM	108	59	338	Deflection	
Huhtala, et al (*13*)	SINGLE	82	93	529	TS, thin	CALCULATED LEF's based on tensile strains
		80	90	514	TS, thick	
Bonaquist (*14*)	SINGLE	52	62	354	TS, thin	MEASURED primary response(2)
		45	53	303	TS, thick	
		60	72	409	CS subgrade, thin	
		80	96	545	CS subgrade, thick	

(1) Load Equivalent Factor
(2) Failure Observed but not basis for limits

trates the findings presented in Table 2. Following are general observations regarding the findings.

1. Theoretical and measured results, using either single primary response or load equivalency factors, show that wide-base tires cause substantially more damage to the pavement structure than conventional dual tires under all axle configurations (single, tandem, and tridem) and conditions.
2. Previous studies suggest limits for single-axle configurations ranging between 53 and 96 N/mm (300 and 550 lb/in.) of tire width (Figure 1). Limits for tandem-axle configurations range between 53 and 70 N/mm (300 to 400 lb/in.) of tire width (Figure 1). Insufficient data were found for tridem axles. Most responses are below 79 N/mm (450 lb/in.).
3. Differences were found among the various analyses (Table 2) because all limits, those based on either single primary response or load equivalency factors, presented variations of one or more of the following factors: temperature, pavement structure, tire pressure, tire type and condition (age), tire load, axle configuration, axle spacing, selected response, and load duration.
4. The summation methods used for adding peak responses under tandem and tridem axle configurations affect the comparisons between various axle spacings and load distributions.
5. With respect to mechanistic analysis, none of the reviewed studies accounts for factors such as variable material response (e.g., caused by temperature gradients), pavement response to dynamic axle load variation, and tire-pavement

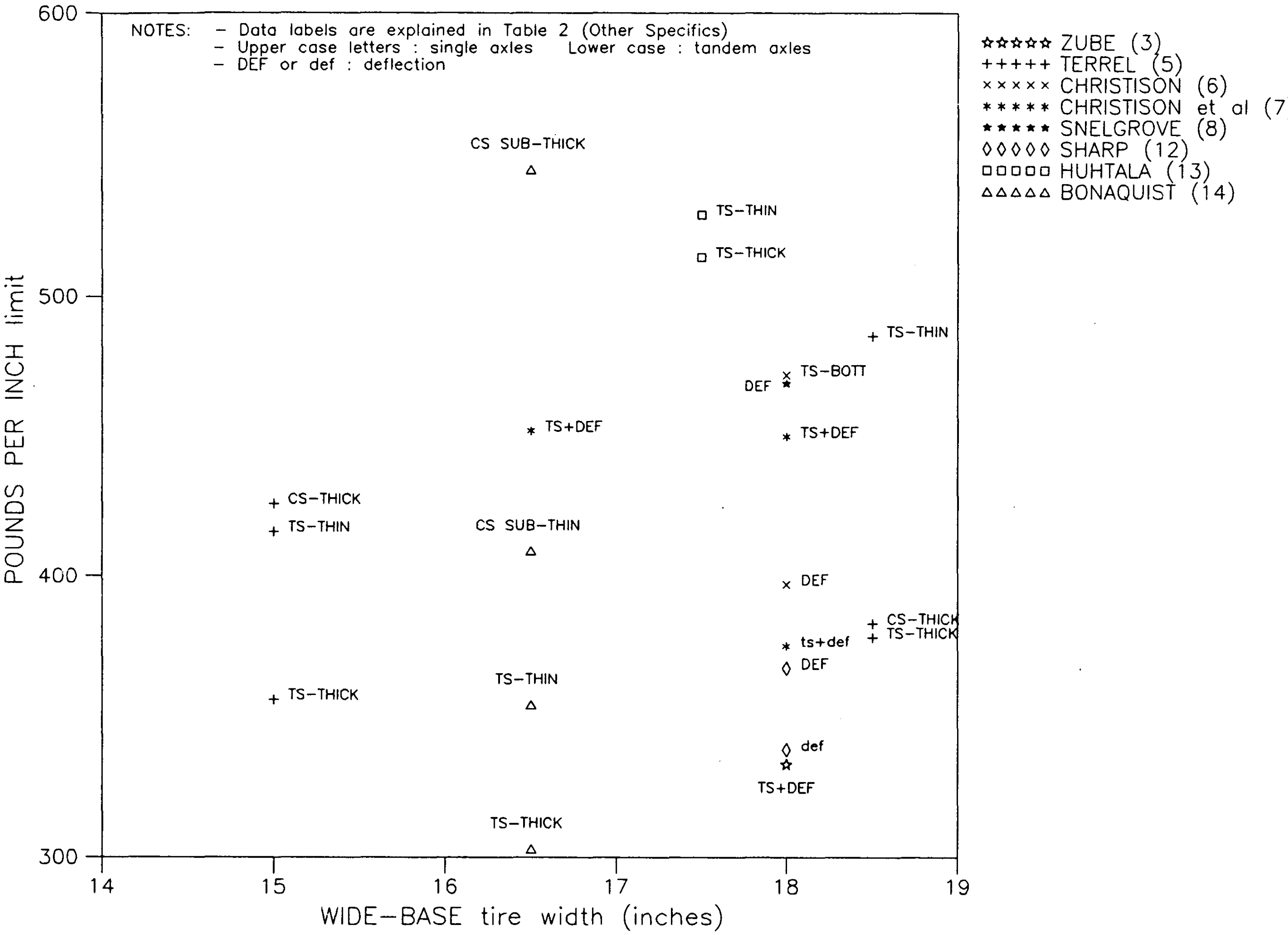

FIGURE 1 Pounds-per-inch limits based on Table 2.

interface effects. Some of these factors can be studied using the numerical method presented in this paper.

Significance

The information discussed previously suggests the need to reexamine the type of criterion or criteria by which to determine increased damage from wide-base tires. Selection of a reliable pounds-per-inch limit to protect flexible pavements is not possible using available information. In addition, the selection of a limit requires understanding the limitations of the method(s) used and augmenting or adjusting for factors that have not been adequately addressed by previous researchers. Some of these factors are mentioned in the summary section above.

Perhaps most significant is that previous studies of measured pavement response did not attempt to validate a mechanistic approach that subsequently could be used to evaluate different conditions. Conversely, other studies based on a mechanistic analysis did not validate fully their predictions by comparing primary response results with actual measurements. These facts imply a difficulty in setting a practical limit. More important, a criterion of pounds per inch may correlate weakly with other attributes of wide-base tires, such as tire construction, condition, and pressure. Such factors may contribute substantially to accelerated pavement damage.

In the following section, an analytical method is used to compare dual and wide-base tires by addressing shear effects at the pavement-tire interface, nonuniform contact pressure distributions, and temperature gradients within the surface layer.

THEORETICAL ANALYSIS

This section presents an analytical evaluation of a typical California pavement structure using a computer program (CIRCLY) (*16*) that uses multilayered elastic theory and is capable of solving cases with multiple loads, several load types (i.e., vertical and shear loading), and anisotropic material characterization. Some of these capabilities are important in the design of surface layers when conditions of high stresses and loads at the tire-pavement interface exist, as in the case of wide-base tires.

Any theoretical evaluation requires thorough experimental supporting work to validate and calibrate the analytical model. In the absence of this work, this paper intends to highlight

main factors to consider when the surface effects of wide-base tires are studied and to indicate directions for further theoretical and experimental investigation. Among the main factors are the realistic modeling of surface stresses and the explicit use of energy principles for predicting failure potential.

Analytical Model

The CIRCLY program (*16*) is capable of analyzing multilayered anisotropic media subjected to multiple circular loads. Several load conditions can be modeled, including horizontal and vertical loads, shear stresses, and moments about horizontal and vertical axes (Figure 2). All loading conditions can be simulated using polynomial-type distributions.

Each layer is assumed to be of infinite extent in the horizontal direction. The layer interfaces can be modeled to be smooth (fully frictionless) or rough (fully continuous), and the bottom layer may be assumed to have infinite or finite depth (resting on a rigid base). All layer interface planes are assumed to be horizontal, and the elasticity in each layer is homogeneous and of cross-anisotropic or isotropic symmetry. Compressive strains and stresses are denoted as positive.

Pavement Structure

The selected pavement structure, as shown in Figure 3, consists of a thick surface layer, an asphalt-treated permeable layer, an aggregate base, and a weak subgrade (*R* value around 15). All layers were assumed to be isotropic for this analysis, even though other findings (*17,18*) indicate anisotropy in some granular layers. Further investigation of this anisotropy is beyond the scope of this paper.

The surface layer was divided into sublayers to account for a temperature gradient that is reflected in the assumed mod-

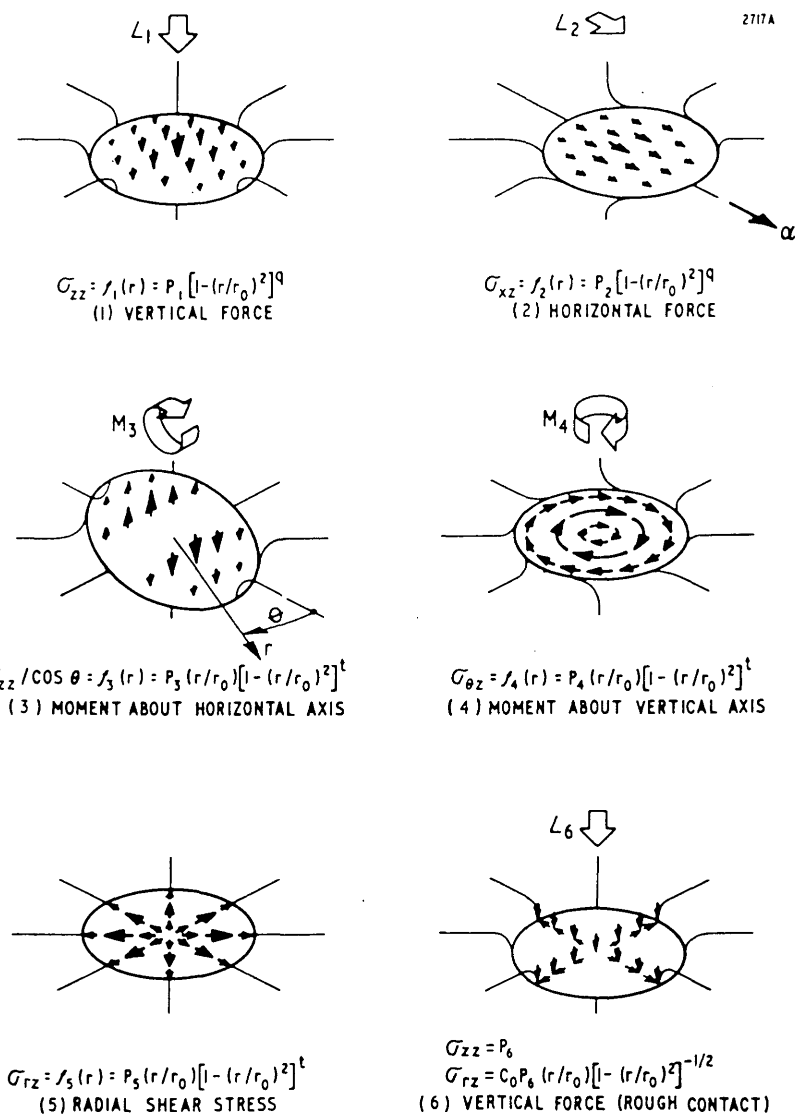

FIGURE 2 Loading types [after Wardle (*16*)].

	Thickness (mm)	Poisson's Ratio	Modulus (MPa)
DGAC	56	0.45	689
	56	0.40	827
	56	0.40	965
ATPB	76	0.35	1033
AB	427	0.35	207
SG	INF	0.40	24

FIGURE 3 Selected pavement structure.

uli. Selected moduli values attempt to represent critical day summer conditions. The section and materials are typical of Highway 99, north of Sacramento in California's Central Valley.

Loading Conditions

Two loading cases applied to the pavement structure were considered along with the effects of multiple loads. The two cases consisted of (a) nonuniform vertical stresses only and (b) nonuniform vertical stresses accompanied by nonuniform inward shear stresses. Both loading cases were assumed to be applied over circular contact areas.

The first loading case, under uniform conditions, is the most commonly assumed case in pavement analysis and design. The second loading case includes the observed and measured inward shear stresses for static and moving pneumatic tires (*19,20*) that have been ignored in most previous studies. These shear stresses develop from inward lateral tread movement caused by side-wall deflection within the contact area (*21*).

The following maximum legal axle loadings were analyzed: 89kN (20 kips) total load for the single axle, 151 kN (34 kips) total load for the tandem axle having 1.22-m (4-ft) spacing between axles, and 151 kN (34 kips) for the tridem axle having the same 1.22-m (4-ft) spacing between axles. In general, the legal axle loadings vary with axle spacing according to the California Vehicle Code (22). The typical nonuniform loading distributions used are shown in Figure 4. Evidence (*23*) in-

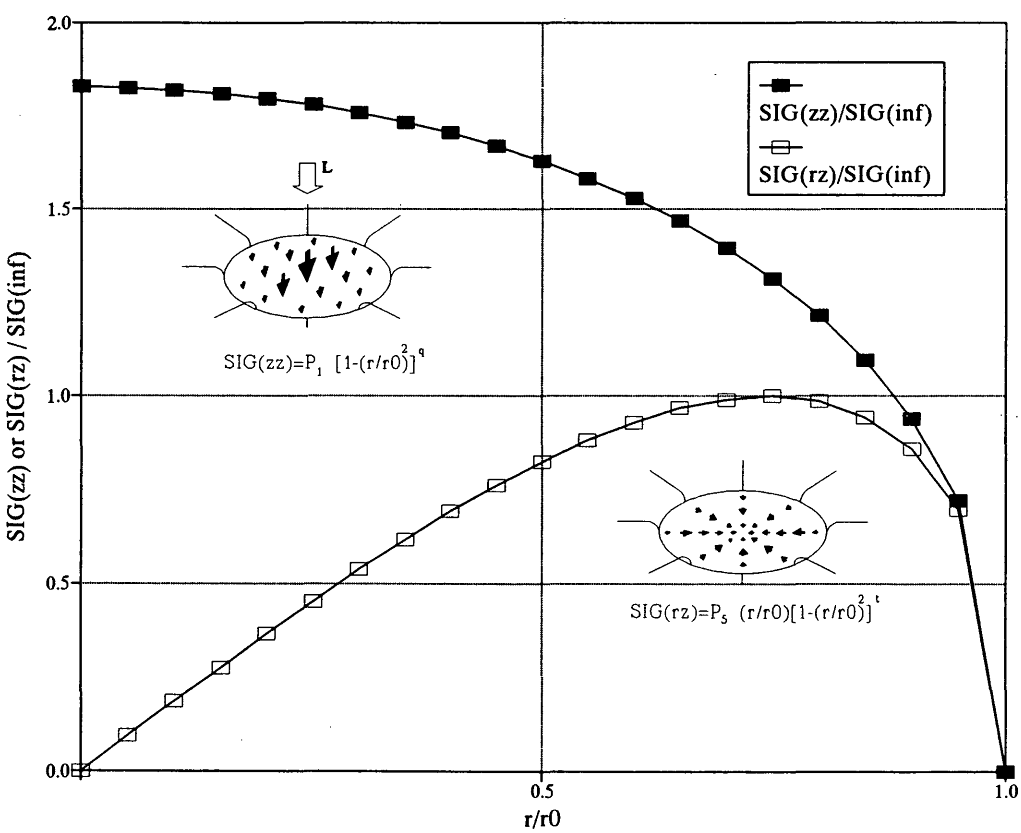

FIGURE 4 Typical nonuniform vertical and inward shear load distributions.

dicates that both vertical and shear stress distributions are parabolic in shape for the tire loadings and pressures commonly used in practice. In this analysis, the q-exponent for vertical stress distributions [Figure 2 (1)] varied between 0.15 and 0.30, whereas the t-exponent for inward shear stress distributions [Figure 2 (5)] maintained a constant value of 0.40. These values were selected on the basis of actual measured data from dual and wide-base tires (*23*).

The various radii used for all axle configurations were calculated from the following equation [derived from the parabolic vertical stress distribution equation presented in Figure 2 (1)]:

$$r_0 = \frac{L(q + 1)}{P_1 \pi}$$

where

q = parabolic exponent,
P_1 = maximum contact stress (160 psi for duals, 220 psi for wide-base),
L = resultant force on tire (varies with axle configuration), and
r_0 = calculated radius.

Performance Criteria

The selection of representative response parameters is a key factor in assessing unusual loading conditions and their effects on pavements. Surface response (top layer) is important when comparing the influence of wide-base and dual tires. This importance derives from the fact that vertical and shear forces have a significant effect at the tire-pavement interface.

This paper is limited to the evaluation of tensile strains (fatigue life determinant) and strain energies of distortion (failure criteria) within the surface layer. Tensile strains (at the bottom of the surface layer) have been linked to fatigue failure using an extended concept of Miner's hypothesis for damage (*24*). Strain energy (SE) is the work done on an element and stored within it and under elastic conditions is defined as follows (*25*):

$$\text{SE/volume} = \frac{1}{2}(\sigma_x \epsilon_x + \sigma_y \epsilon_y + \sigma_z \epsilon_z + \tau_{xy}\gamma_{xy} + \tau_{yz}\gamma_{yz} + \tau_{xz}\gamma_{xz})$$

where σ_i, τ_{ij} are elastic stress components and ϵ_i, γ_{ij} are elastic strain components. The strain energy can be divided into two parts—one caused by distortion and the other caused by volume change. The part caused by distortion, called the strain energy of distortion, has been correlated with failure conditions (*25*). Strain energy of distortion (SED) is defined as follows:

$$\text{SED/volume} = \text{SE/volume} - \frac{1 - 2\nu}{6E}(\sigma_x + \sigma_y + \sigma_z)^2$$

where ν is the Poisson's ratio and E is the elastic modulus.

Results

Figure 5 shows all the axle configurations studied. Figure 6 shows typical results from the mechanistic analysis in the form of contour plots. All the results (*26,27*) were plotted using contour lines to draw conclusions with respect to both critical (peak) values and overall trends. Tensile strains were calculated in both the longitudinal (direction of travel) and transversal directions. Units for the strain energy of distortion are given in megapascals per unit volume (cubic meters). Tables 3 through 11 summarize the results for all axle configurations.

Tire Type

The main reason for this analytical evaluation was to compare the effects of wide-base tires and dual tires under more realistic loading conditions (nonuniformity and shear). Tables 5, 8, and 11 give us good insight into this part of the analysis. Wide-base tires produced 15 to 40 percent higher critical strain values than dual tires, and 30 to 115 percent higher critical strain energy of distortion values.

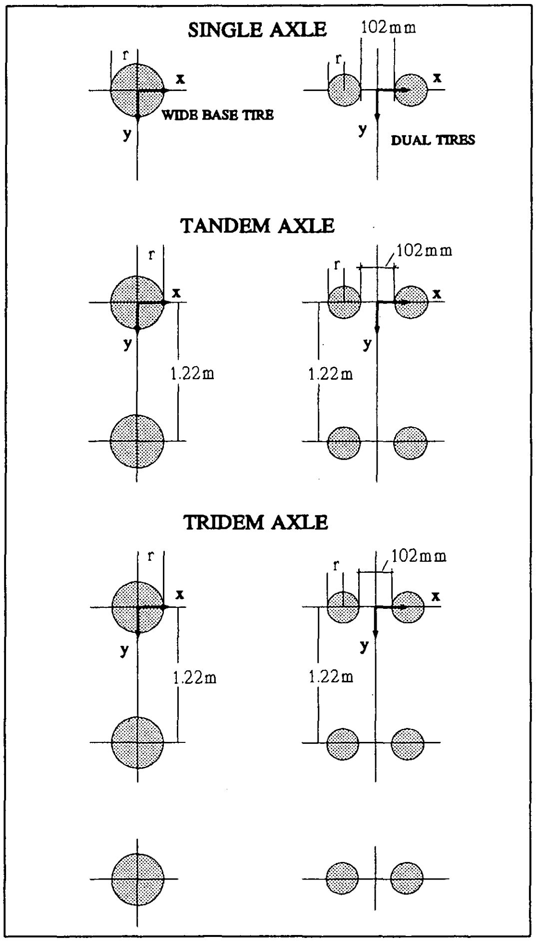

FIGURE 5 Axle configurations.

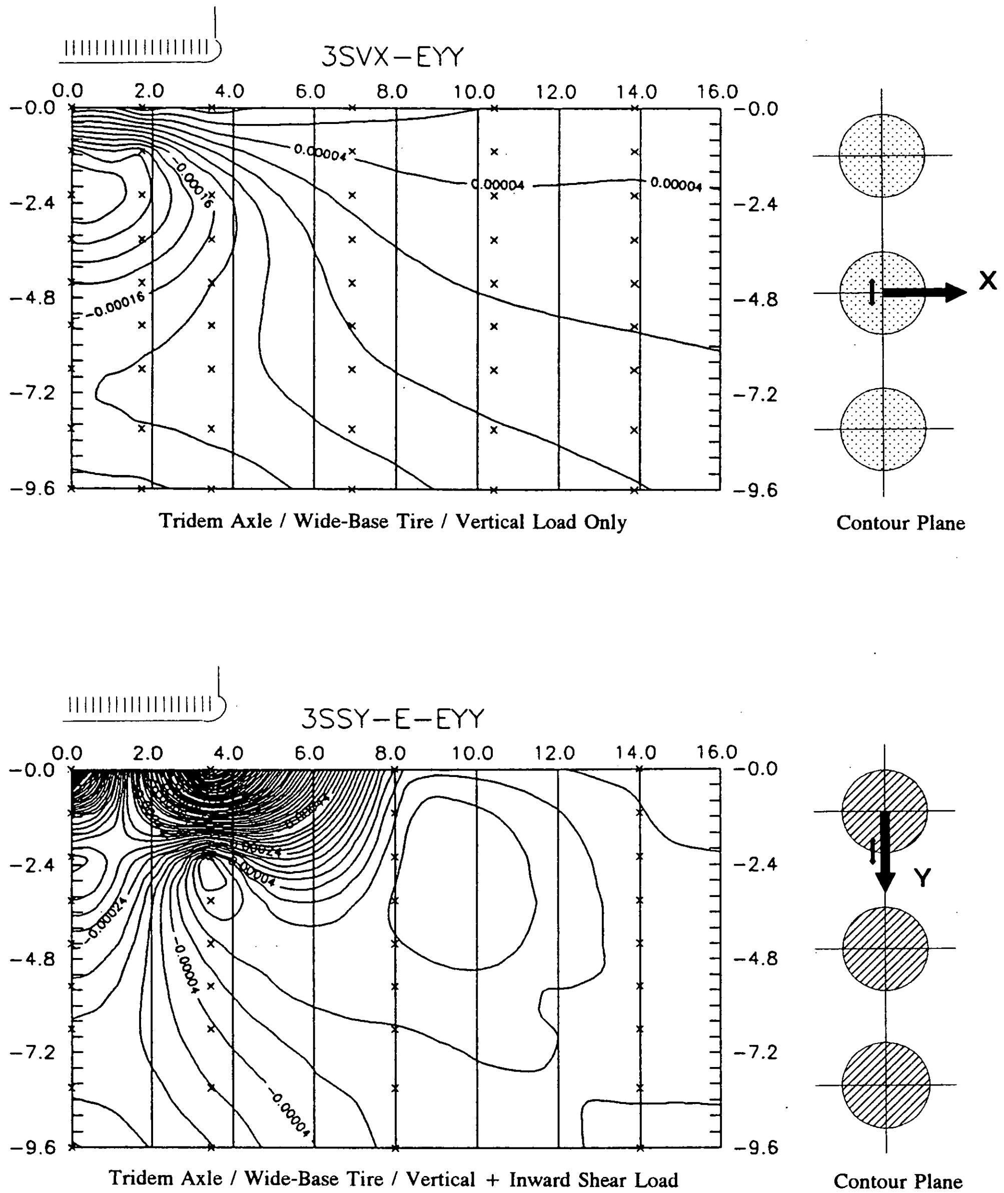

FIGURE 6 Typical contour plots. [Note: The contour plots presented are for peak tensile strains. The "contour plane" plots show planes where maximum strains occur (and directions). All values are in inches.]

Response Distribution

The typical contour plots presented in Figure 6 describe unique response distributions. Contour plots for all the cases analyzed are presented in other technical reports (*26,27*). In general, for the cases of vertical loading only, all the predicted responses (tensile strains and strain energies of distortion) present the greatest contour line variation (i.e., highest contour density) under the center of the tire for both wide-base and dual tires. In contrast, the cases of normal plus inward shear loading show the greatest contour line variation under the edges of the tire for the tensile strain and under the center of the tires for the strain energy of distortion. High contour line variations of strain energy of distortion imply potential areas where failure can originate.

Inward Shear Stresses

The presence of inward horizontal shear stresses as part of the pavement loading has a very important effect on pavement response. When inward shear loads are considered in the analysis, as they should, the critical (maximum) tensile strains for wide-base tires increase by factors between 6 and 6.7 (Tables 4, 7, and 10), depending on the axle configuration. As for dual tires, the multipliers are between 6.5 and 8.2. All these new maximum tensile stains occur on the surface of the pavement at the edges of the tires. On the other hand, the strain energies of distortion for wide-base tires increase by factors between 5.5 and 5.8 (Tables 4, 7, and 10), depending on the axle configuration. As for dual tires, the multipliers are between 8.9 and 9.2. In general, the results clearly indicate

TABLE 3 Single-Axle Critical Values

TIRE TYPE	LOADING STRESSES	MAXIMUM TENSILE STRAIN (ϵ_{xx} or ϵ_{yy} in microstrains)	MAXIMUM SED [1] (MPa/m^3)	LOCATION OF MAXIMA (x,y,z)[2] in mm	
				ϵ_{xx} or ϵ_{yy}	SED
WB tire	Vertical only	-320 ($\epsilon_{xx}/\epsilon_{yy}$)	24	0,0,-56	0,0,-56
	Vertical plus shear	-2140 (ϵ_{xx})	132	r[3],0,0	0,0,0
Dual tires	Vertical only	-230 (ϵ_{yy})	11	50+r,0,-56	50+r,0,-56
	Vertical plus shear	-1880 (ϵ_{xx})	102	50+2r,0,0	50+r,0,0

(1) SED is strain energy of distortion
(2) See Figure 5 for location convention
(3) r = radius of tire (in mm)

TABLE 4 Ratios of Maxima: Constant Tire Type

TIRE TYPE	ϵ_{max} for (VERT+SHEAR) / ϵ_{max} for (VERT only)	SED_{max} for (VERT+SHEAR) / SED_{max} for (VERT only)
WB tire	6.7	5.5
Dual tires	8.2	9.2

Note: WB is Wide Base

TABLE 5 Ratios of Maxima: Constant Loading Stress

LOADING STRESSES	WB ϵ_{max} / DUAL ϵ_{max}	WB SED_{max} / DUAL SED_{max}
Vertical only	1.4	2.15
Vertical plus shear	1.15	1.3

Note: WB is Wide Base tires, DUAL is Dual tires

that ignoring the shear stress effects leads to overestimating the life of the surface layers under actual conditions of contact stresses, regardless of the failure criterion being used (critical tensile strain or strain energy of distortion).

Another important observation is that primary response (tensile strain) and strain energy equivalencies between wide-base and dual tires are lower when inward shear stresses are considered (Tables 5, 8, and 11). This observation has direct implications in the analysis of fatigue load equivalency factors (power ratios of peak tensile strains) and it should be further investigated before any final conclusions are made.

Temperature Gradient

Consideration of a temperature gradient has a significant effect on predicted pavement response. The location of the critical tensile strains and strain energies of distortion is partly associated with the fact that the three surface sublayers have different modulus values. In all cases, the peak response values shifted in location to either the surface of the structure or within the first sublayer (Tables 3, 6, and 9). This finding may be relevant in explaining some actual observed surface distresses (*28*, *29*).

TABLE 6 Tandem-Axle Critical Values

TIRE TYPE	LOADING STRESSES	MAXIMUM TENSILE STRAIN (ϵ_{xx} or ϵ_{yy} in microstrains)	MAXIMUM SED [(1)] (MPa/m^3)	LOCATION OF MAXIMA (x,y,z)[(2)] in mm	
				ϵ_{xx} or ϵ_{yy}	SED
WB tire	Vertical only	-340 ($\epsilon_{xx}/\epsilon_{yy}$)	22	0,0,-56	0,0,-56
	Vertical plus shear	-2110 (ϵ_{xx})	129	r[(3)],0,0	0,0,0
Dual tires	Vertical only	-250 (ϵ_{yy})	11	50+r,0,-56	50+r,0,-56
	Vertical plus shear	-1870 (ϵ_{xx})	101	50+2r,0,0	50+r,0,0

(1) SED is strain energy of distortion
(2) See Figure 5 for location convention
(3) r = radius of tire (in mm)

TABLE 7 Ratios of Maxima: Constant Tire Type

TIRE TYPE	ϵ_{max} for (VERT+SHEAR) / ϵ_{max} for (VERT only)	SED$_{max}$ for (VERT+SHEAR) / SED$_{max}$ for (VERT only)
WB tire	6.2	5.8
Dual tires	7.5	8.9

Note: WB is Wide Base

TABLE 8 Ratios of Maxima: Constant Loading Stress

LOADING STRESSES	WB ϵ_{max} / DUAL ϵ_{max}	WB SED$_{max}$ / DUAL SED$_{max}$
Vertical only	1.4	2
Vertical plus shear	1.15	1.3

Note: WB is Wide Base tires, DUAL is Dual tires

Axle Configurations

Comparisons are possible among all axle configurations from the results presented in Tables 3, 6, and 9. In general, similar critical tensile strains occur for both tire types (duals and wide-base) among all axle configurations, being slightly higher for the tridem axle case. The critical strain energies of distortion are also similar for all axle configurations, being slightly higher for the single-axle case.

In all cases, the ratios of maxima presented in Tables 3 through 11 are similar under all axle configurations, being slightly higher for the single axle.

An important observation was made regarding the predicted peak responses (tensile strains and strain energies of distortion) for the tridem axle configuration. Peak response locations change (center or extreme tire), and sometimes peak tensile strain directions (x or y) as well (*27*), when inward shear stresses are present. Experimental work is needed to

TABLE 9 Tridem-Axle Critical Values

TIRE TYPE	LOADING STRESSES	MAXIMUM TENSILE STRAIN (ϵ_{xx} or ϵ_{yy} in microstrains)	MAXIMUM SED [(1)] (MPa/m³)	LOCATION OF MAXIMA (x,y,z)[(2)] in mm	
				ϵ_{xx} or ϵ_{yy}	SED
WB tire	Vertical only	-360 (ϵ_{yy})	22	0,1220,-56	0,0,-56
	Vertical plus shear	-2190 (ϵ_{yy})	123	0,r[(3)],0	0,1220,0
Dual tires	Vertical only	-290 (ϵ_{yy})	11	50+r,1220,-38	50+r,0,-38
	Vertical plus shear	-1900 (ϵ_{xx})	97	50+2r,0,0	50+r,1220,0

(1) SED is Strain Energy of Distortion
(2) See Figure 5 for location convention
(3) r = radius of tire

TABLE 10 Ratios of Maxima: Constant Tire Type

TIRE TYPE	ϵ_{max} for (VERT+SHEAR) / ϵ_{max} for (VERT only)	SED_{max} for (VERT+SHEAR) / SED_{max} for (VERT only)
WB tire	6	5.5
Dual tires	6.5	9

Note: WB is Wide Base

TABLE 11 Ratios of Maxima: Constant Loading Stress

LOADING STRESSES	WB ϵ_{max} / DUAL ϵ_{max}	WB SED_{max} / DUAL SED_{max}
Vertical only	1.25	2
Vertical plus shear	1.15	1.3

Note: WB is Wide Base tires, DUAL is Dual tires

carefully address and analyze this finding. The analysis of damage accumulation models for tridem axle configurations is another issue that merits further investigation. This paper, however, concentrated only on the analysis of primary responses.

CONCLUSIONS

1. On the basis of the literature review, a definitive tire load limit (pounds per inch) does not exist that will enable one to reliably predict the pavement effects from wide-base tires compared with dual tires under any axle configuration. Despite this, the data show that if a tire load limit is required for wide-base tires it should be substantially less than values that are typical for dual tires. A limit greater than 88 N/mm (500 lb/in.) is not justified using available literature cited in this study. Limits between 60 and 80 N/mm (350 and 450 lb/in.) are justifiable on the basis of published investigations.

2. Previous studies assume simple and incomplete loading conditions that differ from actual circumstances. The mechanistic analysis in this paper shows that the effects of these simplifications significantly alter the predicted pavement response. Future mechanistic evaluations should continue to

simulate the nonuniform vertical and inward shear loadings exerted by tires on the pavement. Laboratory and field measurements should verify the influence of these factors.

3. The mechanistic analysis presented in this paper shows that peak tensile strains may occur in a more shallow part of the surface layer. This finding derives from the use of sublayers for modeling temperature gradients and from the inclusion of inward shear contact stresses. In addition, the use of strain energy of distortion to characterize failure potential leads to substantial differences among the conditions studied. Future studies should expand the use of sublayers to predict spatial distribution and critical values of both strain and strain energy.

4. The study of anisotropy is another subject that demands further attention, as well as specific loading conditions such as braking and turning stresses. CIRCLY can model such cases, being a unique characteristic of this analytical tool.

5. Further investigations should be focused on specific pavement response in well-designed and controlled experiments. These efforts will help establish a sound scientific basis for predicting the pavement effects from wide-base tires. Related research is part of an on-going project conducted by the Caltrans Division of New Technology, Materials, and Research, and other researchers at the PACCAR (parent company of Kenworth Trucking Company) test track in Washington State.

ACKNOWLEDGMENT

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