1-36 ORIGINAL

# Determination of Pavement Damage From Super-Single and Singled-out Dual Truck Tires

## PRELIMINARY DRAFT
## INTERIM REPORT

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# CHAPTER 1

# INTRODUCTION

The use of "super-single" tires and the practice of removing one tire from a conventional dual tire configuration, known as "singled-out dual" tires, have increased in recent years, primarily because of their favorable effects on a truck's tare weight and rolling resistance. In comparison to trucks equipped with conventional dual-tire configurations, trucks equipped with such single-tire configurations allow a higher pay load and increased fuel efficiency. However, single-tire configurations have different tire widths, pressures, and footprint dimensions than do conventional dual tires.

Research has been performed on the effects of super-single and singled-out dual tire configurations on pavement performance and damage. Although this research has shown that pavement deflections caused by single-tire configurations were higher than those caused by conventional dual-tire configurations, it has not provided clear conclusions concerning the extent of pavement damage or the measures needed to limit such damage. Further research is needed to address the effects of using single-tire configurations on pavement damage and to identify possible approaches for controlling pavement damage that will yield reduced life-cycle costs, improved ride quality, and other economic and environmental benefits.

The primary objective of the research is to develop a procedure to estimate pavement damage associated with the use of single-tire configurations compared with that of conventional dual-tire configurations. The research will also seek to identify technical and regulatory approaches for controlling pavement damage from single-tire use on both flexible and rigid pavements.

# CHAPTER 2

# LITERATURE REVIEW

## SINGLE TIRES DAMAGE ON FLEXIBLE PAVEMENTS

Numerous studies have been conducted to evaluate flexible pavement damages due to super-single and singled-out tires. Some studies used theoretical analyses while others conducted field experiments to evaluate the relative pavement damage caused by single tires as compared to dual tires configurations. In order to facilitate the review and summary process, the identified studies were grouped into four different categories based on the procedure that they used to evaluate the relative damage: a) theoretical-response, b) theoretical-performance, c) experimental-response, and d) experimental-performance.

Prior to presenting the methodologies and findings of the various studies, it would be beneficial to define certain common terminology which will be used throughout the report.

Tire Configuration:

a. Dual tires:a set of two tires fitted to each side of an axle in a dual wheel configuration.

b. Singled-out tire: one of the dual tires has been removed and one tire is left on each side of the axle.

c. Super-single tire: a wider tire than the conventional dual tire that is fitted on each side of an axle in a single wheel configuration.

At various occasions, the report may refer to the singled-out and super-single tires simply as "single tires," except when a direct comparison between the two types of tires is being presented.

Tire Size:

The following convention is used to identify tire sizes:

Dual and singled-out tires: 11R22.5

Width of tire (in)    Radial    Inner diameter of tire (in)

****The same convention is used for bias tires except that the R is eliminated****

Super-single tires: 425/65R22.5

Width of tire (mm)    aspect ratio: height/width    Inner diameter of tire (in)

Pavement Performance:

Fatigue: alligator cracking of the pavement surface.

Rutting: permanent deformation in the wheel tracks.

Roughness: Waviness of the pavement surface.

## Theoretical-Response

This group of studies used theoretical analyses to evaluate pavement responses under single and dual tires configurations. The calculated pavement responses were then used to evaluate the relative pavement damage caused by single tires as compared to dual tires. For example, the multi-layer elastic theory is used to calculate tensile strain at the bottom of the asphalt concrete (AC) layer under single and dual tires configurations. The relative pavement damage caused by single tires as compared to dual tires is then calculated as the ratio of the strains calculated under the single tires over the strains under dual tires. Only one study was identified under this category which is summarized below.

Perdomo and Nokes (1) used the multi-layer elastic theory with surface shear stresses to evaluate the impact of super-single tires on flexible pavements. Two loading cases were considered: (1) Non-uniform vertical stress, (2) Non-uniform vertical stress with non-uniform inward surface shear stress. The pavement section analyzed had a 168 mm (6.6") dense graded AC layer, 76 mm (3") asphalt base, and 427 mm (16.8") aggregate base. The evaluated axle loads consisted of 89 kN (20 kips) for single axle, 151 kN (34 kips) for tandem axle, and 151 kN (34 kips) for tridem axle. The tensile strains and strain energy of distortion at the bottom of the AC layer were used as the pavement response parameters. The strain energy (SED) of distortion was evaluated through the following equation:

$$\text{SED/volume} = 1/2(\sigma_x\,\epsilon_x+\sigma_y\epsilon_y+\sigma_z\epsilon_z + \tau_{xy}\gamma_{\kappa y} + \tau_{yz}\gamma_{yz} + \tau_{xz}\gamma_{xz})\text{-}[(1\text{-}2\nu)/6E\ [(\sigma_x+\sigma_y+\sigma_z)^2]]$$

Tables 1, 2, and 3 give the values of critical tensile strains and strain energy of distortion for the two loading conditions on single, tandem, and tridem axles respectively. This study concluded that the critical tensile strain and strain energy of distortion are higher under super-single tires than dual tires. Also the inclusion of the surface shear stresses significantly increased the magnitude of both the tensile strain and strain energy of distortion. The study, however, failed to relate the strain energy of distortion to any mode of pavement failure.

**Theoretical-Performance:**

This category used theoretical analyses to evaluate pavement responses under single and dual tires configurations and used the calculated responses in performance prediction models to evaluate the relative damage caused by single tires as compared to dual tires. For example, the multi-layer elastic theory is used to calculate the tensile strains while a fatigue performance model is used to calculate the number of load repetitions to fatigue failure. The following represents a summary of the studies that fit under this category.

Deacon (2) derived theoretical load equivalency factors based on the strain at the bottom of the AC layer using the multi-layer elastic theory. A variety of axles, tire configurations, and pavement structures were analyzed with circular tire contact area and uniform contact pressure. Load equivalencies

Table 1: Pavement responses under 89 kN single axle load. (1)

| Tire Type | Loading Stresses | Max. Tensile Strain | Max SED |
|---|---|---|---|
| Super single Tire | Vertical only | -320 | 24 |
| | Vertical + Shear | -2140 | 132 |
| Dual Tires | Vertical only | -230 | 11 |
| | Vertical + Shear | -1880 | 102 |

Table 2: Pavement responses under 151 kN tandem axle load. (1)

| Tire Type | Loading Stresses | Max. Tensile Strain | Max SED |
|---|---|---|---|
| Super single Tire | Vertical only | -340 | 22 |
| | Vertical + Shear | -2110 | 129 |
| Dual Tires | Vertical only | -250 | 11 |
| | Vertical + Shear | -1870 | 101 |

Table 3: Pavement responses under 151 kN tridem axle load. (3)

| Tire Type | Loading Stresses | Max. Tensile Strain | Max SED |
|---|---|---|---|
| Super single Tire | Vertical only | -360 | 22 |
| | Vertical + Shear | -2190 | 123 |
| Dual Tires | Vertical only | -290 | 11 |
| | Vertical + Shear | -1900 | 97 |

$F_i$ were derived as a function of the exponential strain ratios. The exponential represents the conversion from strains into fatigue life.

$$Fi = [\epsilon_i / \epsilon_b]^{5.5}$$

where, $\epsilon_i$ and $\epsilon_b$ are the calculated tensile strains at the bottom of AC layer under the load in question and the reference load of 80 kN (18,000 lb) on a single axle with dual tires, respectively. Figure 1 shows a summary of the results in terms of the pavement structure number (SN). The SN is based on the definition of the AASHTO Design of Pavement Structures. It can be seen that an 80 kN (18,000 lb) single axle load on dual tires is equivalent to a 52-64 kN, (11,700-14,400 lb) axle load on singled-out tires depending on the pavement structure. The equivalent load on a singled-out tired axle becomes smaller as the SN value decreases which indicates that singled-out tires are more damaging on weaker and/or thinner pavement structures. For example, an 80 kN (18,000 lb) single axle load with dual tires is equivalent to a single axle load of 52 kN (11,700 lb) and 64kN (14,400 lb) with singled-out tires on pavements with SN value of 2 and 6, respectively.

Southgate and Deen (3) presented a theoretical study to evaluate the effects of load distribution, axle type, and tire configuration on the fatigue of flexible pavements. They used the strain energy concept which they defined as the work done internally by the body and is equal and opposite in direction to work done upon the body by an external force. The multi-layer elastic solution was used to compute the work strain. Different tire loads were analyzed ranging from 24.5 kN (5.5 kips) to 42.3 kN (9.5 kips). The tire pressures investigated in this study were 552 kPa (80 psi), 793 kPa (115 psi), 1030 kPa (150 psi), and 1380 kPa (200 psi). The calculated work strains were then used to evaluate the number of load repetitions to fatigue failure through the following equation.

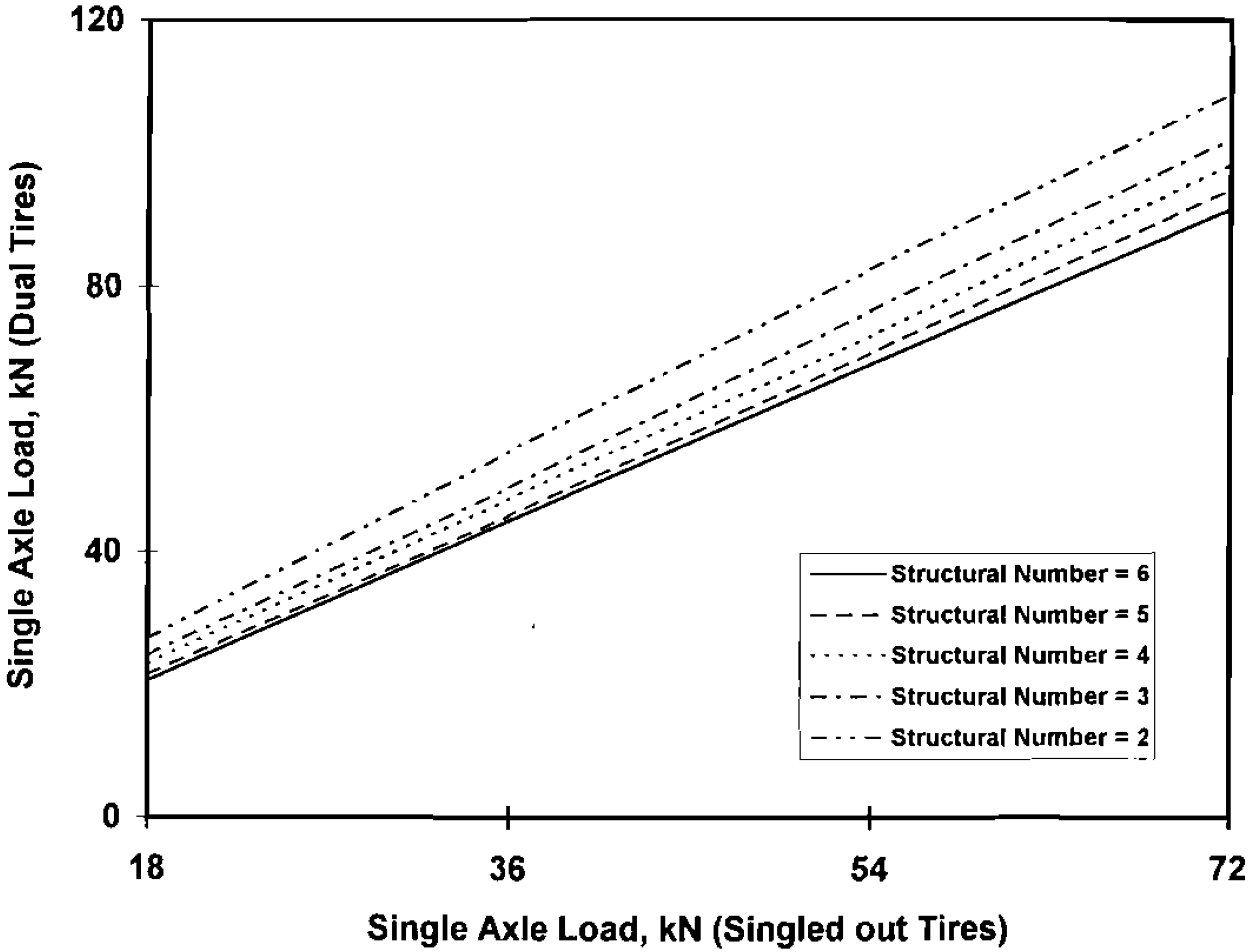

Figure 1. Equivalent single axle loads when using singled-out tires. (2)

$$\log(N) = -6.4636 \log(e_w) - 17.3081$$

where: $e_w$ is the work strain.

The damage factors were evaluated as the ratio of the number of load repetitions to failure under the standard 80 kN (18,000 lb) single axle load with dual tires over the number of repetitions of the axle and tire configurations in question. Figure 2 compares damage factors for tandem and tridem axles using super-single and dual tires configurations. The results from this study indicated that super-single tires are more damaging to flexible pavements than dual tires. However, the damage factors approached equality at higher loads of 222 kN (50 kips) for tandem axle and 311 kN (70 kips) for tridem axles. These load levels are above the legal load limits throughout the U.S.

Hallin et al (4) used the tensile strain at the bottom of the AC layer to evaluate the impact of tires configurations on flexible pavements. A nonlinear multi-layer elastic solution was used to model the response of flexible pavements. Different axle loads were analyzed ranging from 44.5 kN to 180 kN (10 kips to 40 kips) with tire widths of 254 mm, 381 mm, 457 mm (10", 15", and 18"). Different pavement sections were included in the analysis: 76 mm, 152 mm, and 241 mm (3", 6", and 9.5") of asphalt concrete over 203 mm (8") of crushed aggregate base. The relative damage was assessed using equivalency factors. The load equivalency factors were calculated according to the following equation:

$$\text{Equivalency Factor} = N_{18} / N_i$$

where $N_{18}$ is the number of load repetitions to fatigue failure for 80 kN (18 kip) single axle load with dual tires and $N_i$ is the number of load repetitions to fatigue failure for the axle load/tire configuration being evaluated. The number of load repetitions was calculated according to the following equation:

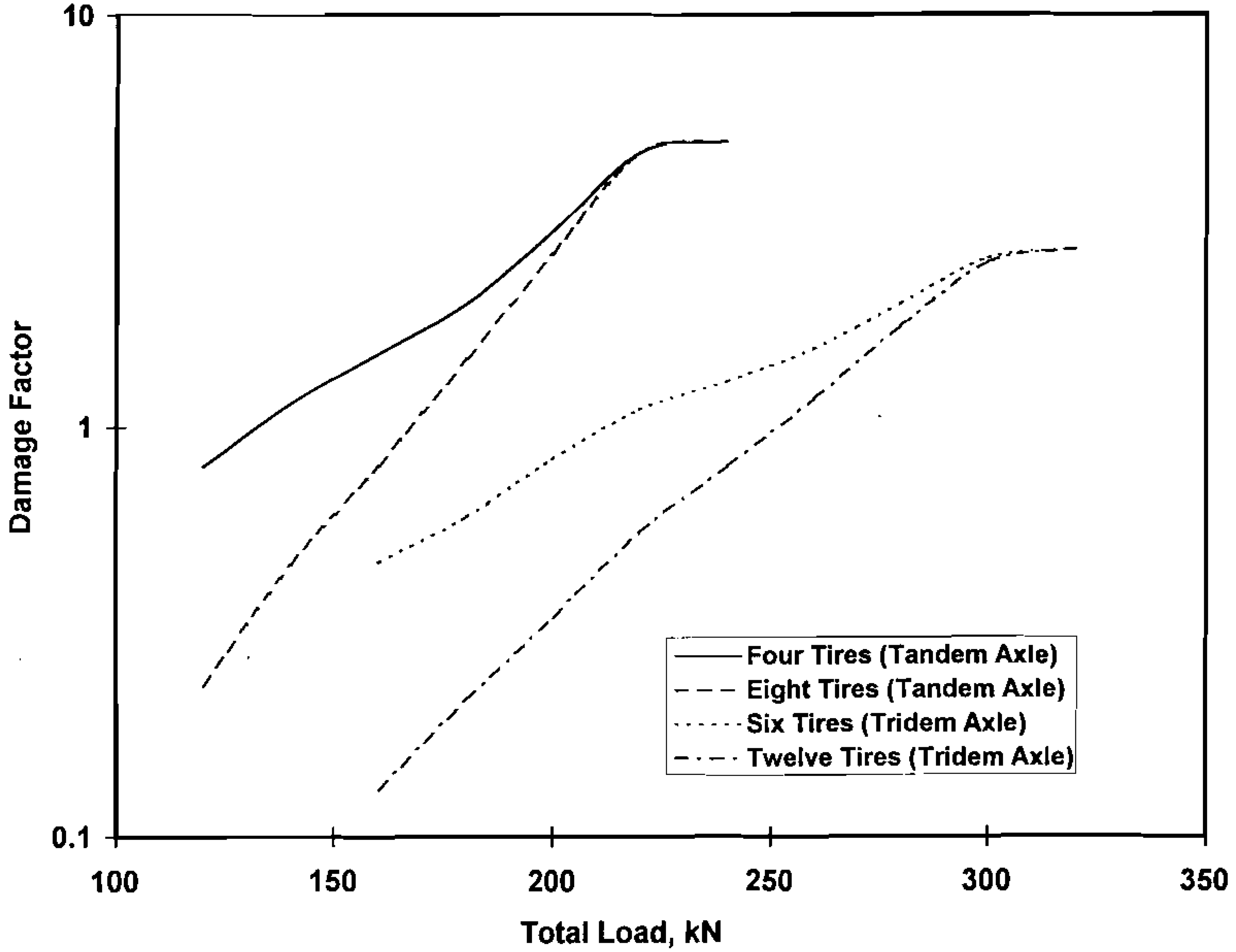

Figure 2. Pavement damage created by single tires as compared to dual tires. (3)

$$\log N_f = 15.947 - 3.291 \log (\epsilon) - 0.854 \log (E/10^3)$$

where $\epsilon$ is the tensile strain at the bottom of the asphalt concrete layer and E is the resilient modulus of the asphalt concrete layer. Table 4 summarizes a typical set of the equivalency factors for single axles with single tires, for an asphalt concrete pavement with a structural number of 4.

This study concluded that, for the same axle load, as the width of the single tire decreases, the equivalency factor increases which indicates more damage. As the axle load increases, the equivalency factor also increases. The data from this study showed that single tires can be as much as 25 times more damaging than dual tires as the axle load increases and the tire width decreases.

Bell and Randhawa (5) used the multi-layer elastic theory to evaluate the effects of singled-out tires on pavement damage. Three different types of trucks were studied 3-S2, 3-S3, and 2-S1-2. Two sets of pavement thicknesses were analyzed. Thick section with 178 mm (7") asphalt concrete over 305 mm (12") granular base and thin section with 89 mm (3.5") asphalt concrete over 305 mm (12") granular base.

Equivalency factors were used to assess the relative damage. The equivalency factors were calculated by dividing the fatigue and rutting lives produced by the application of a standard 80 kN (18,000 lb) by the lives produced by the axle under consideration. The following equation was used to estimate the number of load applications to fatigue failure (N) associated with each level of calculated tensile strain ($\epsilon_t$).

$$N = 18.4 (C) (0.00432 \times \epsilon_t^{-3.29} \times E^{-0.854})$$

Table 4: Equivalency factors For single axles with single tires and SN = 4. (4)

| Equivalent 80 kN Dual Tire, Single Axle Loads | | | | | |
|---|---|---|---|---|---|
| Axle Load (kN) | Single Tire Width (mm) | | | | |
| | 254 | 305 | 356 | 406 | 457 |
| 44.5 | 0.631 | 0.479 | 0.373 | 0.297 | 0.241 |
| 53.4 | 1.029 | 0.781 | 0.608 | 0.484 | 0.392 |
| 62.3 | 1.555 | 1.181 | 0.919 | 0.732 | 0.593 |
| 71.2 | 2.224 | 1.689 | 1.315 | 1.047 | 0.848 |
| 80.1 | 3.050 | 2.316 | 1.804 | 1.435 | 1.163 |
| 89.0 | 4.046 | 3.072 | 2.393 | 1.904 | 1.542 |
| 97.9 | 5.223 | 3.966 | 3.089 | 2.458 | 1.991 |
| 106.8 | 6.596 | 5.001 | 3.901 | 3.104 | 2.515 |
| 115.7 | 8.175 | 6.206 | 4.834 | 3.847 | 3.116 |
| 124.6 | 9.972 | 7.571 | 5.897 | 4.692 | 3.801 |
| 133.4 | 11.998 | 9.109 | 7.096 | 5.646 | 4.573 |
| 142.3 | 14.264 | 10.829 | 8.435 | 6.712 | 5.438 |
| 151.2 | 16.782 | 12.741 | 9.924 | 7.897 | 6.397 |
| 160.1 | 19.561 | 14.851 | 11.568 | 9.205 | 7.457 |
| 169.0 | 22.612 | 17.167 | 13.372 | 10.640 | 8.620 |
| 177.9 | 25.946 | 19.698 | 15.343 | 12.209 | 9.891 |

where:

C reflects the mix components: $C = 10^M$

$M = 4.84 (A - 0.69)$

$A = V_b/(V_v + V_b)$

$V_b$ = Volume of Asphalt

$V_v$ = Volume of Air

The following equation was used to estimate the number of load repetitions to rutting failure (N) associated with each level of compressive strain ($\epsilon_c$).

$$N = 1.36 \times 10^{-9} \times \epsilon_c^{-4.48}$$

$\epsilon_t$, $\epsilon_c$ and E represent the tensile strain at the bottom of the AC layer, the compressive strain on top of the subgrade and the resilient modulus of the AC layer, repsectively.

Tables 5 and 6 show the equivalency factors for fatigue and rutting for thick and thin pavements. The data showed that the load/tire has the most significant impact on the fatigue damage while the total axle load has the most significant impact on the rutting damage. The data showed that singled-out tires can cause as high as 100% more damage than dual tires. Also the location of the singled-out axles within the axle group significantly imapct the magnitude of the damage.

Gillipsie et al (6) used analytical methods to analyze the mechanics of vehicle-pavement interaction and to evaluate pavement damage. This study used VESYS-DYN to compute the primary responses of flexible pavement structures to applied tire loads. The program handles elastic and viscoelastic analysis of any number of pavement layers. Several thicknesses of the AC layer were analyzed. The evaluated tires included: conventional 11R22.5, low profile 215/75R17.5, low profile

Table 5. Equivalency factors For thin pavement. (5)

| Case | Axle Group | Axle Load kN | Load/Tire kN | Tire Pressure (kPa) | LEF Fatigue | LEF Rut |
|---|---|---|---|---|---|---|
| 1 | Single Axle (4 tires) | 80 | 20 | 703 | 1.00 | 1.00 |
| 2 | Tandem Axle (8 tires) | 151 | 18.9 | 703 | 0.87 | 0.72 |
| 3 | Tandem Axle (6 tires) one axle singled out | 151 | 25.2 | 703 | 1.66 | 2.64 |
| 4 | Tandem axle 4 tires (both axles singled out) | 117 | 29.4 | 724 | 1.25 | 0.63 |
| 5 | Tridem axle (12 tires) | 187 | 15.6 | 703 | 0.57 | 0.30 |
| 6 | Tridem axle (10 tires) one axle singled out (mid axle) | 187 | 18.7 | 703 | 0.86 | 0.70 |
| 7 | Tridem axle (10 tires) one axle singled out (outer axle) | 187 | 18.7 | 703 | 0.85 | 0.69 |
| 8 | Tridem axle (8 tires) two axles singled out (outer axles) | 187 | 23.4 | 703 | 1.37 | 1.86 |
| 9 | Tridem axle (8 tires) two axles singled out (outer and inside axles) | 187 | 23.4 | 703 | 1.34 | 1.82 |
| 10 | Tridem axle (6 tires) three axles singled out | 176 | 29.4 | 724 | 1.26 | 0.63 |
| 11 | Tridem axle (6 tires) three axles singled out | 187 | 31.1 | 724 | 1.40 | 0.82 |

Table 6. Equivalency Factors for thick pavement. (5)

| Case | Axle Group | Axle Load kN | Load/Tire kN | Tire Pressure (kPa) | LEF Fatigue | LEF Rutting |
|---|---|---|---|---|---|---|
| 1 | Single Axle (4 tires) | 80 | 20 | 703 | 1.00 | 1.00 |
| 2 | Tandem Axle (8 tires) | 151 | 18.9 | 703 | 0.63 | 0.83 |
| 3 | Tandem Axle (6 tires) one axle singled out | 151 | 25.2 | 703 | 1.72 | 2.87 |
| 4 | Tandem axle 4 tires (both axles singled out) | 117 | 29.4 | 724 | 1.02 | 0.37 |
| 5 | Tridem axle (12 tires) | 187 | 15.6 | 703 | 0.33 | 0.38 |
| 6 | Tridem axle (10 tires) one axle singled out (mid axle) | 187 | 18.7 | 703 | 0.66 | 0.72 |
| 7 | Tridem axle (10 tires) one axle singled out (outer axle) | 187 | 18.7 | 703 | 0.58 | 0.82 |
| 8 | Tridem axle (8 tires) two axles singled out (outer axles) | 187 | 23.4 | 703 | 1.33 | 1.99 |
| 9 | Tridem axle (8 tires) two axles singled out (outer and inside axles) | 187 | 23.4 | 703 | 1.16 | 2.12 |
| 10 | Tridem axle (6 tires) three axles singled out | 176 | 29.4 | 724 | 1.14 | 0.40 |
| 11 | Tridem axle (6 tires) three axles singled out | 187 | 31.1 | 724 | 1.33 | 0.52 |

245/75R19.5, super-single 15R22.5, and super-single 18R22.5. The 11R22.5, 15R22.5, and 18R22.5 were considered to represent the nominal sizes required to carry front axle loads of 53, 71, and 89 kN (12,000, 16,000, and 20,000 lb), respectively, in a single tire configuration. The 11R22.5 was also suited for dual tire applications on 89 kN (20,000 lb) single axle and 151 kN (34,000 lb) tandem axles. The 15R22.5 was selected as the tire size typically used on axles intended to carry 71 kN (16,000 lb) and the 18R22.5 was selected for axles rated at 89 kN (20,000 lb). The tire inflation pressure varied between 517 kPa and 827 kPa (75 and 120 psi).

The horizontal tensile strain at the bottom of the AC layer was used as an indicator of fatigue cracking. The vertical compressive strains on top of each layer were used as indicators of rutting. The relative damage was assessed using the equivalency factors approach. The equivalency factors for fatigue damage were defined as the ratio of number of passes of an 80 kN (18-kip) single axle fitted with dual tires 11R22.5 required to consume the same amount of fatigue life in the AC layer as an axle with single tires at their rated load. Table 7 shows the equivalency factors for low profile duals and single tires over a range of tire sizes.

The study also developed rut depth equivalency factors which are defined as the ratio of the number of passes of an 80 kN (18 kip) axle fitted with dual tires required to cause the same rut depth as an axle with singled-out or super-single tires. Tables 8 and 9 show the equivalence factors for a range of AC thickness and two pavement surface temperatures.

The data show that single tires are more damaging than dual tires. However, the damage created by single tires increases as the thickness of the AC layer increases. The increase in the equivalency factors as a function of the AC layer thickness is the most

Table 7. Fatigue equivalency factors for various sizes of tires (6).

| AC Thickness mm | LP Duals 215/75R17.5 Axle Load 76 kN | 11R22.5 Axle Load 53 kN | 15R22.5 Axle Load 71 kN | 18R22.5 Axle Load 89 kN |
|---|---|---|---|---|
| 51 | 1.95 | 1.81 | 0.81 | 0.51 |
| 76 | 1.61 | 1.81 | 1.23 | 0.95 |
| 102 | 1.29 | 1.67 | 1.52 | 1.43 |
| 127 | 1.17 | 1.44 | 1.67 | 1.86 |
| 165 | 1.04 | 1.13 | 1.7 | 2.28 |

Table 8. Rutting equivalency factors for various sizes of tires, AC temperature 25 °C. (6)

| AC Thickness mm. | 11R22.5 Axle Load 53 kN | 15R22.5 Axle Load 71 kN | 18R22.5 Axle Load 89 kN |
|---|---|---|---|
| 51 | 1.05 | 1.21 | 1.39 |
| 76 | 1.11 | 1.24 | 1.38 |
| 102 | 1.20 | 1.32 | 1.45 |
| 127 | 1.28 | 1.38 | 1.5 |
| 165 | 1.38 | 1.47 | 1.6 |

Table 9. Rutting equivalency factors for various sizes of tires, AC temperature 49 °C. (6)

| AC Thickness mm. | 11R22.5 Axle Load 53 kN | 15R22.5 Axle Load 71 kN | 18R22.5 Axle Load 89 kN |
|---|---|---|---|
| 51 | 1.5 | 1.4 | 1.38 |
| 76 | 1.57 | 1.53 | 1.55 |
| 102 | 1.51 | 1.41 | 1.40 |
| 127 | 1.50 | 1.43 | 1.44 |
| 165 | 1.59 | 1.5 | 1.53 |

contradicting conclusion of this study. This finding contradicts the fundamental principles of flexible pavement design. Therefore, the validity of the approach used to calculate the equivalency factors is highly questionable.

### Experimental-Response

This group of studies conducted field experiments to measure the relative pavement damage caused by single tires as compared to dual tires configurations. The studies in this category measured the pavement responses under different tire configurations but they did not monitor the actual performance of the pavements as being loaded by single and dual tires configurations. However, most of the studies in this group used the measured pavement responses in pavement performance models to estimate the relative damage. The following represents a summary of the studies in this group.

One of the earliest efforts to evaluate pavement damage from super-single tires relative to conventional dual tires was done by Zube et al (7). Pavement surface deflections were used as indicators of relative damage. Surface deflections were measured with a Benkelman-Beam and LVDT's embedded into the pavement. Testing took place on 8 sites surfaced with 50-70 mm (2" - 2.8") thick asphalt concrete layer.

Pavement responses were compared under single axles on single bias tires 18.00x19.50 and dual bias tires 10.00X20.00 inflated at 517 kPa (75 psi) and 482 kPa (70 psi), respectively. On the average, a 57 kN (12,814 lb) load on a single tired axle was equivalent, in terms of pavement surface deflection, to an 80 kN (18,000 lb) single axle load with dual tires. Therefore, this early observation indicated that bias single tires could be 30% more damaging than dual bias tires.

Christison (8) conducted a field study at the Alberta Research Council's instrumented flexible pavement site to evaluate the relative damage caused by single tires as compared to dual tires. The longitudinal strains at the bottom of the asphalt concrete layer, pavement surface deflections, and pavement temperatures at various depths within the pavement structure were recorded under moving vehicle loads. Equivalency factors were calculated on the basis of the measured pavement responses as follows:

$$Fi = [\epsilon_i / \epsilon_b]^{5.5}$$

where, $\epsilon_i$ and $\epsilon_b$ are tensile strains under the load in question and the reference load of 80 kN (18,000 lb) on a single axle with dual tires, respectively. Pavement response parameters were found to depend on temperature, and vehicle speed. In order to eliminate the effect of temperature and vehicle speed, each pass of the axle load to be evaluated was followed by the reference axle load at the same speed. All tested tires were bias type tires. The axle load varied from 56 to 117 kN (12,600 to 26,302 lb) for single axle with dual tires, 9 to 53 kN (2,023 to 11,914 lb) for single axle with singled-out tires, and 62.7 to 86.4 kN (14,100 to 19,400 lb) for single axle with super-single tires.

Table 10 shows the equivalency factors for singled-out tires. Unfortunately, most of the load levels were kept low which generated equivalency factors less than 1.0 in most cases. However, the data showed that for singled-out tires, an axle load of 51.6 kN (11,610 lb) could be equivalent to 80 kN (18,000 lb) single axle load on dual tires. Table 11 shows the equivalency factors for super-single tires which indicate that a single axle load of 76 kN (17,100 lb) with super-single tires is equivalent to 80 kN (18,000 lb) single axle load with

Table 10. Equivalency factors for singled-out bias tires based on tensile strains and surface deflections. (8)

| Bias Tire Size | Axle Load kN | Average AC Temperature | $e_{ten}(L)/e_{ten}(80\ kN)$ | d(L)/d(80 kN) |
|---|---|---|---|---|
| 10.00 x 20 | 28 | 22 | 0.44 | 0.57 |
| 10.00 x 20 | 28.5 | 19 | 0.52 | 0.57 |
| 10.00 x 20 | 29.4 | 20 | 0.55 | 0.58 |
| 10.00 x 20 | 30.7 | 22 | 0.62 | 0.67 |
| 10.00 x 20 | 36.5 | 24 | 0.68 | 0.72 |
| 11.00 x 20 | 37.4 | 19 | 0.60 | 0.65 |
| 11.00 x 20 | 37.4 | 19 | 0.60 | 0.65 |
| 11.00 x 20 | 51.6 | 20 | 0.95 | 0.98 |
| 12.00 x 20 | 51.6 | 23 | 1.083 | 1.13 |
| 12.00 x 22.5 | 51.6 | 23 | 0.94 | 0.95 |

Table 11. Equivalency factors for super-single bias tires based on tensile strains and surface deflections. (8)

| Tire Size | Axle Load kN | Average AC Temperature | $e_{ten}(L)/e_{ten}(80\ kN)$ | d(L)/d(80 kN) |
|---|---|---|---|---|
| 18 x 22.5 | 62.7 | 16 | 0.86 | 0.99 |
| 18 x 22.5 | 76.0 | 15 | 1.00 | 1.10 |
| 18 x 22.5 | 85.3 | 14 | 1.11 | 1.17 |

Table 12. Equivalent axle loads for dual and single tires. (9)

| Tire Type/ (inner/outer pressure) | Single Axle (t) | Tandem Axle (t) | Tridem (t) |
|---|---|---|---|
| 10R20 (550/550) | 8.2 | 13.6 | 18.5 |
| 10R20 (550/689) | 7.4 | NA | NA |
| 15R22.5 (792) | 5.9 | 10.5 | 17.0 |

dual tires. In summary, the data from this study indicate that singled-out tires are more damaging than both dual tires and super-single tires. The applicability of this data is diminishing as the use of bias tires on highway pavements has been significantly reduced.

Sharp et al (9) performed a field study to evaluate the relative damage of super-single tires on flexible pavements. The study measured surface deflections of a flexible pavement section (75 mm AC, 150 mm aggregate base, and 200 mm aggregate subbase). The tested tires were the 10R20 dual and the 15R22.5 super-single. The inflation pressures of the dual tires were varied between the two tires to simulate differential wearing of the tires. The relative damage was evaluated in terms of equivalent axle loads based on the ratios of the measured deflections. Table 12 summarizes the data for the single, tandem, and tridem axles. The data show that differential wearing of the dual tires can significantly impact the equivalent load that a single axle with dual tires can carry. In addition, the use of super-single tires reduces the allowable loads by 28, 22, and 8 percent for single, tandem, and tridem, respectively. This indicates that the damage from single tires decreases as the number of axles increases. In another word, the use of single tires on tridems may not significantly reduces the allowable loads while providing an economic incentive for the trucking industry.

Sebaaly and Tabatabaee (10) extensively studied the influence of tire pressure and type on the response of flexible pavements through a field experiment at the Penn State Test Track. Strain gauges were installed at the bottom of the AC layer to measure longitudinal strains and geophones were used to measure vertical surface deflections. A thermocouple tree consisting of four sensors at various depths was installed to monitor temperature variations throughout the AC layer. Six tire types were evaluated in the experiment:

(a) dual 11x22.5 bias ply tires

(b) dual 11R22.5 radial ply tires

(c) dual 245/75R22.5 low profile dual radial tires

(d) 425/65R22.5 super-single tire

(e) 385/65R22.5 super-single tire

(f) 350/75R22.5 super-single tire

The following axle loads were investigated: for dual tires 44.5, 75.6, 97.9 kN/axle (10, 17, 22 kips/axle ) and 44.5, 75.6, 89 kN/axle (10, 17, 20 kips/axle) for single tires. Two pavement sections were evaluated: 1) thin pavement section with 152 mm (6") asphalt concrete and 203 mm (8") base course and 2) thick section with 254 mm (10") asphalt concrete and 254 mm (10") base course. Actual truck loading was used at speed of 65 km/h (40 mph). Pavement performance were evaluated using the following models:

Fatigue:

$\log N_f\,(10\%) = 15.947 - 3.291 \log (\epsilon/10^{-6}) - 0.854 \log (E/10^3)$

$\log N_f\,(45\%) = 16.086 - 3.291 \log (\epsilon/10^{-6}) - 0.854 \log (E/10^3)$

where :

$N_f$ = Number of load applications required to cause 10 or 45 percent cracking of the wheel tracks.

$\epsilon$ = tensile strain at the bottom of asphalt concrete layer.

$E$ = resilient modulus of asphalt concrete layer.

Rutting:

For Asphalt concrete layer less than 152.4 mm (6 in).

$$\log RR = -5.617 + 4.343 \log d - 0.16 \log (N_{18}) - 1.118 \log sc$$

For Asphalt concrete layer greater than or equal to 152.4 mm (6 in).

$$\log RR = -1.173 + 0.717 \log d - 0.658 \log (N_{18}) + 0.666 \log (sc)$$

Where :

RR = rate of rutting, micro-inches per axle-load repetition

d = surface deflection x $10^3$ in

sc = Vertical compressive stress at interface of base course with AC

$N_{18}$ = Equivalent of 18-kip single-axle load x $10^5$

The relative damage was assessed using the following relationships:

Damage Factor (Fatigue) = $N_f$ (11R22.5) / $N_f$ (any tire)

Damage Factor (Rutting) = RR (11R22.5) / RR (any tire)

Tables 13 through 20 show some of the fatigue and rutting damage factors that were developed in this study. The data showed that the 11R22.5 had the smallest measured strains for both thick and thin pavement sections. The tire inflation pressure did not have any impact on the measured strains for both thin and thick pavement sections. There was a significant difference in the response between single and dual tires for the thin and thick pavement sections which resulted in a significant difference in the evaluated damage factors.

Table 13. Fatigue damage factors for the tandem-axle load of 76.5 kN/axle (17.2 kip/axle) for the thin section. (10)

| Tire Type | Pressure kPa | Microstrain (70 °F) | Nf (10%) X10$^3$ | Damage Factor | Nf (45%) X10$^3$ | Damage Factor |
|---|---|---|---|---|---|---|
| 11R22.5 | 827 | 253 | 700 | 1.00 | 964 | 1.0 |
| | 724 | 247 | 758 | 0.90 | 1,043 | 0.9 |
| 245/75R22.5 | 827 | 264 | 608 | 1.2 | 838 | 1.2 |
| 425/65R22.5 | 827 | 283 | 484 | 1.4 | 667 | 1.4 |
| 385/65R22.5 | 896 | 313 | 347 | 2.0 | 479 | 2.0 |

Table 14. Fatigue damage factors for the tandem-axle load of 76.5 kN/axle (17.2 kip/axle) for the thick section. (10)

| Tire Type | Pressure kPa | Microstrain (70 °F) | Nf (10%) X10$^3$ | Damage Factor | Nf (45%) X10$^3$ | Damage Factor |
|---|---|---|---|---|---|---|
| 11R22.5 | 827 | 133 | 4,227 | 1.00 | 5,821 | 1.0 |
| | 724 | 129 | 4,674 | 0.90 | 6,436 | 0.9 |
| 245/75R22.5 | 827 | 138 | 3,743 | 1.1 | 5,155 | 1.1 |
| 425/75R22.5 | 827 | 148 | 2,974 | 1.4 | 4,095 | 1.4 |
| 385/65R22.5 | 896 | 153 | 2,666 | 1.6 | 3,671 | 1.6 |

Table 15. Fatigue damage factors for the Single-axle load of 78.3 kN (17.6 kip) for the thin section. (10)

| Tire Type | Pressure kPa | Microstrain (21.1 °C) | Nf (10%) X10$^3$ | Damage Factor | Nf (45%) X10$^3$ | Damage Factor |
|---|---|---|---|---|---|---|
| 11R22.5 | 827 | 268 | 579 | 1.00 | 798 | 1.0 |
| | 724 | 258 | 656 | 0.90 | 904 | 0.9 |
| 245/75R22.5 | 827 | 270 | 565 | 1.0 | 778 | 1.0 |
| 425/65R22.5 | 827 | 302 | 391 | 1.5 | 538 | 1.5 |
| 385/65R22.5 | 896 | 315 | 340 | 1.7 | 469 | 1.7 |

Table 16. Fatigue damage factors for the Single-axle load of 78.3 kN (17.6 kip) for the thick section. (10)

| Tire Type | Pressure kPa | Microstrain (21.1 °C) | Nf (10%) X$10^3$ | Damage Factor | Nf (45%) X$10^3$ | Damage Factor |
|---|---|---|---|---|---|---|
| 11R22.5 | 827 | 145 | 3,181 | 1.00 | 4,381 | 1.0 |
| | 724 | 139 | 3,655 | 0.90 | 5,034 | 0.9 |
| 245/75R22.5 | 827 | 156 | 2,500 | 1.3 | 3,444 | 1.3 |
| 425/75R22.5 | 827 | 159 | 2,349 | 1.5 | 3,234 | 1.5 |
| 385/65R22.5 | 896 | 164 | 2,121 | 1.5 | 2,921 | 1.5 |

Table 17. Rutting damage factors for the tandem-axle load of 76.5 kN/axle (17.2 kip/axle) for the thin section. (10)

| Tire Type | Pressure kPa | Deflection (mils) | Compressive stress KPa | Rate of Rutting ($10^{-6}$) | Damage Factor |
|---|---|---|---|---|---|
| 11R22.5 | 827 | 16.7 | 47.6 | 10.2 mm | 1.0 |
| | 724 | 16.3 | 47.6 | 10.2 mm | 1.0 |
| 245/75R22.5 | 827 | 18.6 | 48.3 | 11.2 mm | 1.1 |
| 425/75R22.5 | 827 | 23.1 | 63.4 | 15.5 mm | 1.5 |
| 385/65R22.5 | 896 | 23.7 | 63.4 | 16.0 mm | 1.6 |

Table 18. Rutting damage factors for the Tandem-axle load of 76.5 kN/axle (17.2 kip/axle) for the thick section. (10)

| Tire Type | Pressure kPa | Deflection (mils) | Compressive stress KPa | Rate of Rutting ($10^{-6}$) | Damage Factor |
|---|---|---|---|---|---|
| 11R22.5 | 827 | 4.4 | 30.34 | 2.8 mm | 1.0 |
| | 724 | 4.1 | 30.34 | 2.8 mm | 1.0 |
| 245/75R22.5 | 827 | 4.4 | 31.03 | 3.1 mm | 1.1 |
| 425/75R22.5 | 827 | 5.0 | 37.9 | 3.8 mm | 1.4 |
| 385/65R22.5 | 896 | 5.2 | 37.9 | 3.8 mm | 1.4 |

Table 19. Rutting damage factors for the single-axle load of 78.3 kN (17.6 kip) for the thin section. (10)

| Tire Type | Pressure kPa | Deflection (mils) | Compressive stress KPa | Rate of Rutting ($10^{-6}$) | Damage Factor |
|---|---|---|---|---|---|
| 11R22.5 | 827 | 9.4 | 47.6 | 6.9 mm | 1.0 |
| | 724 | 8.6 | 47.6 | 6.4 mm | 0.9 |
| 245/75R22.5 | 827 | 10.6 | 49 | 7.6 mm | 1.1 |
| 425/75R22.5 | 827 | 10.8 | 64.1 | 9.1 mm | 1.3 |
| 385/65R22.5 | 896 | 12.3 | 64.1 | 9.9 mm | 1.4 |

Table 20. Rutting damage factors for the single-axle load of 78.3 kN (16.7 kip) for the thick section. (10)

| Tire Type | Pressure kPa | Deflection (mils) | Compressive stress KPa | Rate of Rutting ($10^{-6}$) | Damage Factor |
|---|---|---|---|---|---|
| 11R22.5 | 827 | 2.9 | 29 | 2 mm | 1.0 |
| | 724 | 2.6 | 29 | 2 mm | 0.9 |
| 245/75R22.5 | 827 | 2.9 | 36.5 | 2.5 mm | 1.3 |
| 425/75R22.5 | 827 | 3.1 | 36.5 | 2.5 mm | 1.3 |
| 385/65R22.5 | 896 | 3.2 | 36.5 | 2.5 mm | 1.3 |

The evaluated fatigue and rutting damage factors were similar in magnitude for all combinations of axle loads and configurations. In summary, super-single tires are more damaging than dual tires and specially when they are used on tandem axles.

Akram et al (11) presented the results of a field study designed to evaluate the damage produced by super-single tires as compared to conventional dual truck tires. Two in service pavements were instrumented with multi-depth deflectometers to measure vertical deflections at various depths. The sections chosen represented thick and thin pavements. The thin section had an AC thickness of 38 mm (1.5") over 254 mm (10") aggregate base, while the thick pavement section had an AC thickness of 178 mm (7") over 356 mm (14") aggregate base. The conventional dual truck tires were 11R22.5 with inflation pressure of 827 kPa (120 psi). The super-single tire was 425/65R22.5 with inflation pressure of 896 kPa (130 psi). Four different speeds were evaluated in this study 16, 32, 56, and 89 km/h (10, 20, 35, and 55 mph).

The first set of tests replaced the conventional dual tires on the tandem axle of the trailer with super-single tires. The second set of tests replaced the conventional dual tires on the drive axle of the tractor with super-single tires. The Asphalt Institute criterion was used to evaluate the allowable number of equivalent 80 kN (18,000 lb) single axle loads (ESALs) for the two tire configurations.

$$\epsilon_v = L\ (1/N)^m$$

Where

N = permissible number of ESALs

$\epsilon_v$ = Subgrade vertical strain

L = 1.05 X $10^{-2}$ and m = 0.223

The compressive strains on top of the subgrade were calculated as the slope of the vertical deflections curve measured using the MDD. Tables 21 through 24 give a summary of the results for rutting. The relative damage of single tires was expressed as the percent reduction in the allowable number of ESALs to rutting failures (i.e. reduction in pavement performance life). The data generated from this study indicated that single tires produce an average of 65 percent reduction in the rutting ESALs for the thin section and an average of 30 percent reduction for the thick section. These reductions would indicate that single tires are 2.5 and 1.5 times more damaging for thin and thick sections, respectively.

The measured surface deflections basins were converted into surface curvature index which is then related to the horizontal tensile strain. The surface curvature index is defined as the maximum deflection under a given load minus the deflection measured at a distance from the center of the load (typically 305 mm). Regression equations were developed to relate the horizontal tensile strain at the bottom of the asphalt concrete layer to the surface curvature index. The predicted horizontal tensile strain was then used to calculate the number of load repetitions to failure using the following equation:

$$\log N_f\,(10\%) = 15.947 - 3.291 \log (\epsilon/10^{-6}) - 0.854 \log (E/10^{3})$$

Where $N_f$ is the number of load applications required to cause 10% cracking of the wheel tracks, $\epsilon$ is the tensile strain at the bottom of AC layer, and E is the resilient modulus of asphalt concrete layer.

Table 21. Rutting ESALs for thin pavement, tandem axle load 147 kN, temp. on top of AC layer 27 °C, bottom of AC layer 26 °C. (11)

| Tire | Axle | Speed-km/h | Compressive Strain on Top of SG (microns) | ESALs |
|---|---|---|---|---|
| Duals | Drive | 16 | 1355 | 9719 |
| Super single | Trailer | 16 | 1690 | 3609 (63%) Red |
| Duals | Drive | 32 | 1332 | 10495 |
| Super single | Trailer | 32 | 1665 | 3858 (63%) Red |
| Duals | Drive | 56 | 1294 | 11950 |
| Super single | Trailer | 56 | 1623 | 4327 (64%) Red |
| Duals | Drive | 89 | 1246 | 14157 |
| Super single | Trailer | 89 | 1570 | 5021 (65%) Red |

Table 22. Rutting ESALS for thin pavement, tandem axle load 76 kN, temp. on top of AC layer 35 °C, bottom of AC layer 36 °C. (11)

| Tire | Axle | Speed-km/h | Compressive Strain on Top of SG (Microns) | ESALs |
|---|---|---|---|---|
| Duals | Trailer | 16 | 1626 | 4291 |
| Super single | Drive | 16 | 2087 | 1401 (67%) Red |
| Duals | Trailer | 32 | 1617 | 4399 |
| Super single | Drive | 32 | 2081 | 1419 (68%) Red |
| Duals | Trailer | 56 | 1601 | 4600 |
| Super single | Drive | 56 | 2071 | 1450 (68%) Red |
| Duals | Trailer | 89 | 1581 | 4866 |
| Super single | Drive | 89 | 2060 | 1485 (69%) Red |

Table 23. Rutting ESAls for thick pavement, tandem axle load 147 kN, temp. on top of AC layer 27 °C, bottom of AC layer 23 °C. (11)

| Tire | Axle | Speed-km/h | Compressive Strain on Top of SG (Microns) | ESALs |
|---|---|---|---|---|
| Duals | Drive | 16 | 297 | 8782890 |
| Super single | Trailer | 16 | 334 | 5187769 (41%) Red |
| Duals | Drive | 32 | 289 | 9926930 |
| Super single | Trailer | 32 | 330 | 5475794 (45%) Red |
| Duals | Drive | 56 | 275 | 12402795 |
| Super single | Trailer | 56 | 325 | 5863820 (53%) Red |
| Duals | Drive | 89 | 258 | 16511743 |
| Super single | Trailer | 89 | 317 | 6557210 (60%) Red |

Table 24. Rutting ESALs for thick pavement, tandem axle load of 147 kN, temp. on top of AC layer 39 °C, bottom of AC layer 29 °C. (11)

| Tire | Axle | Speed-km/h | Compressive Strain on Top of SG (Microns) | ESALs |
|---|---|---|---|---|
| Duals | Trailer | 16 | 361 | 3660915 |
| Super single | Drive | 16 | 390 | 2588858 (29%) Red |
| Duals | Trailer | 32 | 358 | 3800507 |
| Super single | Drive | 32 | 385 | 2743075 (28%) Red |
| Duals | Trailer | 56 | 354 | 3996905 |
| Super single | Drive | 56 | 382 | 2841008 (29%) Red |
| Duals | Trailer | 89 | 348 | 4315343 |
| Super single | Drive | 89 | 376 | 3050031 (29%) Red |

In the case of fatigue, the average percent reductions in ESALs were 60 percent for the thin section and 83 percent for the thick section. Vehicle speed did not impact the relative damage of single tires. The higher percent reduction in fatigue ESALs on the thick section than on the thin section could be due to the fact that the tensile strains were estimated from vertical deflections instead of direct measurement. The use of surface vertical deflection basins to estimate tensile strains at the bottom of the AC layer is an invalid approach. Therefore, the fatigue analysis part of this study should not be seriously considered.

The Road and Research Laboratory (12) in Finland completed a research program at the Virttaa test field, which is 3 km (1.9 miles) long and 40 m (130 ft) wide part of a highway that is used as a temporary airfield by the Finnish Air Force. Two flexible pavement sections with AC layer thickness of 150 mm (5.9") and 79 mm (3.1") over 399 mm (15.7") base course were used to evaluate the effects of several tire configurations.

Single axle loads varied between 71.2 kN and 106.8 kN (16,000-lb and 24,000-lb.) and tire pressures were varied between 483 kPa and 1082 kPa (70 psi and 157 psi). Five different tire configurations were compared:

(a) 12R22.5 dual tires

(b) 265/70R19.5 dual tires

(c) 445/65R22.5 super-single tire

(d) 385/65R22.5 super-single tire

(e) 350/75R22.5 super-single tire

The horizontal tensile strains at the bottom of the AC layer were measured using strain gauges. The strain measurements were converted to equivalent number of axle load passes required to produce fatigue failure. The concept of equivalency factors was also used. Equivalency factors were defined as the ratio of damage produced by a given axle load to the damage produced by a 89 kN (20,000 lb) single axle with 12R22.5 dual tires inflated to 703 kPa (102 psi). Damage was defined as the reciprocal of the fatigue life. Table 25 shows the equivalency factors for all five different tire configurations while Table 26 presents the data based on equivalent axle loads to produce the same damage as the standard axle.

The results show that super-single tires are more damaging than dual tires. Within super-single tires, wider tires are less damaging than narrower tires. The super-single tires are more damaging on thin pavements than on thick pavements.

The South Dakota Department of Transportation conducted a field study to estimate the pavement damage caused by singled-out dual and super-single tires (13). The pavement section tested was representative of a typical flexible pavement in South Dakota. It consisted of approximately 127 mm (5 in) of asphalt concrete surface placed over 152 mm (6 in) base course and 203 mm (8 in) subbase course. Deflection measuring devices were installed at two locations in the outer wheel track 6 m (20 ft) apart. Dual, singled-out, and super-single tires with different load magnitudes were evaluated. Table 27 shows the different tire configurations and loads. The pavement deflections were obtained for two experimental matrices with the following factors:

Table 25. Fatigue equivalency factors for different tire configurations. (12)

| Tire Type Axle Load 84 kN (18.9 kip) | AC layer 79 mm (3.1") Damage ratio | AC layer 150 mm (5.9") Damage ratio |
|---|---|---|
| 12R22.5 Duals | 0.33 | 0.35 |
| 265/70R19.5 | 0.87 | 0.58 |
| 445/65R22.5 Super single | 1.23 | 1.14 |
| 385/65R22.5 Super single | 2.34 | 1.22 |
| 350/75R22.5 Super single | 2.37 | 1.28 |

Table 26. Equivalent axle loads required to cause the same damage. (12)

| Tire Type | AC Layer 79 mm (3.1") Equivalent Axle Load | AC layer 150 mm (5.9") Equivalent Axle Load |
|---|---|---|
| 12R22.5 Duals | 100 kN (22,5 kip) | 100 kN (22,5 kip) |
| 265/70R19.5 Duals | 86 kN (19,3 kip) | 93 kN (20,9 kip) |
| 445/65R22.5 Super single | 81 kN (18,2 kip) | 81 kN (18,2 kip) |
| 385/65R22.5 Super single | 65 kN (14,6 kip) | 78 kN (17,5 kip) |
| 350/75R22.5 Super single | 61 kN (13,7 kip) | 75 kN(16,9 kip) |

Table 27. Wheel configurations and wheel loads. (13)

| Wheel Configuration | Tire Width (mm) | Load Intensity (N/mm) | Total Wheel Load (kN) |
|---|---|---|---|
| Dual | 508 | 70.1 | 35.6 |
| | | 105.1 | 53.4 |
| | | 140.2 | 71.2 |
| Singled out dual | 254 | 70.1 | 17.8 |
| | | 105.1 | 26.7 |
| | | 140.2 | 35.6 |
| Super single | 381 | 70.1 | 26.7 |
| | | 105.1 | 40.0 |
| | | 140.2 | 53.4 |

Matrix 1

| | |
|---|---|
| Season | 4 levels (Summer, Fall, Winter, Spring) |
| Tire configuration | 3 levels (Dual tires, super-single tires, singled-out duals) |
| Tire Load | 3 levels (70.1, 105.1, 140.2 N/mm) |

Matrix 2

| | |
|---|---|
| Season | 4 levels (Summer, Fall, Winter, Spring) |
| Tire configuration | 3 levels (Dual tires, super-single tires, singled-out duals) |
| Tire Load | 3 levels (26.7, 40.0, 53.4 N/mm) |

Equivalency factors were used to assess the relative damage. The equivalency factors were computed according to the following equation:

$$LEF = [\ D_i / D_s\ ]^{3.8}$$

where:

$D_i$ = Deflection under a given load

$D_s$ = Deflection under the standard load (80 kN with dual tires)

Table 28 shows a summary of the equivalency factors. The data in Table 28 show that super-single tires produced higher deflections at lower tire loads; but the singled-out dual tires were more damaging at higher loads. The singled-out dual tires produced the largest deflection during fall; the super-single tires produced the largest deflection in winter.

The data showed some significant differences between the equivalency factors calculated from the two locations along the wheel track. This indicates the impact of materials variability

Table 28. Summary of equivalency factors developed by South Dakota DOT. (13)

| Season | Wheel Configuration | Load = 70.1 N/mm | | Load = 105.1 N/mm | | Load = 140.2 N/mm | |
|---|---|---|---|---|---|---|---|
| | | Ch1 | Ch2 | Ch1 | Ch2 | Ch1 | Ch2 |
| Summer | Dual | 0.566 | 0.617 | 3.188 | 2.365 | 10.11 | 6.573 |
| | Singled-out | 0.053 | 0.068 | 0.426 | 0.274 | 1.268 | 0.888 |
| | Super-single | 0.827 | 0.679 | 2.17 | 1.697 | 8.57 | 5.229 |
| Fall | Dual | 0.948 | 0.727 | 4.335 | 3.536 | 9.005 | 7.795 |
| | Singled-out | 0.351 | 0.145 | 0.876 | 0.665 | 2.758 | 1.457 |
| | Super-single | 0.625 | 0.371 | 2.744 | 2.177 | 7.479 | 5.732 |
| Winter | Dual | 0.553 | 0.341 | 1.116 | 2.112 | 2.768 | 5.534 |
| | Singled-out | 0.324 | 0.254 | 0.844 | 1.061 | 1.211 | 2.362 |
| | Super-single | 1.298 | 2.941 | 1.872 | 5.759 | 3.192 | 13.172 |
| Spring | Dual | 0.597 | 0.632 | 2.492 | 2.408 | 6.198 | 5.113 |
| | Singled-out | 0.24 | 0.246 | 0.724 | 0.835 | 1.961 | 1.75 |
| | Super-single | 0.813 | 1.026 | 2.962 | 2.369 | 8.802 | 6.105 |

Table 29. Predicted pavement damage by TRRL. (14)

| AC Thickness (mm) | Ratio of Damage Super single / Dual |
|---|---|
| 150 | 2.05 |
| 200 | 1.80 |
| 250 | 1.63 |
| 300 | 1.53 |

and dynamic loading on pavement response and damage. Some of these factors vary by more than 4 times. This observation emphasizes the need for pavement models which take into account the effect of materials variability and dynamic loading along the pavement longitudinal dimension.

Addis (14) conducted tests at the transport research laboratory (TRL) pavement test facility by applying super-single and dual tire loads to full scale experimental pavements. The principal strains generated in the pavement under a 40 kN (9 kip) load traveling at a speed of 20 km/h (12.4 mph) were measured. The super-single tire was found to increase the two principal strain measurements in the pavement by about 50% when compared to conventional dual tires. Addis used performance models to evaluate the damage factors as shown in Table 29.

**Experimental-Performance**

This type of studies conducted field experiments to measure the relative pavement damage caused by single tires through measurements of actual pavement performance. Identical pavement sections were loaded with both single and dual tires and their actual performance were compared. The following represents a summary of these studies.

Bonaquist (15) studied the effect of a super-single truck tire on pavement response and performance. The research was conducted on full-scale pavement test sections in attempt to directly compare the super-single tire with conventional dual tires. The experiment compared pavement responses and performance created by a 425/65R22.5 super-single tire with those observed under the dual 11R22.5 tire. The tires were selected on the basis of similar load ratings of 46.7 kN (10,500 lb) for the super-single tire and 23.6 kN (5,300 lb) for each of the dual tires.

The Accelerated Loading Facility (ALF), was used to load two flexible pavement sections. The ALF is capable of loading a 12 m (40 ft) pavement section with both single and dual tires configurations at a speed of 19 km/h (12 mph). Two pavement sections were constructed at the FHWA's pavement testing facility in Mclean, Virginia. The first section consisted of 178 mm (7.0") thick AC layer over 305 mm (12.0") base course and the second section consisted of 89 mm (3.5") thick AC layer over 305 mm (12.0") base course. Both sections were used to evaluate the effects of dual and super-single tires. The axle loads varied between 41 kN and 74 kN (9,217 lb. and 16,635 lb) and the tire inflation pressure varied between 520 kPa and 959 kPa (75 psi and 139 psi). Tensile strains at the bottom of the asphalt concrete layer and average vertical compressive strains in the asphalt layer, crushed aggregate base, and the upper 152 mm (6")of the subgrade were measured.

Since the test program was conducted on outdoor pavement sections, pavement temperatures could not be controlled. The fatigue and rutting behavior of the flexible pavement sections are expected to change as the temperature varies. If measured responses produced by the super-single tire are to be compared to those associated with conventional dual tires, the pavement temperature should be the same. This was not possible for this experiment since a time period of one to two hours was required to change tire configurations. Therefore, an indirect data comparison approach was adopted.

The first phase of the study used the measured pavement responses along with selected pavement performance models to evaluate the relative damage of the single tire as compared to the dual tire. The axle loads varied between 41 and 74 kN (9,200 and 16,600 lb) and the tire inflation pressure varied between 520 and 959 kPa (75 and 139 psi). Using the broad samples of collected data, statistical regression models were developed to predict pavement responses as a function of pavement temperature, load, and tire pressure. Figures 3 and 4 present comparisons of the strains under dual and single tires at 703 kPa (102 psi) and average pavement temperature of 14 and 23 °C (57 and 73 °F) for the 89 mm and 178 mm asphalt pavement, respectively. The relative damage was assessed using the damage ratios concept as shown below.

$$\text{The damage ratio for fatigue} = \frac{(\epsilon_t)^b \text{ Super single tire}}{(\epsilon_t)^b \text{ Dual tire}}$$

$$\text{The damage ratio for rutting} = \frac{\delta_r \text{ Super single tire}}{\delta_r \text{ Dual tire}}$$

Where $\epsilon_t$ and $\delta_r$ are the tensile strain at the bottom of the AC layer and the vertical deflection, respectively. Table 30 presents the damage ratios for the super-single tire relative to the dual tire. The data indicate that the super-single tire generates 25 to 50 percent more rutting damage than the dual tire. The rutting damage in the subgrade decreases as the thickness of AC layer increases. This observation coincides very well with the traditional concepts of pavement design. In the case of fatigue damage, the data show that the single tire generates 350 to 450 percent more damage than the dual tire. The data also shoe that the fatigue damage decreases as the thickness of AC layer increases.

The second phase of this study provided pavement performance data for the direct comparison of the two tire configurations. These data also allowed the statistical work previously completed with pavement responses to be checked and verified. The ALF

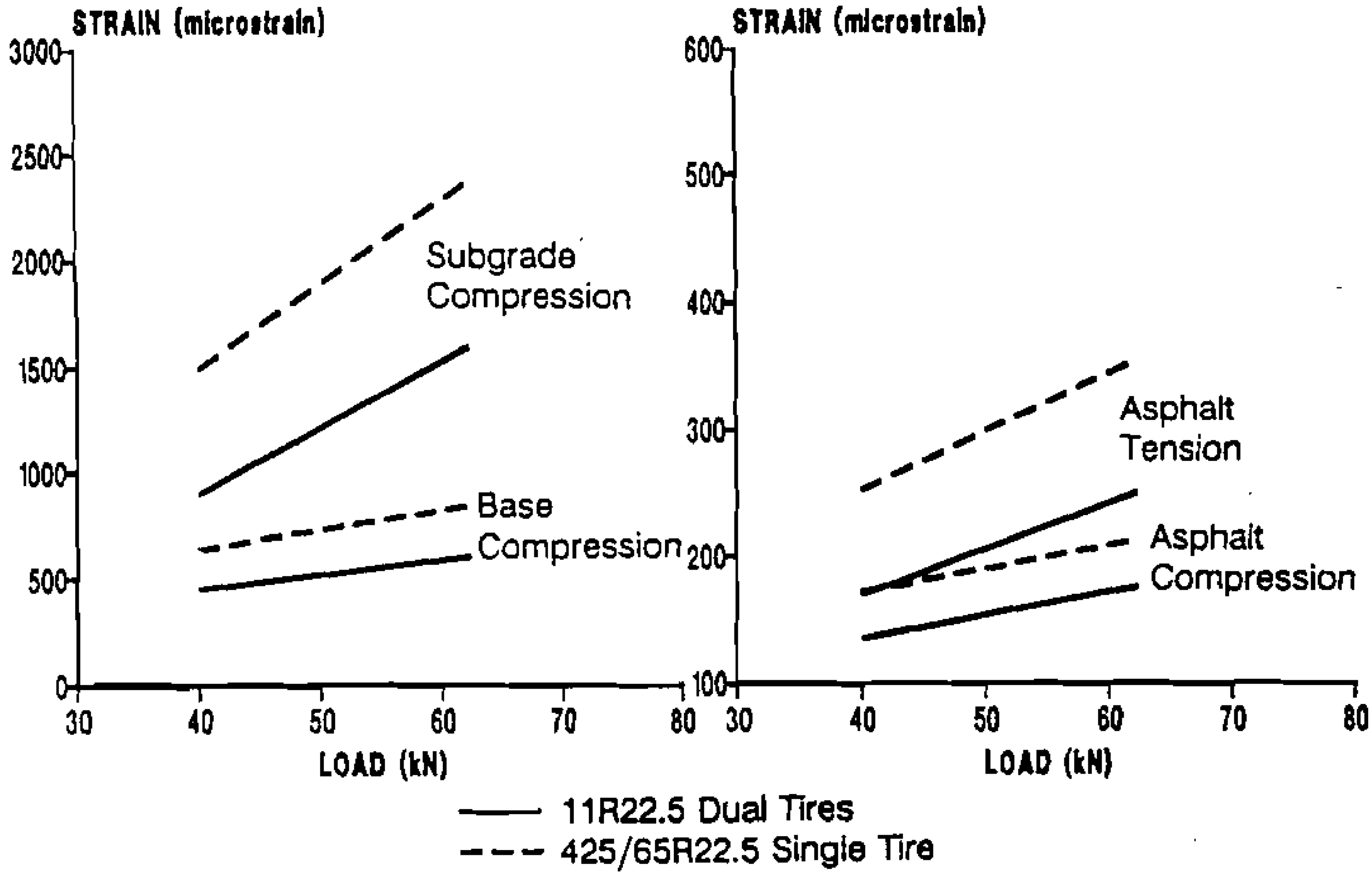

Figure 3. Comparison of pavement responses for the 89 mm AC section, tire pressure 703 kPa, pavement temp. 14 C. (15)

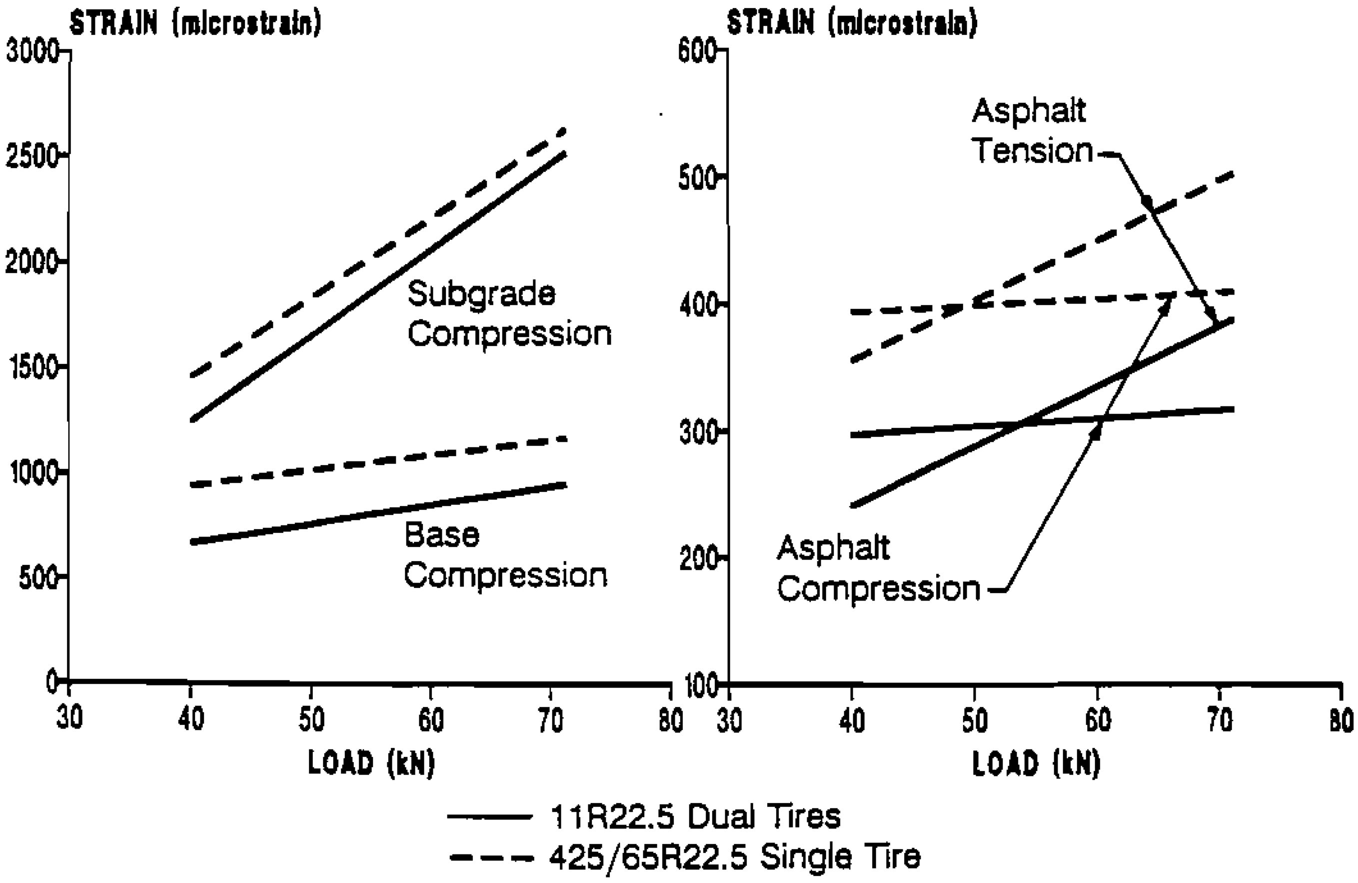

Figure 4. Comparison of pavement responses for the 178 mm AC section, tire pressure 703 kPa, pavement temp. 23 C. (15)

machine was modified to allow simultaneous testing of adjacent pavement sections. Thus, the super-single tire and conventional dual tire loadings could be directly compared under close environmental conditions. The ALF machine was used to load pavement section 1 one week with the single tire and the following week load section 2 with the dual tire and so on. Both the dual and super-single tires were loaded at 54.5 kN (12,250 lb) per tire set which translates into 109 kN/single axle (24,500 lb) and at inflation pressure of 803 kPa (102 psi). Bonaquist concluded that the results of the performance test compared well with the damage estimates from the response experiment. The observed increase in fatigue damage caused by the super-single tire was approximately 4 times and rutting damage was between 1.0 to 2.4 times relative to the dual tires. Figures 5 and 6 present a summary of the performance data.

The results of this research show that the 425/65R22.5 super-single tire is significantly more damaging to flexible pavements than the traditional 11R22.5 dual tire. For the same load and tire pressure, the super-single tire produced higher vertical compressive strains in all layers of the pavement, and higher tensile strains at the bottom of the asphalt concrete layer. These increased strains translated into greater rutting and shorter fatigue life for pavements loaded with the super-single tire.

The performance data presented in Figures 5 and 6 indicate that the relative pavement damage caused by the super-single tire can be reduced by increasing the thickness of the AC layer. Increasing the thickness of the AC layer is also equivalent to strengthening the flexible pavement structure through stronger hot mixed asphalt concrete (HMAC) mixture. Therefore, designing stronger HMAC mixtures could be an effective way to reduce the pavement damage caused by single tires relative to dual tires.

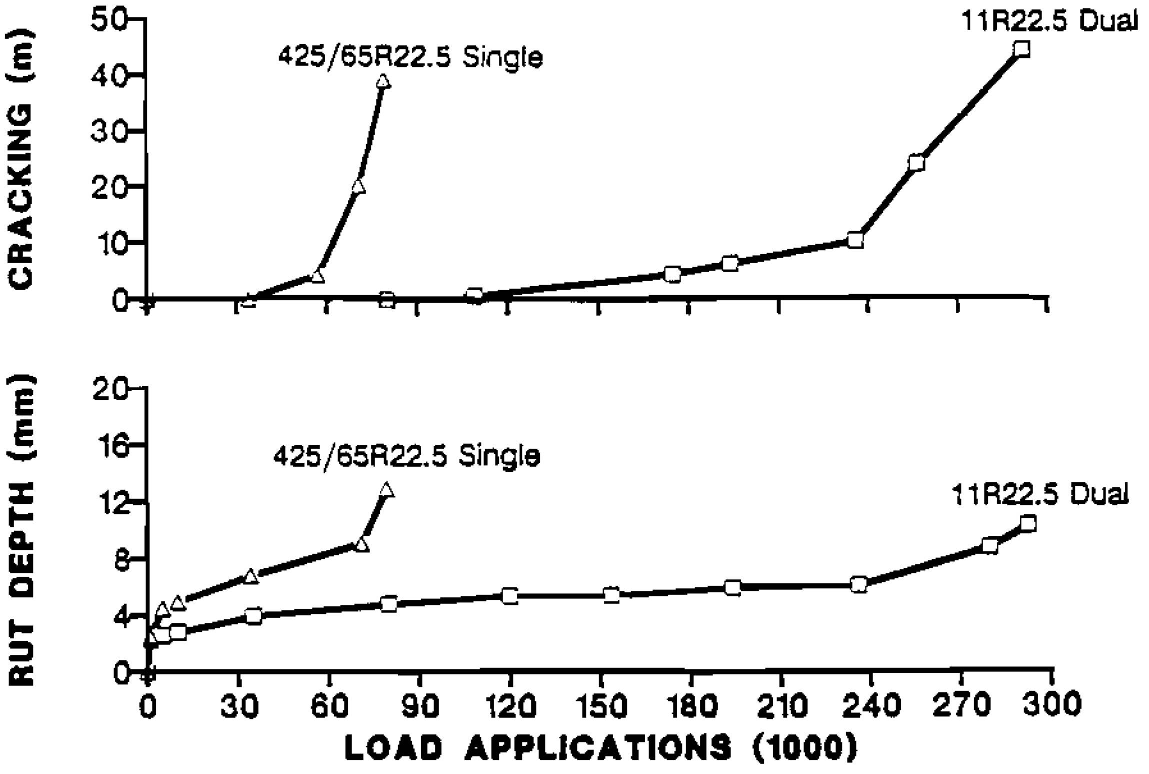

Figure 5. Summary of the 89 mm AC section performance test. (15)

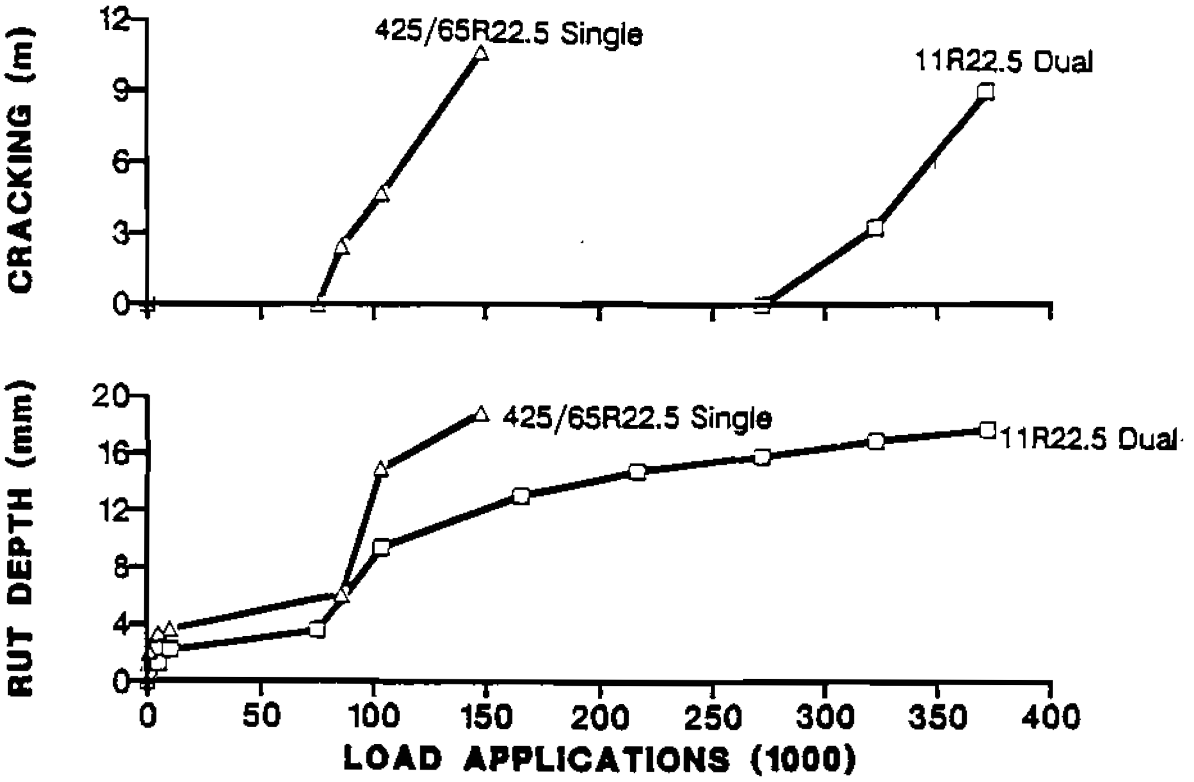

Figure 6. Summary of the 178 mm AC section performance test. (15)

Pidwerbesky and Dawe (16) conducted a field study to evaluate the rutting of flexible pavements caused by single tires relative to dual tires. The testing was conducted at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) which is located in Christchurch, New Zealand. The primary feature of the facility is the dual-armed Simulated Loading and Vehicle Emulator, which is capable of applying variable loading conditions. The loading device is also capable of simulating vehicle wandering at a traveling speed varying from 1 km/h (0.6 mph) up to a maximum of 50 km/h (31 mph). The circular track is 58 m (190 ft) long, 1.5 m (4.9 ft) deep, and 4 m (13 ft) wide with a radius of 9.26 m (30.4 ft). The pavement structure consisted of 30 mm (1.2 in) AC layer over 150mm (6 in) aggregate base, and 150 mm (6 in) aggregate subbase. The section is a representative of pavement structures in New Zealand but it represents a very thin section on the U.S. road system.

The study evaluated the 356/80R20 low profile super-single tire and a 10R20 dual tire. The test section was loaded with 15,591 cycles at a standard load of 80 kN (18,000 lb) single axle load. The relative damage was assessed based on the measured rut depths under the super-single and dual tires. Figures 7 and 8 show typical rut depth formation under both the dual tires and the super-single tire configurations. The results of this study showed that the low profile super-single tire created rut depths 92% greater than the standard dual radial tires for the same loading. The average rut depth under the dual tires was 15.2 mm ( in) and 29.2 mm ( in) uder the super single tire.

Eisenmann and Hilmer (17) presented a laboratory investigation of the impact of wheel load, tire pressure, and tire configuration on pavement rutting. The test facility used

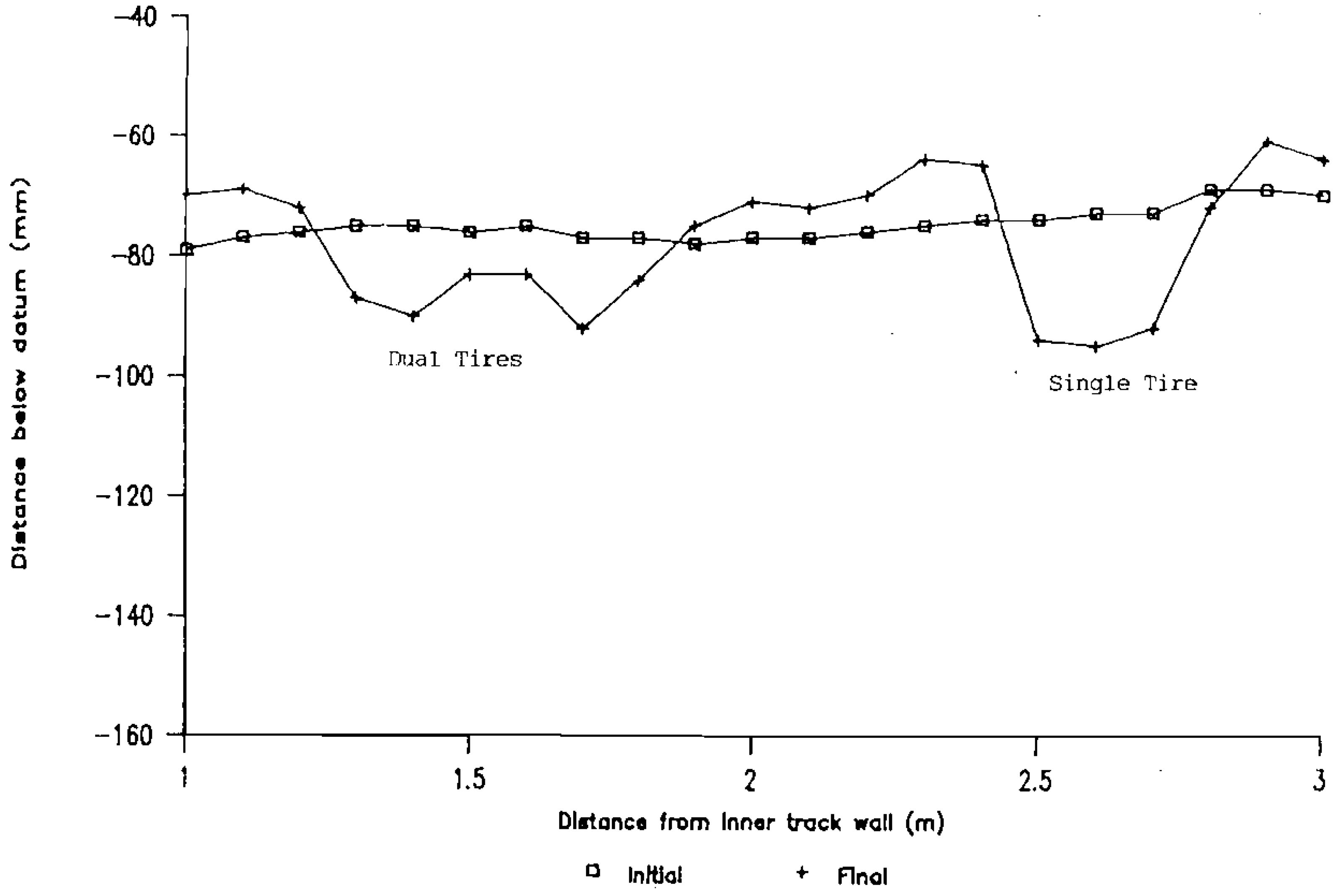

Figure 7. Typical transverse profile from the CAPTIF test. (16)

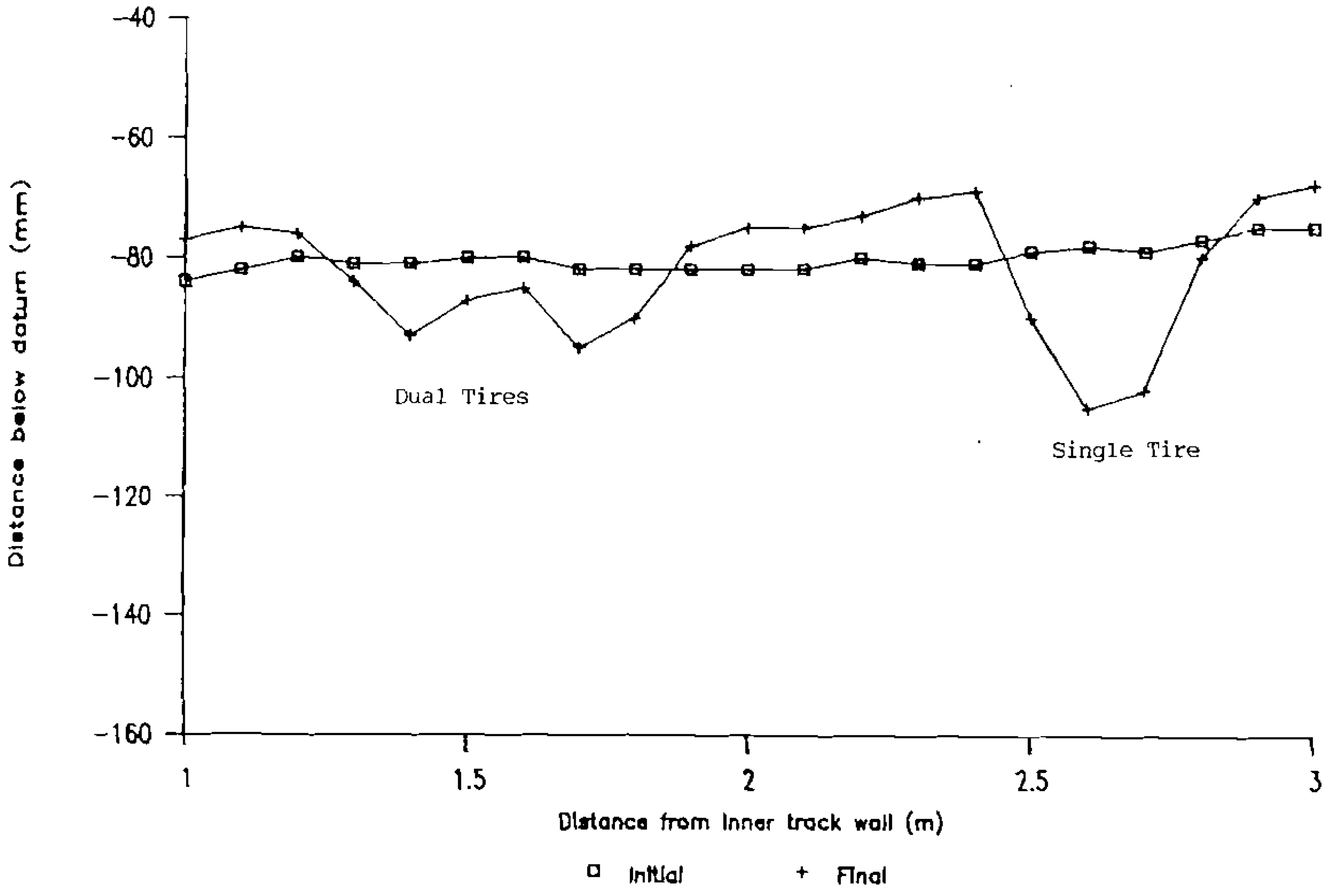

Figure 8. Typical transverse profile from the CAPTIF test. (16)

consisted of a loading frame that allows longitudinal and transverse movement of a set of wheels over an asphalt concrete layer supported by a rubber plate. The rolling speed of the applied load was about 1 km/h (0.62 mph). Dual and single tire configurations of 254x424 mm (10"x16.7") size tires were used for testing. The dual tires were inflated at pressures ranging from 800 to 1,100 KPa (116 to 160 psi) and carried loads from 31.45 to 49.7 kN (7.1 to 11.2 kip). The single tire was inflated at pressures ranging from 800 to 1,250 kPa (116 to 181 psi) and carried loads from 31.7 to 45.2 kN (7.1 to 10.2 kip).

Figures 9 and 10 show the rut depth for single tires and dual tires for different load cycles, respectively. The study concluded that the rut depth is higher under the single tire than the dual tires also the volume of deformation below the single tire is higher than dual tires.

## SINGLE TIRES DAMAGE OF RIGID PAVEMENTS

An effort was exerted to identify previous studies that evaluated the damage caused by singles tires on rigid pavements. The following two studies were identified:

1. NCHRP Report 353, "Effects of Heavy-Vehicles Characteristics on Pavement Response and Performance," Transportation Research Board, 1993.
2. Ioannides, et.al., "Super-Singles- Implications for Design," Proceedings of the 3rd International Symposium on Heavy Vehicle Weights and Dimensions, Cambridge University, UK, 1992.

Both studies are based on theoretical analyses and do not include any pavement performance

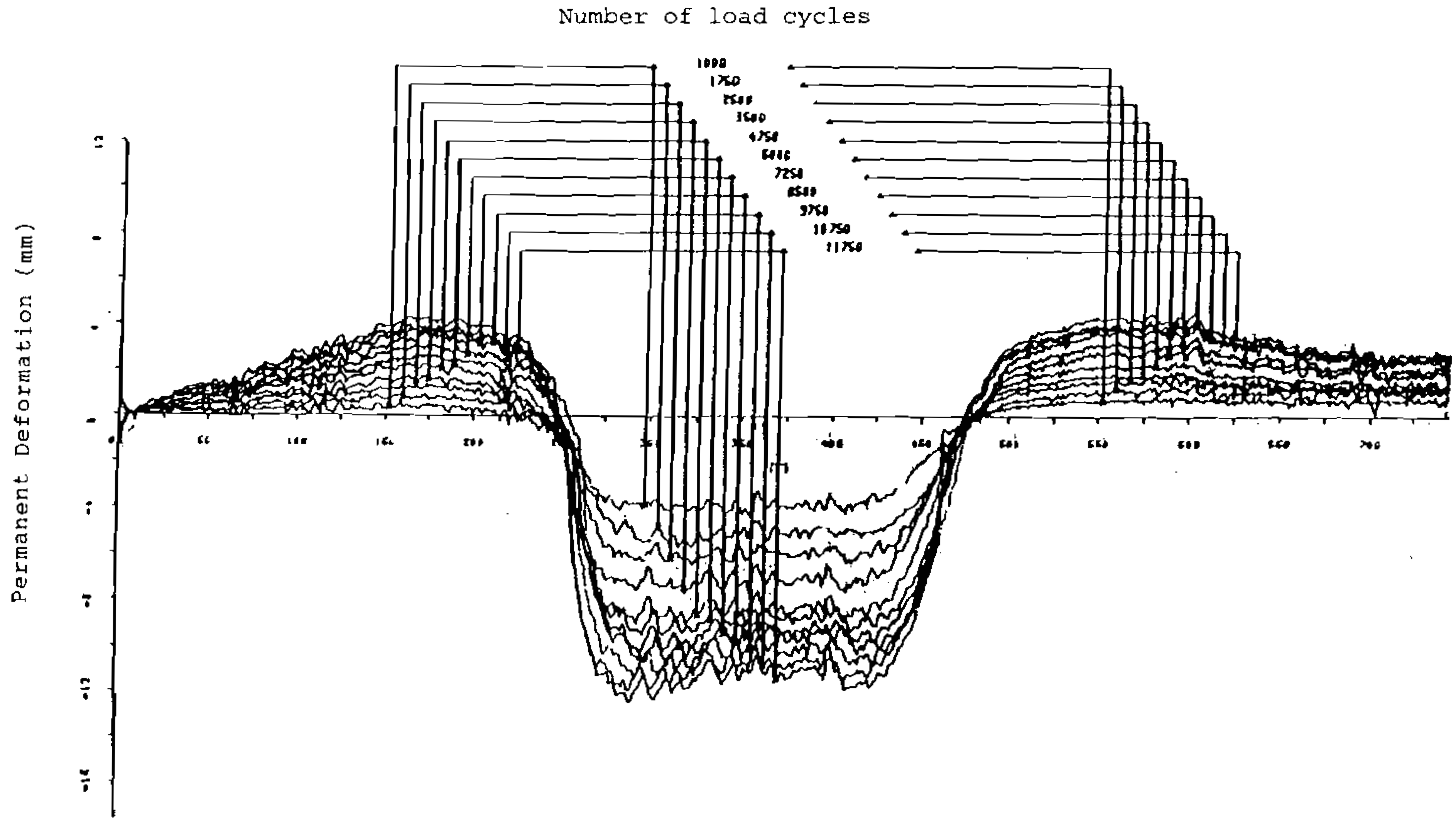

Figure 9. Development of rutting under single tire loading in the laboratory. (17)

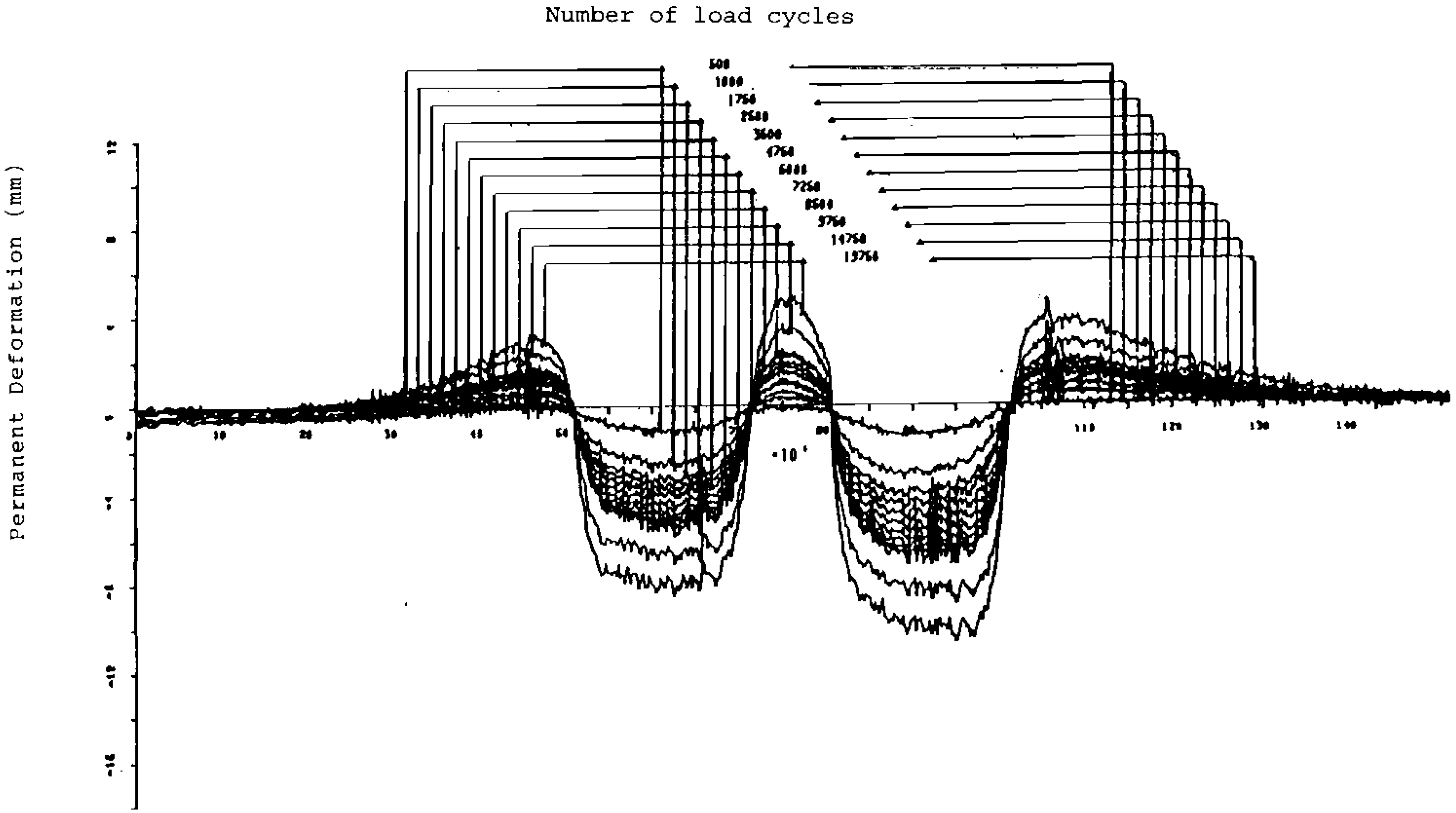

Figure 10. Development of rutting under dual tire loading in the laboratory. (17)

measurements. The following represents a summary of each of the studies.Effects of Heavy-

### Vehicles Characteristics on Pavement Response and Performance

This study evaluated the interaction between heavy vehicles and the pavement system. As part of the study, rigid pavement responses under heavy loadings were studied using a finite element analysis (ILLI-SLAB). With respect to the damage potential of single, dual, and super-single tires, the study concluded that: "rigid pavement fatigue is not as sensitive to tire contact conditions (area and pressure). Thus, axles with single tires are no more damaging than those with duals when operated within the rated loads of tires." The study showed that super-single tires increased the tensile stresses in the rigid pavement by 2 to 9 percent when only the axle load stresses are considered (e.g. no temperature stresses), with the stress increase becoming lower as the slab thickness increases. It was also noted that when temperature stresses are added, the increase in the combined stresses due to single tires will be very insignificant.

### Super-Singles -- Implication for Design

This study used a dimensional analysis algorithm to analyze the effects of complex loading on rigid pavements edge stresses. The proposed algorithm was verified based on the 1984 PCA Concrete Pavement Design Procedure. The verified algorithm was then used to evaluate the effect of single tires on rigid pavements. The study indicated that super-single tires loadings cause a 10% increase in the calculated edge stresses over the conventional dual tires for U.S. loading conditions. It was also noted that the increase in stresses was mainly due to the increase in the inflation pressure for the super-single tires.

In summary, the literature review effort discovered that very little information is available on the relative damage of single tires of rigid pavements. The limited information that was identified indicated that rigid pavements are not sensitive to the configuration of the tires. The NCHRP 1-36 research team conducted a theoretical study to evaluate the damage caused by single tires on rigid pavements as compared to dual tires configuration.

## NCHRP 1-36 Theoretical Study

The objective of this study was to evaluate the relative damage caused by single tires on rigid pavements as compared to dual tires configurations. Rigid pavement responses were calculated in terms of edge stresses as fatigue indicators and corner deflections as faulting indicators. The following combinations of tires, axle loads, and inflation pressures were used.

| Tire Type | Tire Size | Axle Load, kN | Tire Pressure, KPa |
|---|---|---|---|
| Conv. Dual | 11R22.5 | 89 | 690 |
| Singled-out | 11R22.5 | 53 | 690 |
| Super-Single A | 15R22.5 | 71 | 863 |
| Super-Single B | 18R22.5 | 89 | 932 |

The following pavement parameters were considered:

| | |
|---|---|
| Slab thickness: | 254 and 305 mm |
| Joint spacing: | 4.9 m |
| Slab width: | 3.7 m |
| Dowel Diameter: | 32 mm |

Dowel Spacing: 305 mm

Concrete Modulus of Elasticity: 27,600 MPa

Modulus of subgrade reaction: 5,536 $g/cm^3$

Concrete flexural strength: 4.8 MPa

Temperature Differential: 11°C

*Edge Stresses Analysis*

The edge stresses analysis was conducted using the ILLI-SLAB computer program. The first part of the analysis calculated edge stresses under axle loading alone while the second part of the analysis calculated the stresses under the combined action of axle load and environmental impact (i.e. curling). Tables 31 and 32 summarize the loading stresses and combined stresses, respectively. The percent change in stresses is defined as follows:

$$\text{Percent Change:} \quad \frac{(\text{Stress under any tire} - \text{Stress under dual tire}) \text{X } 100}{\text{Stress under dual tire}}$$

The data in Tables 31 and 32 indicate that the highest percent change in the edge stresses was caused by super-single tires under an axle load that is similar to the dual tires configuration. However, when the combined effect of load and temperature is considered, the maximum percent change is reduced by 65%. The evaluation of this data leads to the following conclusions:

1. Singled-out tires are more damaging than dual tires.

Table 31. Calculated edge stresses due to axle loading only.

| Tire Type | Axle Load, kN | Edge Stress, Kpa | Percent Change |
|---|---|---|---|
| Slab Thickness: 254 mm | | | |
| Dual - 11R22.5 | 89 | 1,663 | 0 |
| SOD - 11R22.5 | 53 | 1,304 | -21 |
| SSA - 15R22.5 | 71 | 1,684 | 1 |
| SSB - 18R22.5 | 89 | 2,084 | 25 |
| Slab Thickness: 305 mm | | | |
| Dual - 11R22.5 | 89 | 1,263 | 0 |
| SOD - 11R22.5 | 53 | 973 | -23 |
| SSA - 15R22.5 | 71 | 1,290 | 2 |
| SSB - 18R22.5 | 89 | 1,566 | 24 |

SOD: Singled-out Dual
SSA: Super-Single A
SSB: Super-Single B

Table 32. Calculated edge stresses due to axle loading and temperature differential.

| Tire Type | Axle Load, kN | Edge Stress, Kpa | Percent Change |
|---|---|---|---|
| Slab Thickness: 254 mm | | | |
| Dual - 11R22.5 | 89 | 2,705 | 0 |
| SOD - 11R22.5 | 53 | 2,381 | -12 |
| SSA - 15R22.5 | 71 | 2,677 | -1 |
| SSB - 18R22.5 | 89 | 3,029 | 12 |
| Slab Thickness: 305 mm | | | |
| Dual - 11R22.5 | 89 | 2,428 | 0 |
| SOD - 11R22.5 | 53 | 2,167 | -11 |
| SSA - 15R22.5 | 71 | 2,381 | -2 |
| SSB - 18R22.5 | 89 | 2,643 | 9 |

2. Super-Single tires are more damaging than dual tires only when used under the same axle load.
3. The relative damage caused by single tires is significantly reduced when the combined load and temperature stresses are considered.

*Joint Faulting Analysis*

Corner deflections and shear forces on dowels were used as indicators of joint faulting potential. The computer program JSLAB was used to calculate corner deflections and shear forces on dowels under the axle loading alone. Since temperature differential does not directly impact the corner deflections and shear forces on dowels, only the axle loading case was evaluated. Tables 33 and 34 summarize the results of this part of the study.

The data in Table 33 indicate that the super-single tires generate lower corner deflections than the dual tires. In other words, the super-single tires are less detrimental toward faulting than the dual tires. In the case of shear forces on the dowels (Table 34), the super-single tires showed a maximum increase of 21% in the transferred shear force. However, all shear forces are well below the expected bearing strength of the concrete which is around 14 kN (3,150 lb). Therefore, the percent increase in the shear forces on dowels becomes insignificant toward the development of faulting.

Table 33. Calculated corner deflections due to axle loading.

| Tire Type | Axle Load, kN | Corner Deflection, mm | Percent Change |
|---|---|---|---|
| Slab Thickness: 254 mm | | | |
| Dual - 11R22.5 | 89 | 0.56 | 0 |
| SSA - 15R22.5 | 71 | 0.48 | -14 |
| SSB - 18R22.5 | 89 | 0.53 | -5 |
| Slab Thickness: 305 mm | | | |
| Dual - 11R22.5 | 89 | 0.46 | 0 |
| SSA - 15R22.5 | 71 | 0.41 | -11 |
| SSB - 18R22.5 | 89 | 0.46 | 0 |

Table 34. Calculated shear forces on dowels due to axle loading.

| Tire Type | Axle Load, kN | Shear Force on Dowel, kN | Percent Change |
|---|---|---|---|
| Slab Thickness: 254 mm | | | |
| Dual - 11R22.5 | 89 | 10.7 | 0 |
| SSA - 15R22.5 | 71 | 11.1 | 4 |
| SSB - 18R22.5 | 89 | 12.9 | 21 |
| Slab Thickness: 305 mm | | | |
| Dual - 11R22.5 | 89 | 10.2 | 0 |
| SSA - 15R22.5 | 71 | 10.2 | 0 |
| SSB - 18R22.5 | 89 | 12.0 | 18 |

*Summary and Recommendations*

In light of the lack of current information regarding the relative damage on rigid pavements caused by single tires as compared to dual tires, a theoretical analysis was conducted to support the research team's recommendations for future directions. The theoretical analysis consisted of evaluating the relative impact of single tires on edge stresses, corner deflections, and shear forces on dowels. These responses were chosen because of their direct impact on cracking and faulting potential of rigid pavements.

The analysis of the data indicated that single tires will generate slightly higher edge stresses when loaded with the same axle load level. However, the increase in edge stresses is significantly reduced when temperature stresses are superimposed to stresses generated by axle loading.

In the case of faulting, the analysis of the data showed that single tires actually reduce corner deflections which indicate that they are less detrimental toward faulting than dual tires. When looking at the shear forces on dowels, single tires showed a maximum increase of 21% in the transferred shear force as compared to dual tires. However, the maximum shear forces on dowels for all tires are well below the bearing capacity of the concrete.

Based on the review of the limited available information and the analysis of the data generated in this study, the following recommendations can be made:

1. The impact of super-single and singled-out tires on rigid pavements as compared to dual tires is insignificant.
2. It is clear that the relative damage of single tires as compared to dual tires on flexible pavements is a lot more significant than on rigid pavements.

3. No additional efforts should be expanded in this project to assess the damage of single tires on rigid pavements as compared to dual tires.
4. Any technical and regulatory approaches that will be developed to control damage on flexible pavements caused by single tires will very adequately cover the anticipated damage on rigid pavements.

## COST-BENEFIT ANALYSIS OF SUPER-SINGLE TIRES

Recent trends in the Netherlands showed that new trailers and semi-trailers are fitted with super-single tires and relatively few dual tires are applied. The super- single has clearly conquered the market in the Netherlands. Figure 11 shows the percentage of axles of trailers and semi-trailers fitted with super-single tires at different locations throughout the Netherlands.

In light of this drastic increase in the use of super-single tires, the Netherlands Road Authority has conducted a cost-benefit analysis of the use of super-single tires on the axles of trailers and semi-trailers (18). The analysis used the concept of damage ratio which is expressed as follows:

$$\text{Damage Ratio} = \{k1 * k2 * k3 * (P_{act}/P_o)\}^{4.0}$$

k1 is a factor which represents the influence of the axle configuration:

k1 = 1.0 for single axle

k1 = 0.6 for tandem axle

k1 = 0.45 for Triaxle

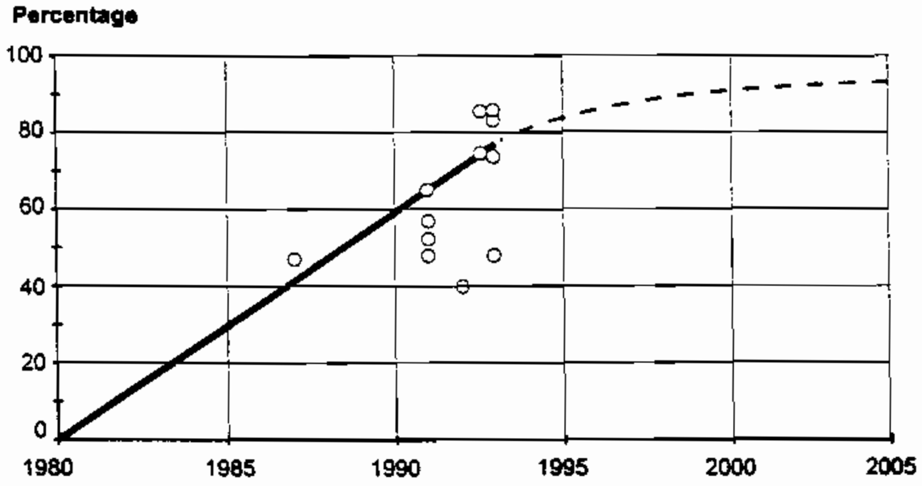

Figure 11. Percentage of axles of trailers and semi-trailers with super-single tires.

k2 is a factor which represents the influence of tire type:

k2= 1.0 for dual tires

k2= 1.3 for singled-out tires

k2= 1.2 for super-single tires

k3 is a factor which represents the influence of suspension:

k3= 1.0 for traditional leaf spring suspension

k3=0.95 for air bag suspension

$P_0$ is the reference axle load which is 10 tonnes.

$P_{act}$ is the magnitude of the actual axle load.

In general, it is assumed that the passage of an axle with super-single tires, with a given load, causes more damage to the pavement than the passage of an axle with dual regular tires. The study evaluated pavement damages for the following cases:

Year 1980 with 0% super-single tires

Year 1993 with 0% and 75% super-single tires

Year 2000/2005 with 0% and 100% super-single tires

Figure 12 shows the ratio of increase in pavement damage for an average motorway in the period 1980 to 2000/2005

## Costs Associated with the Use of Super-Single Tires

The study assumed that loading pavements with super-single tires on all trailer and semi-trailer axles leads to higher maintenance costs as compared with dual tires. The higher maintenance costs were calculated with the aid of the FRAME model (Forecasting Regional

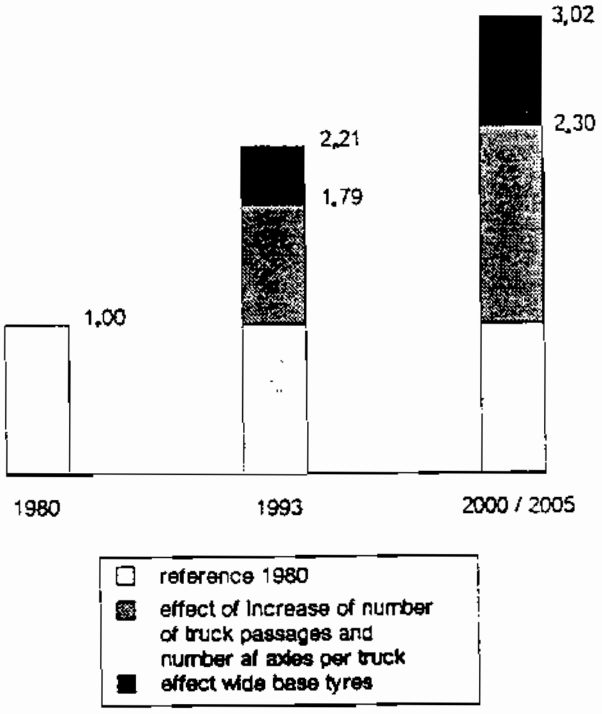

Figure 12. Ratio of increased pavement damage for a typical motorway in Netherlands.

Allocation of Means). This model has been developed by the Road and Hydraulic Division within the framework of the project Road Management 2000 for the allocation of financial means. The 30% increase in pavement damage by applying super-single tires has a cost raising effect of approximately 6%. Assuming a maintenance budget of 250 million guilders ($480 million) per year, this represents a 15 million guilders ($29 million) per year.

It was also assumed that using super-single tires requires higher quality of porous surface layers to resist raveling, cracking and rutting. The additional costs for modified surface layers have been estimated at approximately 7 million guilders ($13.5 million) per year. Using super-single tires also means higher costs for the construction/widening of roads. This additional cost have been estimated at approximately 4 million guilders ($7.7 million) per year. The total costs add up to 26 million guilders ($50 million) per year.

### Savings Associated with the Use of Super-Single Tires

The study identified three sources of savings associated with the use of super-single tires:

1. Increase in net loading capacity
2. Lower tire cost
3. Less fuel consumption

The weight advantage for the 385/65R22.5 super-single tire amounts to 120 kg (264 lb) per axle. Table 35 shows annual cost savings due to higher net loading capacity of heavy vehicles by using super-single tires on all trailer and semitrailer axles forecasted for the 1997 year.

The use of super-single tires result in lower tire costs. This is mainly because when purchasing a new trailer or semi-trailer less tires and wheels are needed and at the end of the life span less tires need retreading or complete replacement will be required. The annual mileage was assumed at 75,000 km, with an estimated life span of 12 years. It was also assumed that the life span of the tire tread is 150,000 km for both types of tires and that during the life span of the tire the tread is renewed once. Calculations showed that the tire cost per axle for dual tires are 1.43 ct (2.75 cents) per kilometer and 0.9 ct (1.73 cents) per kilometer for super-singles. Using super-single tires results in a 37% savings. Table 36 shows the annual cost savings due to lower tire costs by using super-single tires on all trailer and semi-trailer axles forecasted for the 1997 year.

The super-single tires are used with higher tire pressure than regular dual tires. The higher contact pressure results in a contact area with the road that is smaller than regular dual tires. Because of this the super-single tire has a lower rolling resistance and that results in a decrease in fuel consumption. Savings were calculated for two groups of trucks, namely: a) articulated truck with allowable vehicle-combination weight more than 40 tonnes and b) articulated truck with allowable vehicle-combination weight less than 40 tonnes

An average value of 5% savings on fuel consumption was assumed for group one and 2.5% for group two. A lower value was used for group two because the average number of axles per vehicle fitted with super-single tires is less. Fuel savings also result in lower exhaust fume discharges. Table 37 shows annual cost savings due to lower fuel consumption

Table 35. Annual cost savings due to higher net loading capacity of heavy vehicles.

| Types of Goods | Savings in Millions of Guilders* |
|---|---|
| agricultural products and livestock | 3.36 |
| food products and cattle feed | 5.19 |
| Solid mineral fuels | 0.20 |
| petroleum and petroleum products | 0.6 |
| ores, metal waste | 0.3 |
| iron, steel and non ferrous metals | 1.34 |
| crude minerals and products; building materials | 4.71 |
| fertilizers | 0.5 |
| chemical products | 3.11 |
| vehicle, machines and other goods | 2.98 |
| Total | 22.3 |

* 1 Dollar = 0.521 Guilder

Table 36. Annual cost savings due to lower tire costs.

| Truck category | Savings in millions of guilders |
|---|---|
| articulated truck allowable vehicle-combination weight more than 40 tonnes | 17.8 |
| articulated truck allowable vehicle-combination weight less than 40 tonnes | 22.7 |
| total savings | 40.5 |

Table 37. Annual cost savings due to lower fuel consumption.

| Truck category | Savings in millions of guilders |
|---|---|
| articulated truck allowable vehicle-combination weight more than 40 tonnes | 25 |
| articulated truck allowable vehicle-combination weight less than 40 tonnes | 23 |
| total savings | 48 |

Table 38. Summary of the calculated extra costs and benefits per year for super single tires.

| Costs | in millions of guilders | Benefits | in millions of guilders |
|---|---|---|---|
| MotorWay Network | | Weight Saving | 22 |
| Pavement | 26 | Tire Cost | 41 |
| Bridges | 6 | Fuel Cost | 48 |
| Provincial roads | | | |
| Pavement | 10 - 15 | | |
| Bridges | 6 | | |
| Total | 53 | | 111 |

caused by lower rolling resistance when applying super-single tires on all trailer and semi-trailer axles.

### Conclusions and Recommendation

Using super-single tires in the Netherlands is particularly economical for tires and fuel costs. Besides the financial aspect, there are also favorable environmental aspects, namely less energy consumption, less exhaust-fume emission, less need for raw materials (rubber) and a limit to the waste flow of old tires. Table 38 gives a summary of the calculated extra costs and benefits per year when applying super-single tires.

# CHAPTER 3

# PREVELANCE OF SINGLE TIRES AND ASSOCIATED DISTRESS

## TRAFFIC SURVEYS

Traffic surveys are typically conducted by highway agencies to gather information on the traffic volume and composition using the highway system. The kind of traffic surveys that are of interest to this research project are the ones that include specific information regarding the distribution of tire types.

As part of this research project, a survey questionnaire was sent to the state highway agencies (SHA) requesting information concerning any traffic survey studies that they have conducted. A total of 37 responses were received. Only four SHA's have conducted traffic surveys to identify the types of tires and tires configurations that are being used on the highway system. The following represents a summary of the four SHA's traffic survey studies.

### Washington DOT

In 1983, the Washington Department of Transportation conducted a limited traffic survey study to identify the distribution of tire types, tire loads, and tire inflation pressure (19). A total of 80 trucks were surveyed on the northbound of Interstate I-5 near Fife Washington. The following observations were made:

1. A total of six trucks had singled-out tires on single or tandem axles.
2. One truck exceeded the criterion of 105 N per one millimeter of tire width.
3. One truck with 419 mm (16.5 in) wide super-single tires and one truck with 457

mm (18 in) wide super-single tires.

In summary, the Washington DOT study showed that the percentage of trucks using super-single or singled-out tires is around 10 percent. Also the number of trucks violating the load/tire width regulation is extremely small. However, it should be noted that the sample size is very small which may skew the data in either directions.

### Arkansas DOT

In 1988, the Arkansas DOT conducted a traffic survey study which identified the distribution of tire types on the highway system (20). The survey indicated that 72% of the tires are radial while 28% of tires are bias. A later study by Oregon DOT indicated that the percent of bias tires has been dropping significantly (1.2% in 1992) since the Arkansas study.

### Oregon DOT

In 1992, The Oregon Department of Transportation Conducted a traffic survey study to identify the distribution of super-single and singled-out tires on the state highway system (21). The survey covered five Ports of Entry (POE). Table 39 summarizes the percentages of singled-out tires at the various POE's. This data showed that there the percentage of the trucks on the highway system that are using singled-out tires ranges between 1.5 and 21. It is very clear that the percentage of the trucks using singled-out tires depends on the location within the state highway system.

Table 39. Summary of data on trucks using singled-out tires based on the 1992 survey conducted by Oregon DOT. (20)

| **POE** | **March** | | | **June** | | | **September** | | | **Overall Singled-out, %** |
|---|---|---|---|---|---|---|---|---|---|---|
| | **No. of Trucks** | **Trucks with singled-out** | **%** | **No. of Trucks** | **Trucks with singled-out** | **%** | **No. of Trucks** | **Trucks with singled-out** | **%** | |
| Ashland | 196 | 3 | 1.5 | 169 | 3 | 1.8 | 218 | 3 | 1.4 | 1.5 |
| Woodburn | 113 | 8 | 7.1 | - | - | - | 88 | 12 | 14 | 10 |
| Cascade Locks | 85 | 17 | 20 | 231 | 48 | 21 | 100 | 23 | 23 | 21 |
| Farewell Bends | 132 | 12 | 9.1 | 49 | 4 | 8.2 | 36 | 2 | 5.6 | 8.3 |
| Klamath Falls | 108 | 7 | 6.5 | 115 | 0 | 0 | 65 | 1 | 1.5 | 2.8 |

The Oregon DOT study mentioned that the reason the Cascade Locks POE has the highest percentage is attributable to the large proportion of trucks shipping garbage to Arlington, OR. The study also indicated that: "A large proportion of the tridem axles were singled-out (40% in March and June, and 90% in September). Of these, the majority were partially singled-out. The lead axle was the axle most likely to be singled-out. A small percentage of tandems were singled-out. Of these, the tendency was for both axles to be singled-out."

Table 40 summarizes the overall distribution of tire types for all of the surveyed POE's in Oregon. The data clearly indicate that the majority of the trucks use dual tires. The percent of trucks using singled-out tires ranges between 7 and 10 percent and the percentage of trucks using super-single tires is around 1.5 percent. It should be noted that this data were collected in 1992 and some of these trends may have changed. In addition, the Oregon study indicated the following distribution of the trucks using singled-out dual tires: 40% were carrying groceries, 26% were carrying garbage and waste, and 11% were empty.

Figures 13 and 14 shows the distribution of the singled-out tires as a function of axle combinations for the March and June 1992 surveys, respectively. The data show that there are some differences between the two dates. The lead axle of the tridem group and both axles on the tandem group are among the highest in both surveys. However, the June survey (Figure 14) shows that the percent of single axles using singled-out tires has significantly increased since the March survey.

In summary, the Oregon DOT data showed that the percent of trucks using singled-

Table 40. Summary of the survey data for all the Surveyed POE's based on the 1992 survey conducted by Oregon DOT. (20)

| **Tire Types and Configuration** | **March: 635 Trucks** | | **June: 564 Trucks** | | **September: 511 Trucks** | |
|---|---|---|---|---|---|---|
| | **No. Trucks** | **Percent** | **No. Trucks** | **Percent** | **No. Trucks** | **Percent** |
| Bias Tires on Steering | 0 | 0 | 0 | 0 | 2 | 0.4 |
| Bias Tires on Non-Steering | 63 | 9.9 | 24 | 4.3 | 34 | 6.6 |
| Dual Tires 280 mm wide | 342 | 53.9 | 372 | 66.0 | 210 | 41.1 |
| Other Dual Tires | 227 | 35.7 | 166 | 29.5 | 258 | 50.5 |
| Super-Single Tires | 3 | 0.5 | 1 | 0.2 | 9 | 1.8 |
| Singled-out | 47 | 7.4 | 55 | 9.8 | 41 | 8.0 |

Table 41. Summary of the 1992 traffic survey data conducted by South Dakota DOT. (21)

| **Tire Configuration** | **Percent (%)** | **Tire Width (mm)** |
|---|---|---|
| Dual Tires | 73.0 | 282 |
| Super-Single Tires | 23.3 | 386 |
| Singled-out Dual Tires | 3.7 | 274 |

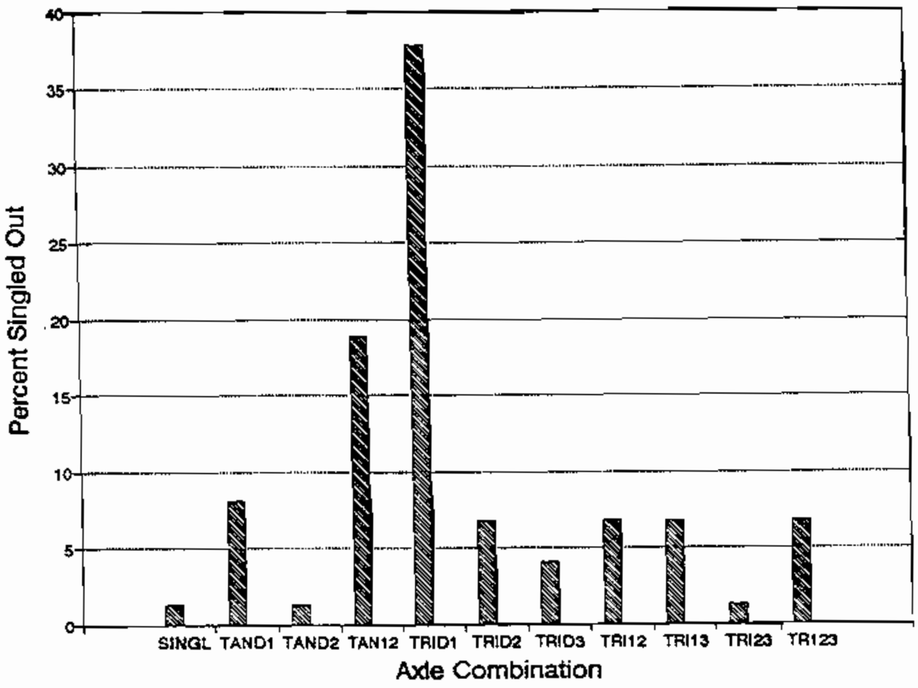

Figure 13. Percent distribution of axles using singled-out tires based on the March 1992 survey.

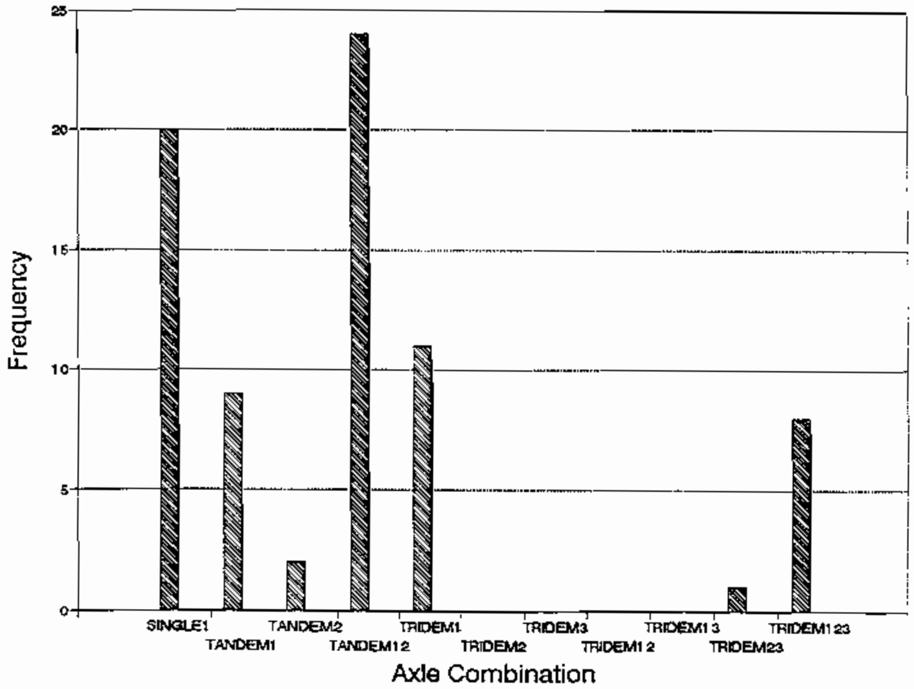

Figure 14. Frequency distribution of axles using singled-out tires based on the June 1992 survey.

out tires maybe significant depending on the location within the state highway system. The data also showed that the majority of truck tires are radial ply tires. In addition, the tendency of using singled-out tires on the lead axle of the tridem group is the highest among all other axle groups, followed by both axles of the tandem group and the single axle.

### South Dakota DOT

In 1992, The South Dakota Department of Transportation conducted a traffic survey study at five locations throughout the state (22). Table 41 shows a summary of the survey data. This survey data showed that the majority of the trucks use dual tires, however, the percentage of trucks using super-single tires in South Dakota is relatively significant (e.g. 23.3 %).

In 1994-1995, the South Dakota DOT conducted another very extensive traffic survey to identify the distribution of tires configurations on the highway system (23). The survey included 36 locations on the South Dakota highway system. Figure 15 shows the distribution of dual tires, super-single, and singled-out tires. The location axis in Figure 15 shows the route number and the milepost separated by a slash (/). The data showed that the great majority of the trucks on the majority of locations use dual tires. The percent of singled-out tires is in the range of 15 to 20 percent on some locations. In fact, the percent of singled-out tires at SD 44 MP 69 exceeds the percent of dual tires. The percent of super-single tires ranges between 0 and 10 percent.

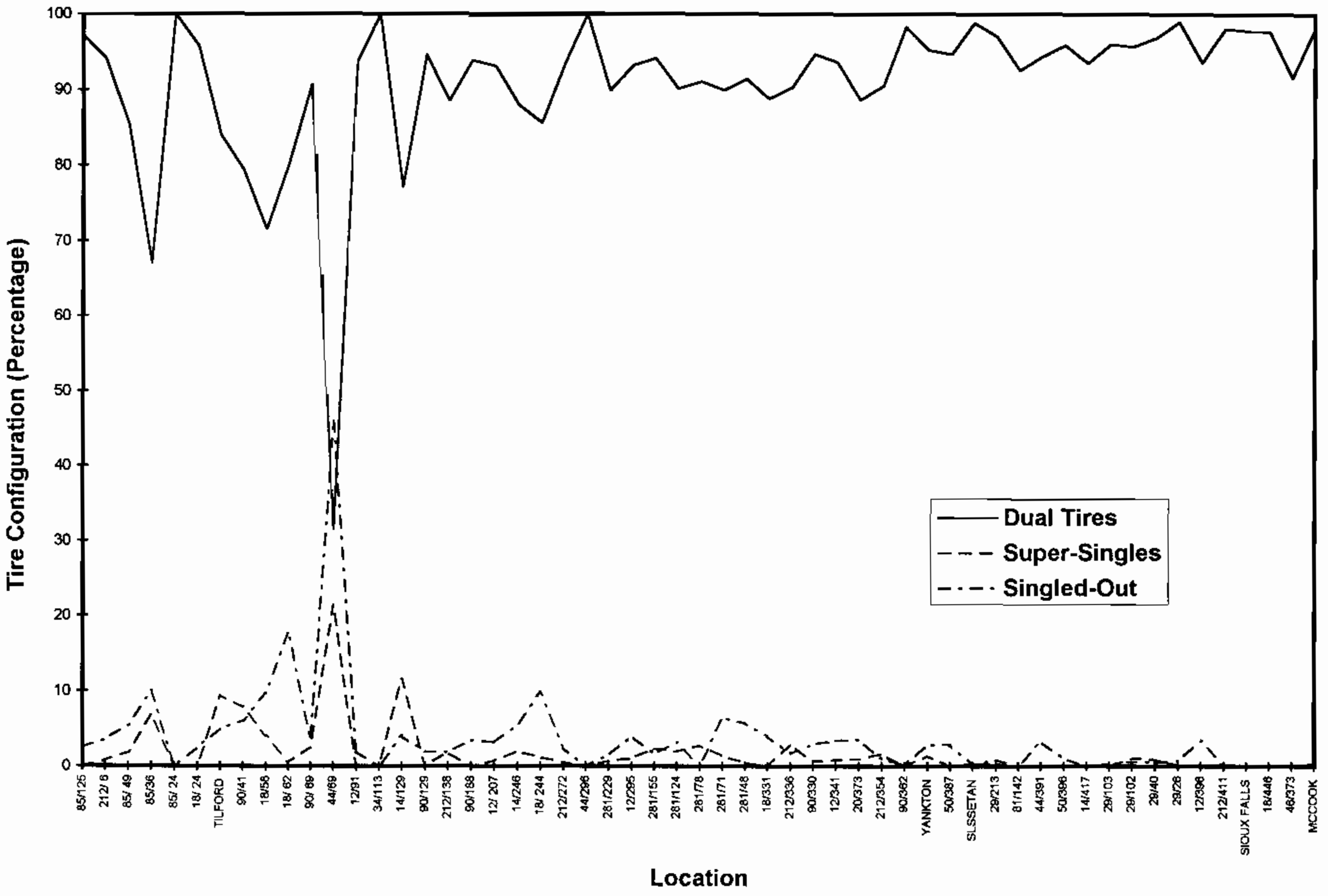

Figure 15. Distribution of tire types at various highway locations.

The South Dakota DOT surveys clearly indicate that there is an upward trend in the use of singled-out tires. The 1992 survey showed very small percentage of trucks using singled-out tires while the 1994-1995 survey showed a significant percentage of trucks using singled-out tires. However, the use of singled-out tires is highly dependend on the location throughout the state.

## Summary and Recommendations

A total of four traffic surveys have been conducted throughout the U.S. to identify the prevailence of single tires on the highway system. Among the four studies, the South Dakota and Oregon studies are the most extensive ones. Based on the analysis of the data from these surveys, the following recommendations can be made:

1. The majority of truck tires are radial ply tires.
2. The majority of trucks still use dual tires configurations.
3. The use of singled-out tires is increasing at an alarming rate at some locations.
4. The increase in the use of singled-out tires seems to be highly dependent on the location within the state highway system.
5. The use of super-single tires has been holding steady within the past five years with an average percentage ranging between 5 and 10%.

## TIRE MARKET DISTRIBUTION

The market shares of the various tire types were collected from the tires manufacturers. Table 42 summarizes the market shares distribution for the various tire types. The data for the years between 1989 and 1994 are missing because most manufacturers do not keep more than three years of data.

Market shares data provides a good indication on the trends of the super-single tires, however, no indication is given on the use of the singled-out tires since the conventioanl and low profile duals can also be used as singled-out tires. The data in Table 42 indicate that dual tires dominates the market either in the form of conventional duals or low profiles duals. The national market has not seen any significant changes in the production and use of the super-single tires. Discussions with tire manufacturers representatives indicated that the majority of the super-single tires are being used for local short hauls such as concrete mixers and garbage trucks. In addition the tires manufactures believe that the 315/80R22.5 super-single tire is the most damaging tire on highway pavements due to its highest unit pressure. This type of tire makes up the following percentages of the market:

| Year | Percent of 315/80R22.5 |
|---|---|
| 1994 | 0.8% |
| 1995 | 0.9% |
| 1996 | 1.1% |

By looking at the above percentages, it can be seen that the 315/80R22.5 tire represents the majority of the super-single tires used in the market today. This type of tire is mainly used on the axle of garbage/waste haulers.

## TIRE LOAD LIMITS

The survey data indicated that only a few state highway agencies consider the use of single tires as being a problem. Several of the surveyed agencies indicated that the percentage of single tires on their highway system is too little to be of any concern. However, the majority of them have implemented a tire load limit criterion which indirectly discourages the use of singled-out or super-single tires on highway traffic. Currently thirty states have regulatory limits on the basis of weight per unit width of the tire. These laws specify the maximum legal wheel load in newton per millimeter of tire width or as the manufacturer's recommended load whichever is less. Table 43 summarizes the regulations of the various agencies.

Table 44 shows the allowable single axle loads in KN based on the various levels of tire load limits. The majority of the states are currently allowing up to 90 kN on single axles. The data in Table 44 show that the tire load limit can be used to discourage the use of singled-out and the regular super-single (385/65R22.5) tires while the use of the wide super-single tires (i.e. 425/65R22.5) may not be affected unless the tire load limit was reduced to 105 N/mm (600 lb/in) or less. In other words, wide super-single tires can currently be used on many highways without violating neither the axle load nor the tire load limits.

## PAVEMENT DISTRESS ASSOCIATED WITH TIRE TYPE

As mentioned earlier the major types of load-associated pavement distresses are the rutting and fatigue failures. Various studies have indicated that tire type significantly impact the loading mechanism at the tire/pavement interface and therefore, may change the mode of Table 42. Market shares distribution for the various tire types

| Tire Type | 1987 (%) | 1989 (%) | 1994 (%) | 1995 (%) | 1996 (%) |
|---|---|---|---|---|---|
| Conventional Duals | 52 | 49 | 55 | 52 | 53 |
| Low Profile Duals | 47 | 49 | 44 | 46 | 45 |
| Super-Singles | 1 | 2 | 2 | 2 | 2 |

Table 43. Tire load limit laws for various state highway agencies.

| Tire Load N/mm (lb./in) | States |
|---|---|
| 96.3 (550 ) | Alaska, Mississippi, North Dakota, South Dakota |
| 105.1 (600 ) | Connecticut, Idaho, Kentucky, Maine, Minnesota, Montana, New Hampshire, New Mexico, Nevada, Oregon, South Carolina, Utah, Vermont, Washington, Wyoming |
| 106.0 (605) | Florida |
| 113.8 (650) | Louisiana, Ohio, Texas, Virginia |
| 122.6 (700) | Michigan |
| 140.1 (800) | Indiana, Massachusetts, New Jersey, New York, Pennsylvania |

Table 44. Allowable single axle loads in kN based on tire load limits.

| Tire Load (N/mm) | Dual 11R22.5 | Singled-out 11R22.5 | Super-Single 425/65R22.5 | Super-Single 385/65R22.5 |
|---|---|---|---|---|
| 96.3 | 108 | 54 | 82 | 74 |
| 105.1 | 118 | 59 | 89 | 81 |
| 113.8 | 127 | 64 | 97 | 88 |
| 122.6 | 137 | 69 | 104 | 94 |
| 140.1 | 156 | 78 | 119 | 108 |

pavement failure. For example, a pavement may fail in fatigue when loaded with dual tires while the predominent mode of failure for the same pavement may be rutting when loaded with single tires.

In order to check the above mentioned theory on the impact of tire type on failure mode, long term pavement performance must be available. There arc two studies that could offer input data for this evaluation: the ALF study conducted by Bonaquist and the CAPTIF study conducted by Pidwerbesky. Both of these stuides compared pavement performance under dual and single tires.

The results of the ALF study were presented in Figures 5 and 6. The trends in these figures show that single tires accelerates the formation of rutting and fatigue of both the thin and thick sections. The performance data presented in these figures can also be used to evaluate the impact of tire type on the failure mode of flexible pavements. This evaluation was done as follows:

1. Identify failure criteria: The following failure criteria was used.
    a. Fatigue failure: 10m of cracking
    b. Rutting failure: 10mm rut depth
2. Identify the number of load repetitions to cause fatigue and rutting failures under dual and super-single tires for both sections based on the performance data presented in Figures 5 and 6:

| | 89 mm Section | |
|---|---|---|
| Tire Type | 10m Fatigue | 10mm Rutting |
| 425/65R22.5 | 60,000 | 75,000 |
| 11R22.5 | 225,000 | 280,000 |

178 mm Section

| Tire Type | 10m Fatigue | 10mm Rutting |
|---|---|---|
| 425/65R22.5 | 140,000 | 90,000 |
| 11R22.5 | 375,000 | 150,000 |

3. Identify the initial mode of failure under each tire for both sections. For example, the initial mode of failure of the 89mm AC section under super-single tire loading is fatigue because the number of load repetitions (60,000) to cause 10m fatigue is lower than the number of load repetitions to cause 10mm rutting (75,000). Using this approach, the following initial failure modes were identified:

| Section | Tire Type | Initial Failure Mode |
|---|---|---|
| 89mm AC | 425/65R22.5 | Fatigue |
| 89mm AC | 11R22.5 | Fatigue |
| 178mm AC | 425/65R22.5 | Rutting |
| 178mm AC | 11R22.5 | Rutting |

4. Evaluate the impact of tire type on the initial failure mode: The above data indicate that the initial failure mode is not impacted by the tire type. On the other hand, the initial failure mode is significantly impacted by the thickness of AC layer

The results of the CAPTIF study are presented in Figures 7 and 8. The data are presented in terms of typical rut depth after the 15,591 load repetitions. The actual report contains the tranverse profiles for all stations along the test section. Personal discussions with the New Zealand researchers indicated that both sections failed in rutting without any significant fatigue cracking.

Based on the very limited data available, it can be concluded that tire type, i.e. dual versus single, does not have any impact on the failure mode of the pavement section. It is very clear, however, that single tires accelerate the failure of flexible pavements but do not change the distress mode.

# CHAPTER 4

# EVALUATION OF ANALYTICAL PROCEDURES

An analytical procedure is defined as the overall process by which the relative pavement damage caused by single tires as compared to dual tires is evaluated. The first step in evaluating this relative damage consists of defining the modes of failure that are impacted by the use of single tires. All previous studies conducted on this topic agree that rutting and fatigue are the two modes of failure that are most significantly impacted by the use of single tires. In addition, previous studies identified the following parameters as indicators of rutting and fatigue failures:

1. Rutting: a. Vertical strain on top of subgrade.
    b. Vertical deflection at the pavement surface.
    c. Compressive stress at the center of the base layer.
2. Fatigue: a. Tensile strain at the bottom of the asphalt concrete layer.

Having identified the critical responses, the impact of single tires on the rutting and fatigue of flexible pavements can be evaluated through any of the following approaches:

1. Calculate the response parameters under dual and single tires through theoretical modeling and use performance models to predict the relative pavement damage caused by single tires.
2. Measure the response parameters under dual and single tires and use performance models to predict the relative pavement damage caused by single tires. The advantage of this approach is that the measured pavement responses would not be significantly

influenced by the assumptions of the theoretical model used to calculate the critical responses.

3. Measure the performance of flexible pavements under both dual and single tires loadings. The advantage of this approach is that the measured performance would not be impacted by the assumptions of the theoretical models nor the performance models.

It should be noted that the complexity and the cost of conducting the evaluation drastically increases as it moves from approach 1 through 3. Considering the list of pavement response parameters, it can be concluded that the following factors are critical to the evaluation of the relative pavement damage caused by single tires as compared to dual tires.

1. Vehicle factors:
    - a. Axle load
    - b. Tire pressure
    - c. Tire type
    - d. Axle configuration
    - e. Speed
2. Pavement factors:
    - a. Structure
    - b. Temperature
    - c. Stiffness

Therefore, the ideal analytical procedure is the one that measures actual pavement performance under dual and single tires while taking into consideration the impact of the above identified factors. Table 45 summarizes all of the previous studies as they compare to the ideal evaluation plan. The data in Table 45 indicate that none of the previously conducted studies includes all of the features of an ideal analytical procedure.

## SELECTION OF PROMISSING PROCEDURES

The evaluation process indicated that there are several previous studies that possess some features of an ideal analytical procedure. This group of studies included the ones that measured pavement responses or performance under full scale loading conditions. The reason for selecting this group of studies is that measuring pavement responses and/or performance under full scale loading would eliminate several limitations of the analytical procedures that are purely theoretical. These limitations include the modeling of the contact pressure at the tire/pavement interface, vehicle speed, pavement dynamics, materials variability, etc....

This section of the report takes a closer look at the results of the selected studies and compares their recommendations concerning the relative damage of single tires as compared to dual tires. The following studies were selected for this evaluation:

1. "An Assessement of the Increased Damage Potential of Wide Base Single Tires," conducted by Bonaquist (ref# 15).
2. "Relative Rutting Effects of Different Tire Types," Conducted by Pidwerbesky and Dawe (ref#16).
3. "Effect of Tire Types and Pressures on Pavement performance," conducted by Sebaaly and Tabatabaee (ref# 10).
4. "Estimating Damage Effects of Dual vs Super Single Tires with Multidepth

Table 45. Comparison of the analytical procedures used in previous studies.

| Study | Vehicle Factors | | | | | Pavement Factors | | | Performance | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Axle Load | Tire Pressure | Tire Type | Axle Config. | Speed | Structure | Temp | Pav. Stifff. | Rutting | | Fatigue | |
| | | | | | | | | | Calc | Measured | Calc | Measured |
| Perdomo (1) | Varied at 89 and 151 kN | Varied at 1103 and 1517 kPa | Super Single and Dual | Single, Tandem Tridem | N/C | One Structure | N/C | N/C | | | | |
| Deacon (2) | Varied at 18, 36, 54, 12 kN | N/C | Dual and Singled Out | Single and Tandem | N/C | 5 levels of Structural Number | N/C | N/C | | | Yes | |
| Southgate (3) | Varied at 25 and 42 kN | Varied at 552, 793, 1030, 1380 kPa | Dual and Singled Out | Tandem and Tridem | N/C | One Structure | N/C | N/C | | | Yes | |
| Hallin (4) | Varied at 44.5 and 180 kN | N/C | Super Single and Dual | N/C | N/C | 3 different AC layer thickness | N/C | N/C | | | Yes | |
| Bell (5) | N/C | N/C | Dual and Singled Out | N/C | N/C | 2 different AC layer thickness | N/C | N/C | Yes | | Yes | |
| Gillipsie (6) | N/C | Varied at 517 and 827 kPa | Dual, Low Profile Dual, Super Single, Singled Out | N/C | N/C | Thick and thin | 25 C<br>49 C | N/C | Yes | | Yes | |
| Zube (7) | N/C | N/C | Super Single and Dual Bias ply Tires | N/C | N/C | 50-70 mm AC layer | N/C | N/C | | | | |
| Christison (8) | Varied at 56 and 117 kN | N/C | Dual, Super Single, Singled Out Bias ply Tires | N/C | N/C | One Structure | N/C | N/C | | | Yes | |
| Sharp (9) | N/C | N/C | Super Single and Dual Radial Tires | N/C | N/C | One Structure | N/C | N/C | | | | |
| Sebaaly (10) | Varied at 44.5 and 97.9 kN | Varied at 723 and 896 kPa | Dual Bias ply tire, Dual Radial ply, Super Singles Radial | Single and Tandem | 65 km/h | Thick and Thin | N/C | N/C | Yes | | Yes | |

Table 45.Comparison of the analytical procedures used in previous studies (Continued).

| Study | Vehicle Factors | | | | | Pavement Factors | | | Performance | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Axle Load | Tire Pressure | Tire size | Axle Config. | Speed | Structure | Temp | Pav. Stifff | Rutting | | Fatigue | |
| | | | | | | | | | Calc | Measured | Calc | Measured |
| Akram (11) | N/C | N/C | Dual and Super Single Radial Tires | N/C | Varied at 16, 32, 56, 89 km/h | Thick and Thin | 27C<br>39C | N/C | Yes | | Yes | |
| Huhtala (12) | Axle Load 10 tons +/- 20% | Varied at 483 to 1082 kPa | Dual, Low Profile Dual, Super Single Radial Tires | N/C | N/A | 2 different AC layer thickness | | N/C | | | Yes | |
| S. Dakota (13) | Tire Load varied at 70.1, 105.1, 140.2 N/mm | N/C | Super single, Dual, Singled Out Radial Tires | N/C | 30 km/h | One Structure | | N/C | Yes | | | |
| Bonaquist (15) | Varied at 41, 54, 64, 74 kN | Varied at 520, 712, 959 kPa | Dual and Super Single Radial tires | N/C | 19km/h | 2 different AC layer thickness | Low, Moderate, high | N/C | | Yes | | Yes |
| Pidwerbesky (16) | N/C | N/C | Dual and Super Single Radial Tires | N/C | N/A | One Structure | | N/C | | Yes | | |
| Eisenmann (17) | Varied at 31.7 and 49.7 kN | Varied at 800 to 1250 kPa | Dual and Singled Out | N/C | N/C | One Structure | | N/C | | Yes | | |

N/C = Not Considered
N/A = Not Available

Deflectometers," conducted by Akram et al. (Ref# 11).

5. "Effects of Tires and Tire Pressures on Road Pavements," conducted by Huhtala et al. (ref# 12).

6. "The Effects of Increased Truck Tire Loads on Pavements," conducted by Huntington/Austin Research Engineers for the S. Dakota DOT (ref# 13).

The selected analytical models used in 1 and 2 measured actual pavement performance while the models in 3-6 used a combination of measured pavement responses and performance models. The use of a combination of measured pavement responses and performance models is very attractive since a large number of variables can be evaluated within limited budget and time constraints. The objective of this evaluation will be to assess how effective the models that use pavement responses are in predicting the relative pavement damage of single tires as compared to dual tires.

The ALF study evaluated the fatigue and rutting damage factors for the super-single tire on both thin and thick sections under single axle load of 109 kN (24,500 lb) and tire pressure of 703 kPa (102 psi). The damage factors shown in Table 30 were based on the measured strains and deflections and the use of performance models. However, if the performance data shown in Figures 5 and 6 are used, performance-based damage factors can be evaluated. This analysis assumed a 10m (33 ft) cracking and 10mm (0.4 in) rut depth as failure limits for both the thin and thick sections. The corresponding numbers of load reptitions to failures were obtained from Figures 5 and 6 as follows:

| | 89 mm Section | |
|---|---|---|
| Tire Type | 10m Fatigue | 10mm Rutting |
| 425/65R22.5 | 60,000 | 75,000 |
| 11R22.5 | 225,000 | 280,000 |

| | 178 mm Section | |
|---|---|---|
| Tire Type | 10m Fatigue | 10mm Rutting |
| 425/65R22.5 | 140,000 | 90,000 |
| 11R22.5 | 375,000 | 150,000 |

Using the above data and defining the damage factor as the number of load repetitions under the dual tires (11R22.5) divided by the number of load repetitions under the super-single tire (425/65R22.5), the following damage factors can be obtained:

| | | |
|---|---|---|
| 89 mm section: | Fatigue damage factor: 3.75 | Rutting damage factor: 3.73 |
| 178 mm section: | Fatigue damage factor: 2.68 | Rutting damage factor: 1.67 |

Table 46 compares the damage factors based on pavement response and pavement performance in the ALF experiment. The highest descripancy occured between the rutting damage factors for the 89mm pavement. The performance-based rutting factor is three times the rutting damage factor based on pavement response. The pavement-response rutting damage factor showed a lower value for the thin pavement (1.23) than the one for the thick pavement (1.31) which

Table 46. Comparison of the pavement response and pavement performance ALF damage factors.

| Damage Factor/Thickness of AC (mm) | Pavement Response | Pavement Performance |
|---|---|---|
| Fatigue/89 mm AC | 4.30 | 3.75 |
| Fatigue/178 mm AC | 3.52 | 2.68 |
| Rutting/89 mm AC | 1.23 | 3.73 |
| Rutting/178 mm AC | 1.31 | 1.67 |

indicates that super-single tires are more damaging on thick pavements. Again, this observation contradicts pavement design theories which makes the pavement-response rutting damage factors somewhat doudtfull. It should be noted that the pavement-response rutting damage factors were calculated as a simple ratio of surface deflections generated under the single tire over the deflections under the dual tires. The fatigue response-based factors were calculated based on the ratio of number of load repetitions to failure produced from the performance models. The fatigue performance-based and response-based damage factors showed that thicker pavements are less damaged by super-single tires (i.e. lower damage factors).

The CAPTIF study presented the data in terms of rut depth under dual tires versus rut depth under a low profile super-single tire. Converting the measured rut depth into a damage factor for rutting, the CAPTIF study indicated that the low profile super-single tire would have a rutting damage factor of 1.92. It should be noted that both the pavement structure and the tire type significantly differ between the ALF and the CAPTIF studies. In addition, the methods of calculating the damage factors are also different: the ALF damage factors represent the ratios of number of load repetitions to achieve a constant level of rutting or fatigue while the CAPTIF damage factor is the ratio of rut depth under a constant number of load repetitions.

Since the pavement sections used in the ALF experiment are more representative of pavements on the U.S. road network than the pavement section in the CAPTIF experiment, the ALF performance-based damage factors will be used to evaluate the merit of the response-based damage factors.

The damage factors generated form the pavement-response based studies (3-6) have been fully discussed and presented in Chapter 2. Some of these factors can be directly compared with the ALF's performance-based factors as will be shown in the following discussions. Efforts will be made to compare damage factors developed under as close conditions as possible.

The Sebaaly et al. study generated damage factors for a thin pavement with AC thickness of 152 mm (6 in) for the 425/65R22.5 super-single tire under single axle load of 96 kN (21,600 lb). Since the same tire type was used and relatively close pavement thickness and axle loads, the damage factors from the Sebaaly et al. study can be compared with the ALF's performance-based damage factors as follows:

| | Fatigue | Rutting |
|---|---|---|
| Sebaaly et al. | 1.40 | 1.40 |
| ALF performance-based | 2.68 | 1.67 |

The above comparison indicates that the fatigue damage factors vary significantly between the response-based and the performance-based studies while the rutting damage factors are relatively close.

The South Dakota study evaluated the rutting damage factors of singled-out and super-single tires relative to the dual tires. The deflection ratios reported in the South Dakota study referred to the ratio of the deflection under a given tire over the deflection under dual tires with 80 kN (18,000 lb) single axle load. In order to make the data consistant with the ALF performance-based data, it was necessary to convert the ratios in terms of deflections under the same axle load raised to the power 3.8. The converted ratios are as follows:

| Season | Damage factor under single axle load of 106.8 kN |
|---|---|
| Summer | 2.48 |
| Fall | 1.68 |
| Winter | 1.98 |
| Spring | 4.96 |

The measurement of seasonal damage factors presented another problem for the comparison of the S. Dakota data with the ALF data. The S. Dakota study showed that the season signicantly impacts the magintude of the damage factor, especially the spring season. The ALF experiment was conducted during the Summer of 1989. In addition, the pavement structure of the S. Dakota study falls in-between the thin and thick sections of the ALF study. Based on these limitations, it was decided to compare the Summer damage factors from the S. Dakota study with the damage factors from the thin and thick sections of the ALF study.

| | | Rutting damage factor |
|---|---|---|
| S. Dakota | | 2.48 |
| ALF performance-based, | | |
| | Thin: | 3.73 |
| | Thick | 1.67 |

The only conclusion that can be drawn from the above comparison is that the S. Dakota rutting damage factor fits very well within the range of the ALF performance-based rutting damage factors. Assuming a linear relationship between damage factors and AC thickness, a linear interpolation of the ALF's factors would indicate that an AC thickness of 127 mm would have a rutting damage factor of 2.85 which is relatively close to S. Dakota factor of 2.48.

The Akram et al. study evaluated the rutting damage factors under tandem axles with 147 kN (33,000 lb) load. The study evaluated the damage factors for a super-single tire (425/65R22.5) at four speeds (16, 32, 56n and 89 km/h). The pavement section had an AC layer of 178 mm which is exactly the same as the ALF thick section. Since the same super-single tire and AC thickness were used, it was decided to ignore the fact that the Akram et al. study evaluated the damage factors under tandem axles while the ALF used single axles and compare the 16 km/h data from Table 23 with the ALF data. The rutting damage factor was obtained as the ratio of the ESALs under the dual-drive over the super-single on the trailer.

| | Rutting damage factor |
|---|---|
| Akram et al. | 1.69 |
| ALF performance-based | 1.67 |

The above comparison indicates that the rutting damage factors generated from the two approaches are very close.

The Huhtala et al. study generated fatigue damage factors for two pavement sections: 80 mm and 150 mm AC layers. The fatigue damage factors for a super-single tire equivalent to the one tested in the ALF experiment are 3.73 and 3.25 for the 80 mm and 150 mm AC, respectively. These fatigue damage factors are different from the ones shown in Table 25 since they are calculated using the same approach used in the ALF experiment. This approach calculates the damage factors based on the fatigue life under the dual and single tires loaded to the same level. The interpolated fatigue damage factor based on the ALF data for the 150 mm AC is 3.02. These fatigue damage factors compare very well with the ALF factors of 3.75 and 2.68 for the 89 mm and 178 mm sections, respectively.

Table 47 summarizes the damage factors from the selected studies and how they compared with the ALF's performance-based damage factors. The data presented in Table 46 indicate the following:

1. Using the simple ratio of strains or deflections will not result in reliable damage factors for neither rutting nor fatigue. The measured pavement responses will have to be converted into number of ESALs to failure and then used to calculate the damage factors. This indicates that a performance model must be used. 2. The rutting damage factors can be effectively determined by using the ratio of the equivalent single axle loads determined from the vertical compressive strain on top of the subgrade or the vertical deflection at the pavement surface.

3. The fatigue damage factors can be effectively determined by using the ratio of the equivalent single axle loads determined from the tensile strain at the bottom of the asphalt concrete layer.

Table 47. Comparison of the ALF performance-based damage factors with response-based studies

| | Rutting Damage Factors | | | Fatigue Damage Factors | | |
|---|---|---|---|---|---|---|
| Study | Thin | 127 mm AC (interpolated) | Thick | Thin | 150 mm AC (interpolated) | Thick |
| ALF | 3.73 | 2.85 | 1.67 | 3.75 | 3.02 | 2.68 |
| Sebaaly et al. | NA | NA | 1.40 | NA | NA | 1.40 |
| S. Dakota | NA | 2.48 | NA | NA | NA | NA |
| Akram et al. | NA | NA | 1.67 | NA | NA | NA |
| Huhtala et al. | NA | NA | NA | 3.73 | 3.25 | NA |

# CHAPTER 5

# RECOMMENDED EVALUATION PLAN

The objective of this part of the research is to recommended a plan which can be used to determine pavement damage from super-single and singled-out dual truck tires relative to dual tires. Before presenting the recommended evaluation plan, it would be beneficial to mention that the primary objective of the research is to develop a procedure to estimate pavement damage associated with the use of single tires as compared with that of conventional dual tire configurations. Therefore, the relative pavement damage caused by single tires should be the primary measure of the recommended evaluation plan.

The recommendations of the evaluation plan are based on the findings of the research tasks that have been completed which summarized below:

1. Numerous studies have evaluated the relative damage caused by single tires as compared to dual tires. The findings and recommendations of these studies vary significantly depending on the approach used in measuring the relative pavement damage caused by single tires.
2. The relative damage of single tires on rigid pavements is very minimal when compared to flexible pavements. Therefore, any technical and regulatory approaches that will be developed to control damage on flexible pavements will very adequately cover the anticipated damage on rigid pavements.
3. Traffic survey studies and market distribution data indicate that the use of super-single tires has been holding steady for the past ten years at a rate of 1-3 percent of total tires

on highway pavements. However, the use of singled-out tires has been increasing at an alarming rate.

4. The use of singled-out tires is very highly dependent on the location of the highway, the type of comodity being transported, and the axle configurations of the truck. The data showed that a high percentage of singled-out tires are being used on tandem and tridem configurations.

5. The ALF experiment offered the best data on the relative flexible pavement damage caused by super-single tires as compared to dual tires configuration. On the other hand some of the pavement-response studies have generated damage factors which are very close to the ones generated from the ALF experiement.

In light of the above observations, the following criteria were established to guide the development of the evaluation plan:

1. The evaluation plan should be capable of measuring or predicting pavement performance under single and dual tires.

2. The evaluation plan should include the evaluation of relative pavement damage under various combinations of single tires on tandem and tridem configurations. For example, the plan should include the evaluation of relative damage caused by tandem axles with singled-out tires on both the front or back axle or any combination of the two. As

3. The evaluation plan should cover a wide range of the critical parameters as identified in Chapter 4 (vehicle and pavement factors). The wider the range of the critical parameters the more applicable the results/recommendations will be.

The analysis presented in Chapter 3 identified the critical factors to be considered in the evaluation of the relative pavement damage caused by single tires as compared to dual tires. The following is a list of these factors along with their recommended levels:

1. Vehicle factors:
    - a. Axle load (3 levels)
    - b. Tire pressure (2 levels)
    - c. Tire type (3 levels)
    - d. Axle configuration (1-single, 2-tandem, and 3-tridem)
    - e. Speed (2 levels)
2. Pavement Factors:
    - a. Structure (2 levels)
    - b. Temperature (2 levels)
    - c. Stiffness (differs for each section)

The 2 and 3 levels for the tandem and tridem represents the combinations of singled-out tires on various axles (i.e. front, back, or middle). It was also inidicated that the ideal analytical procedure is the one that measures actual pavement performance under dual and single tires while taking into consideration the impact of the above identified factors. The options for obtaining actual pavement performance are the following:

1. Use the Accelerated Loading Device (ALF)
2. Use the Heavy Vehicle Simulater (HVS)
3. Use a full scale test track

## ALF EXPERIMENT

Conducting an ALF experiment to evaluate the relative damage of single tires as compared to dual tires will satisfy the majority but not all of the above identified critical factors. Axle configuration and speed are the two factors that could not be handled in an ALF experiment. The ALF machine can only simulate single axle at 16 km/h (10 mph) loading speed. An ALF experiment would require the construction and testing of an individual test section for each combination of the critical factors. Considering only the factors that the ALF can satisfy, this would require the construction and testing of 72 test sections. Discussions with FHWA personnel indicated that the cost of constructing a test section is around $50,000.00 and the operational costs of the ALF machine are around $275,000.00/year. Assuming that three sections can be tested each year, the total cost for each section will be around $ 140,000.00.

## HVS EXPERIMENT

Conducting an HVS experiment to evaluate the relative damage of single tires as compared to dual tires will satisfy the majority but not all of the above identified critical factors. Axle configuration and speed are the two factors that could not be handled in an HVS experiment. The HVS machine can only simulate single axle at 8 km/h (5 mph) loading speed.

An HVS experiment would require the construction and testing of an individual test section for each combination of the critical factors. Considering only the factors that the HVS can satisfy, this would require the construction and testing of 72 test sections. Discussions with

University of California, Berkeley personnel indicated that the cost of constructing a test section is around $50,000.00 and the operational costs of the HVS machine are around $80,000.00/month. Assuming that it will take four month to test a section, the total cost for each section will be around $370,000.00.

## A TEST TRACK EXPERIMENT

A test track experiment will satisfy all of the critical factors since actual trucks will be used to load the pavement which can handle variable speed and multiple axle configurations. Constructing test sections on an existing test track will also allow for multiple structural sections to be tested. The construction of pavement sections on an existing test track similar to the Westrack facility would involve milling of the existing AC layer and replacing it with the desired thickness of the new section. The cost for such activity is $15,000 per section. The operational cost of the truck loading is around $45,000/month.

The advantage of a test track experiment is that multiple sections can be tested at the same time which would greatly reduce the operational cost per test section. For example four or more test sections can be tested at the same time which makes the operational cost at $11,000/month/section.

The above analysis shows that achieving the ideal evaluation plan is outside the financial capabilities of this research project. This observation coupled with the fact that pavement-response based studies compared favorably with the data generated from the ALF experiment led the research team to recommend one main evaluation plan and one alternative plan.

## THE MAIN EVALUATION PLAN

Based on the noticeable success of some of the pavement-response type studies, it is recommended that a pavement-response experiment be conducted to evaluate the relative damage of flexible pavements caused by single tires as compared to dual tires. The concept of the proposed experimental plan consists of measuring pavement responses under a wide range of the critical factors and use performance models to predict pavement damage under both single and dual tires. Use the evaluated damages to determine the relative pavement damage caused by single tires as compared to dual tires. In addition, the measured pavement responses will be used to validate a theoretical analysis model which will be used to predict the relative damages of conditions outside the proposed experimental plan.

### Experimental Program

Construct two test sections at the Westrack facility: one thin section and one thick section. Figure 16 displays the location of these test sections on the Westrack facility. Figure 17 shows the layout of the test sections. The following abreviations are used to describe the test sections:

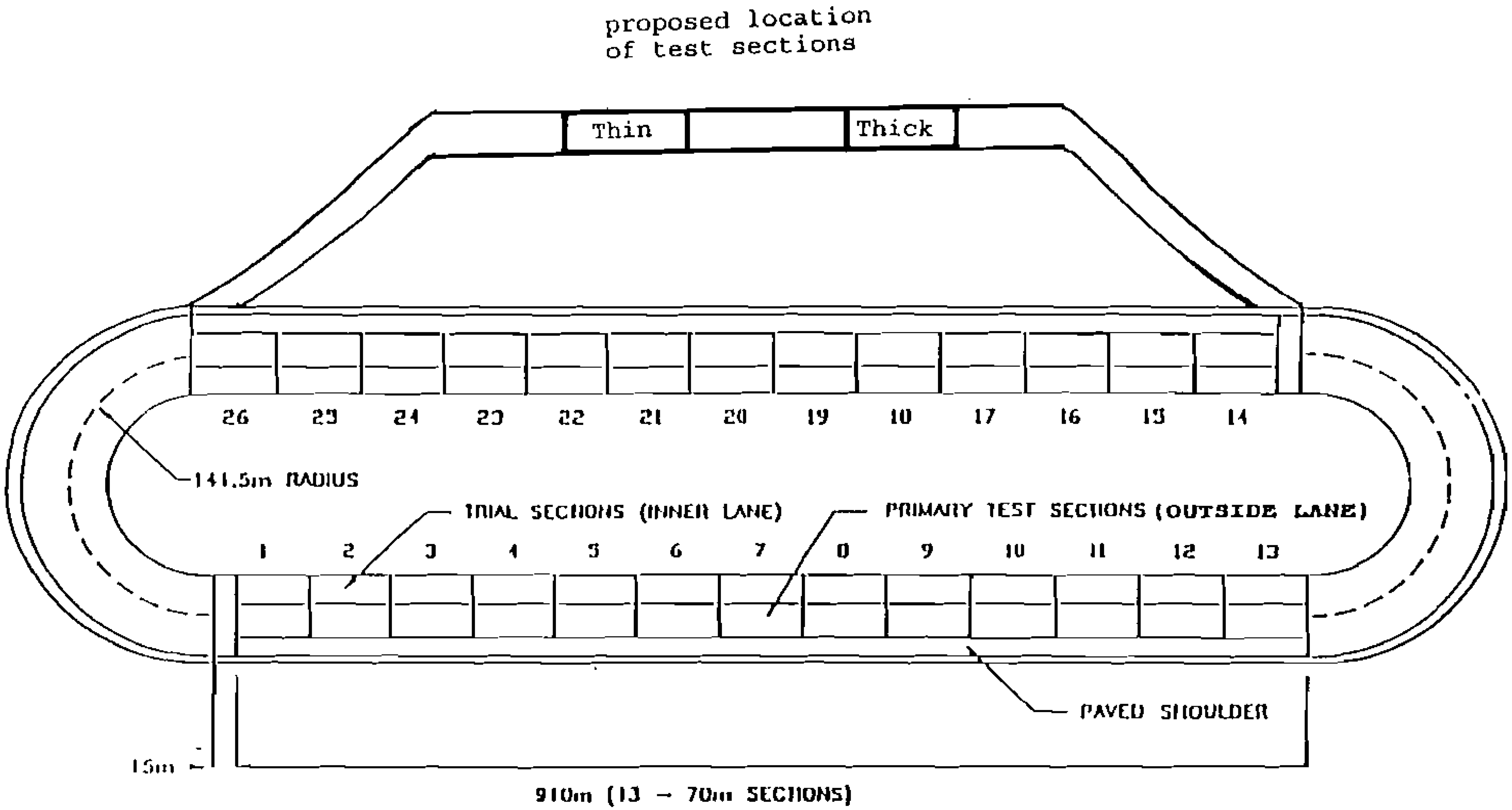

Figure 16. Westrack facility and proposed test sections layout.

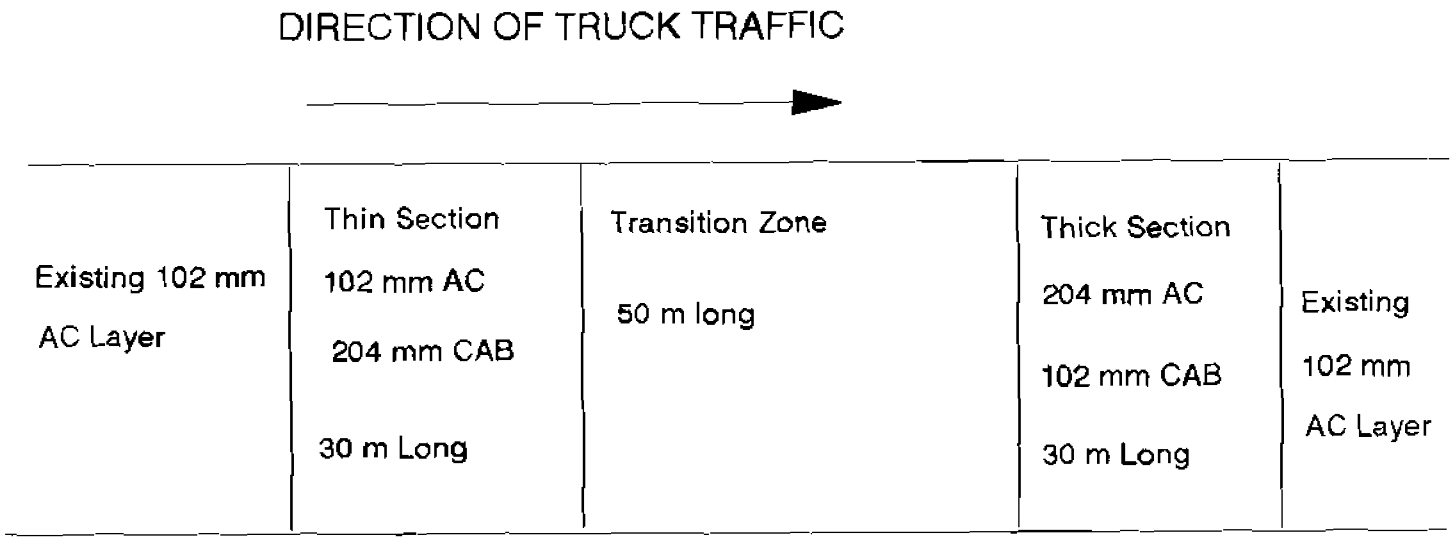

Figure 17. Layout of the proposed flexible pavement test sections.

HMA = Hot Mixed Asphalt

CAB = Crushed Aggregate Base

SG = Subgrade

*Pavement Structures and Materials Properties*

A combination of pavement structure and properties of the HMAC layer will be used to achieve a strong and a weak flexible pavement sections. The two sections will consist of the following:

| Section | Layer | Thickness (mm) | Modulus at 25°C (MPa) |
|---|---|---|---|
| Thin | HMA | 102 | 1,300 - 1,700 |
| | CAB | 204 | 19.3 |
| | Comp. SG | 204 | 9.7 |
| | Nat. SG | | 5.2 |
| Thick | HMA | 204 | 2,400 - 2,800 |
| | CAB | 102 | 19.3 |
| | Comp. SG | 204 | 9.7 |
| | Nat. SG | | 5.2 |

The combination of a thin section with low modulus HMA and a thick section with high modulus HMA will provide two extremely different sections with distinct responses.

*Instrumentation Layout*

The overall objective of this experiment is to measure the pavement responses that can be used to assess the relative damage of single tires as compared to dual tires. As mentioned earlier, the critical responses include the maximum tensile strain at the bottom of the HMA layer, the compressive strain at the top of the SG and the vertical deflection at the pavement surface. The maximum tensile strains will be measured using longintudinal and transverse strain gauges installed at the bottom of the HMA layer while the compressive strain at the top of SG and vertical surface deflection will be measured using the multi-depth-deflectometer (MDD).

Figures 18 and 19 show the proposed instrumentation plans. The longitudinal and transverse strain gauges will be installed in groups of five (30 cm apart) at three locations throughout each of the pavement section. The MDD will be installed in the wheeltrack at the middle of each pavement section. Thermocouples will be installed throughout the depth of the HMA layer to monitor the temperature.

### *Field Test Program*

The following combinations of the test paramters will be used in the field test program:

- Axle Load:
  - Intermediate
  - Full
  - 20% Overload
- Speed:
  - 24 km/h
  - 80 km/h
- Tire pressure:
  1. Manufacturer recommended
  2. 80% of manuf. recommended
  3. 120% of manuf. recommended
- Axle Configuration/ tire type:
  1. Single axle/dual tires
  2. Single axle/low profile dual tires
  3. Single axle/super-single tires
  4. Single axle/singled-out tires
  5. Tandem axle/dual tires on both axles
  6. Tandem axle/low profile dual tires on both

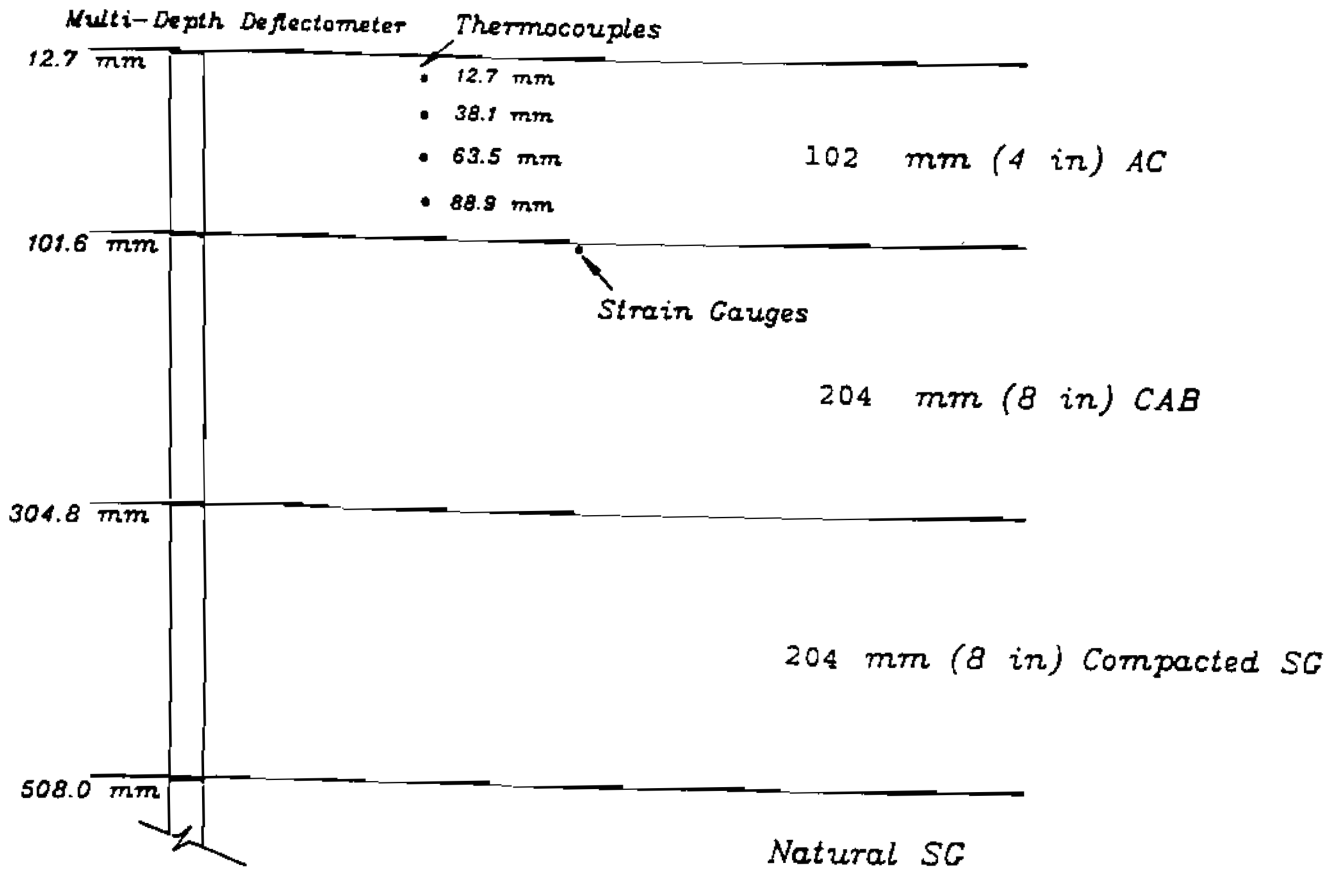

Figure 18. Instrumentation plan for the thin section.

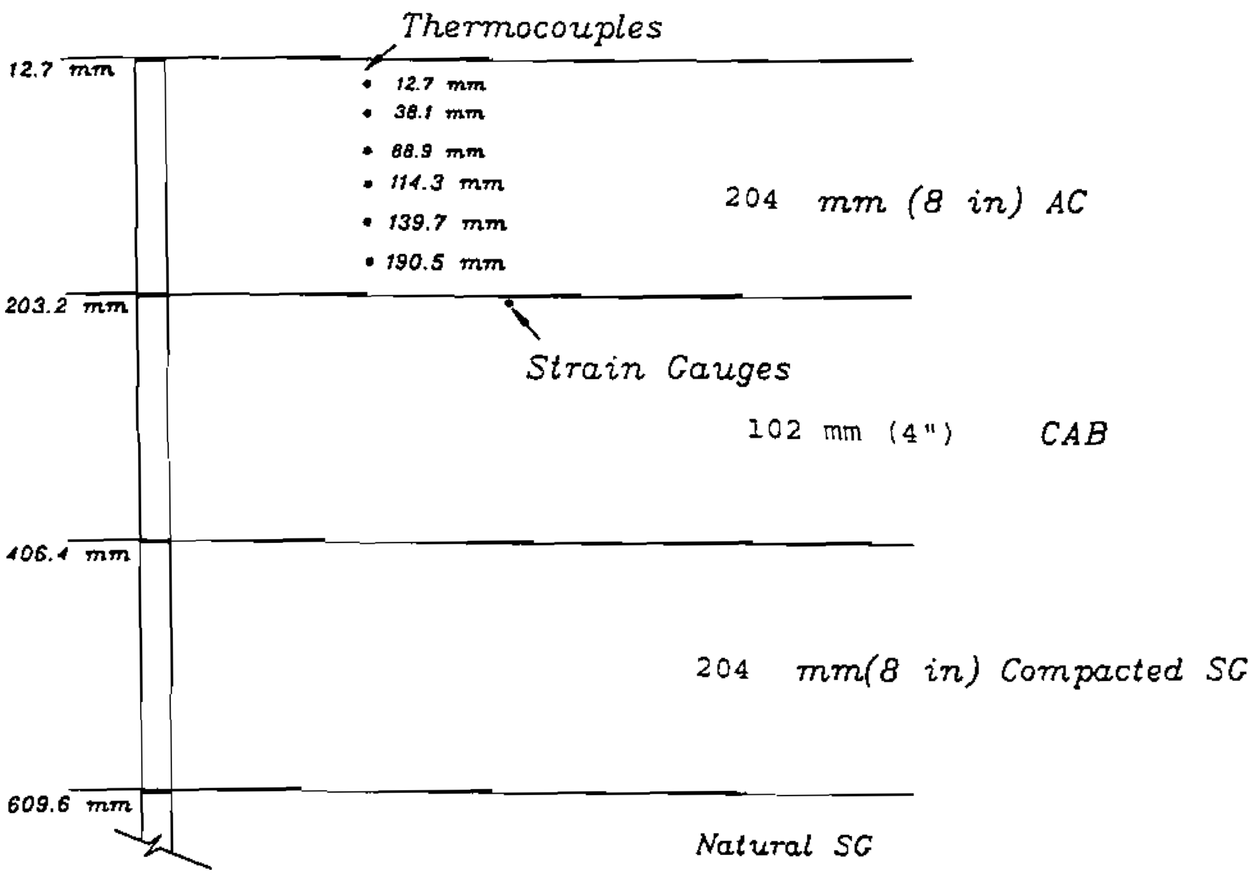

Figure 19. Instrumentation plan for the thick section.

axles
7. Tandem axle/super-single on both axles
8. Tandem axle/singled-out on both axles
9. Tandem axle/singled-out on first and duals on second
10. Tridem/dual tires on all axles
11. Tridem/low profile dual tires on all axles
12. Tridem/super-single on all axles
13. Tridem/singled-out on all axles
14. Tridem/super-single on first and duals on second and third axles
15. Tridem/Singled-out on first and duals on second and third axles
16. Tridem/singled-out on first and second and duals on third axle

- Environment:
  1. Conduct one field test during the Summer of 1998
  2. Conduct one field test during the fall of 1998

- Replicates: Three replicate measurements will be conducted for each combination of test variables.

The total number of response measurements: 3 (load) x 2 (speed) x 3(tire pressure) x 16 (axle/tire configuration) x 3 (replicates) = 864 combinations.

The responses of the strain gauges, MDD's, and thermocouples will be measured under 864 combinations of test parameters.

### *Field Test at The MinRoad Facility*

Personnel at the MinRoad Facitiy have been contacted for the possibility of conducting the above described program in full or partial combinations at the main highway instrumented sections during the Summer of 1998. At the time this report was completed, the MinRoad personnel did not give a final response. However, $8,000.00 have been budgeted as part of the operating budget of the University of Nevada to accommodate the MinRoad Test plan if it can be conducted.

*Field Data Collection*

The following represents the distribution of the intrumentations:

| | |
|---|---|
| Flexible Section I: | 30 strain gauges |
| | 4 LVDT's |
| | 4 thermocouples |
| Flexible Section II: | 30 strain gauges |
| | 4 LVDT's |
| | 6 thermocouples |

The overall instrumentation plan includes: 60 strain gauges, 8 LVDT's, and 10 thermocouples. The output from all the strain gauges and LVDT's will be collected under each of the 864 test variables combinations using An Advantec Model PCA6147 digital data acquisition system. One 64 channel Metrabyte single ended input cards with high gain will be used to condition the signals and sample the data channels (analog-to-digital conversion). The Advantec computer has a maximum aggregate sample rate of 100,000 samples per second. This will allow an individual gauge to be sampled at a rate of 781 samples per second which is sufficient to capture a peak as narrow as 4 msec. The termocouples will be sampled mannually every 30 minutes during testing using a hand-held temperature readout device (Omega Model HH21).

The location of the applied load with respect to the edge of the pavement and the location of the instruments has a significant impact on the measured pavement response. The test vehicle to be used in the field test program will be instrumented with a lateral and longitudinal positioning system. The system will consist of an antenna installed on the front bumper of the test vehicle and a 14-gauge wire placed down the middle of the test sections. Tape will secure the 14-gauge wire to the road surface. The output of the antenna with respect to the reference wire on the pavement surface will allow for lateral location of the truck with respect to the pavement edge and instrumentation to within ± 13 mm (0.5"). NATC has used this approach in several other tire studies, and it has proven to be highly reliable.

The test vehicle proposed to be used in the field test program consists of a tractor-trailer combination. NATC owns the tractor, while the trailer will be leased for this project. The tractor will have a tandem drive axle, while the trailer will have a tridem axle configuration. The field test program will collect and analyze the pavement response data under the trailer axles. The three types of axle configurations will be achieved as follows.

1. For the tridem configuration, use all three axles on the trailer.
2. For the tandem axle configuration, the tires will be removed from the tag axle of the tridem and the payload adjusted accordingly.
3. For the single axle configuration, the tires will be removed from the front two axles and the payload will be adjusted accordingly.

### *Data Analysis*

Once the experiment is conducted, The data collected from the field test program will be used in the following two approaches.

I. The collected data will be used to estimate pavement damage associated with the use of single-tire configurations compared with that of conventional dual-tire configurations for the specific tire types, pavement types, axle types and environmental conditions included in the experiment. The relative damage will be estimated by using the pavement responses collected in this experiment in the selected pavement performance models. Fatigue damage will be estimated through the measured tensile strains and in situ properties of the AC layer. Permanent deformation (rutting) damage will be estimated through the measured pavement vertical deflections at various depths (using the MDD's data) and the vertical compressive strain on top of subgrade.

II. The collected pavement response data will also be used to validate a comprehensive analytical model for flexible pavements. The comprehensive analytical model will include a dynamic load model which can predict the response of flexible pavements under dynamic loads generated by the various combinations of axle configurations, vehicle speed, tire configurations, and tire inflation pressure. The validated comprehensive analytical model will then be used to estimate pavement damage associated with the use of the single tire configuration for conditions that are beyond the ones controlled in the field test program.

As a result of these efforts, a validated comprehensive analytical model will be available for flexible pavements. With this model, the pavement damage associated with the use of single tire configurations compared with that of conventional dual tire configurations will be estimated for conditions beyond the ones controlled in the field test program.

The proposed approach by which the pavement damage caused by single tires is compared with that of dual tires is referred to as the tire equivalency factor (TEF) and is defined as follows.

$$\text{FTEFSS}\ (L,S,A) = \frac{\text{Fatigue life under dual tire}}{\text{Fatigue life under super-single tire}}$$

$$\text{FTEFSO}\ (L,S,A) = \frac{\text{Fatigue life under dual tire}}{\text{Fatigue life under singled-out tire}} \quad \text{life under}$$

Where:

FTEFSS= Fatigue tire equivalency factor for super-single tire
FTESO= Fatigue tire equivalency factor for singled-out tire
L = Axle load level
S = Vehicle speed level
A = Axle configuration (single, tandem, tridem)

$$\text{RTEFSS}\ (L,S,A) = \frac{\text{Rutting life under dual tire}}{\text{Rutting life under super-single tire}}$$

$$\text{RTEFSO}\ (L,S,A) = \frac{\text{Rutting life under dual tire}}{\text{Rutting life under singled-out tire}}$$

Where:

RTEFSS = Rutting tire equivalency factor for super-single tires
RTEFSO = Rutting tire equivalency factor for singled-out tires

The following example describes the proposed TEF approach.

Pavement type: Flexible

Pavement Structure: AC 102 mm (4")
CAB 152 mm (6")

Axle Configuration: single

Axle Load: 98 kN (22,000 lbs.)

Vehicle Speed: 80 km/h (50 mph)

Tire Inflation Pressure: 690 kpa (100 psi) for both dual & single tires

Materials Properties: medium strength pavement
AC- $M_r$ = 1,380 Mpa(200,000 psi)
CAB- $M_r$ = 207 Mpa (30,000 psi)
SG- $M_r$ = 104 Mpa (15,000 psi)

Let us assume that using the data above in the comprehensive model for flexible pavement would generate the following data.

Tensile strain at the bottom of AC under dual tire configuration = 460 microns

Tensile strain at the bottom of AC under single tire configuration = 530 microns

Fatigue life under dual tires = 1,620,000 ESALs

Fatigue life under single tires = 1,040,000 ESALs

The fatigue tire equivalency factor for super-single tires is:

$$FTEFSS = \frac{1,670,000}{1,040,000} = 1.6$$

The sample calculation above indicates that, under these conditions of pavement structure, materials, axle type, and load level, the super-single tire causes 60% more pavement damage than the dual tire.

*Dynamic Load Model*

Based on the review of the ideal analytical procedure (described in Chapter 4) and the pavement response models that were used in the previous studies to evaluate flexible pavement damage caused by single tires as compared to dual tires, it was concluded that the recommended pavement response model should have the following capabilities:

- Simulates the dynamic nature of traffic loads,
- Incorporates the nonuniform tire print pressure distributions, and
- Predicts the dynamic response of the pavement structure.

The dynamic nature of traffic loads are influenced by axle load, gross vehicle weight, speed, pavement roughness, and axle suspension; axle load having the greatest impact on pavement deterioration. Speed and road roughness interact to increase the dynamic wheel loadings. These interactions necessitates that different levels of load, speed, and axle configurations be evaluated for each tire type and tire inflation pressure setting.

The tire-pavement interaction mechanism controls the way in which traffic loads transfer to the pavement surface and, therefore, to the entire pavement structure. The tire inflation pressure and the tire structure are the two most important factors that influence the contact area and contact pressure at the tire-pavement interface for a given load magnitude. Most pavement analysis procedures assume a circular contact area with uniformly distributed pressure equals to the tire inflation pressure. However, several field and laboratory studies have contradicted these assumptions.

The Goodyear Tire and Rubber Company has conducted a laboratory experiment to measure the contact area and stress distributions under various types of truck tires (24). Researchers measured the contact area by inking the tread area of the inflated tire mounted on a special machine that loads it to a preset value. An imprint was left on a piece of paper between the tire and the machine's loading plate. The areas within the imprints were calculated by computer using digitized boundary points as input. Table 48 shows a typical data set of the contact area measurements for a super-single tire. It can be seen from this data that the shape of the contact area changes as a function of tire load and inflation pressure. In general, the width of the contact area remains relatively constant while its length increases as the load increases. At a constant load level, the length of the contact area decreases as the inflation pressure increases. In the case of the super-single tire, the width of the contact measures almost 1½ times its length. One thing these measurements make clear is that the assumption of a circular contact area is not valid.

The Goodyear study also measured the stress distribution within the contact area. A specially instrumented flatbed measured the contact pressures. A strain gauge located in the flatbed provided the contact stresses exerted by the loaded tire. This bed had the capability of

Table 48. Footprint data for the 425/65R22.5 single tire.

| Load (lbs) | Tire Pressure (psi) | Length (in) | Width (in) | Gross Area ($in^2$) | Net Area ($in^2$) |
|---|---|---|---|---|---|
| 4500 | 90 | 7.30 | 11.05 | 71.1 | 48.0 |
| | 105 | 7.05 | 10.90 | 67.7 | 46.6 |
| | 120 | 6.65 | 10.70 | 62.9 | 42.0 |
| 7000 | 90 | 9.00 | 12.65 | 102.2 | 74.0 |
| | 105 | 8.60 | 12.40 | 92.2 | 65.2 |
| | 120 | 8.30 | 11.95 | 87.6 | 60.9 |
| 8500 | 100 | 9.60 | 12.65 | 111.3 | 80.8 |
| | 115 | 9.25 | 12.70 | 103.5 | 75.7 |
| | 130 | 8.85 | 12.60 | 97.3 | 69.5 |
| 11000 | 115 | 10.60 | 12.80 | 124.5 | 93.9 |
| | 130 | 10.10 | 12.70 | 116.9 | 87.1 |
| | 145 | 9.60 | 12.60 | 109.8 | 78.5 |

moving with the tire as it rotated at a slow speed. Numerous points across the tire tread were tracked as they went through the length of contact to obtain an overall pressure profile. Figure 20 shows a typical stress distribution for a super-single tire. These data show that a nonuniform pressure distribution exists at the tire-pavement interface.

Researchers at the Road and Transport Technology Center in South Africa have recently developed a Vehicle-Road Surface Pressure Transducer Array (VRSPTA) system to measure tire print pressure distribution under a moving wheel load (25). The system consists of an array of strain-gauged load cell pins embedded into the pavement surface. The unique feature of this system is its ability to measure the vertical and horizontal pressures within the tire contact area. Figure 21 shows typical measurements from the South African system.

The horizontal pressures within the tire contact area have a significant impact near the surface of a flexible pavement. As recommended by the SHRP A-003 project, the rutting of flexible pavements relates directly to the maximum shear strain within the AC layer (26). Siddharthan et al. (27) evaluated the impact of horizontal pressures at the tire-pavement interface on the shear strain within the AC layer. Figure 22 shows that, as either the rough surface texture or a geometric incline generates the horizontal interface stresses, the maximum shear strain within the AC layer significantly increases.

All previous and current data indicate that the tire contact area is noncircular and that the tire print pressure distribution is nonuniform and exceeds the tire inflation pressure. Therefore, it is highly critical that the pavement response model can handle a noncircular contact area, a nonuniform pressure distribution, and horizontal pressures. Recently, the South African Device (VRSPTA) was evaluated by members of the research team under a FHWA sponsored research

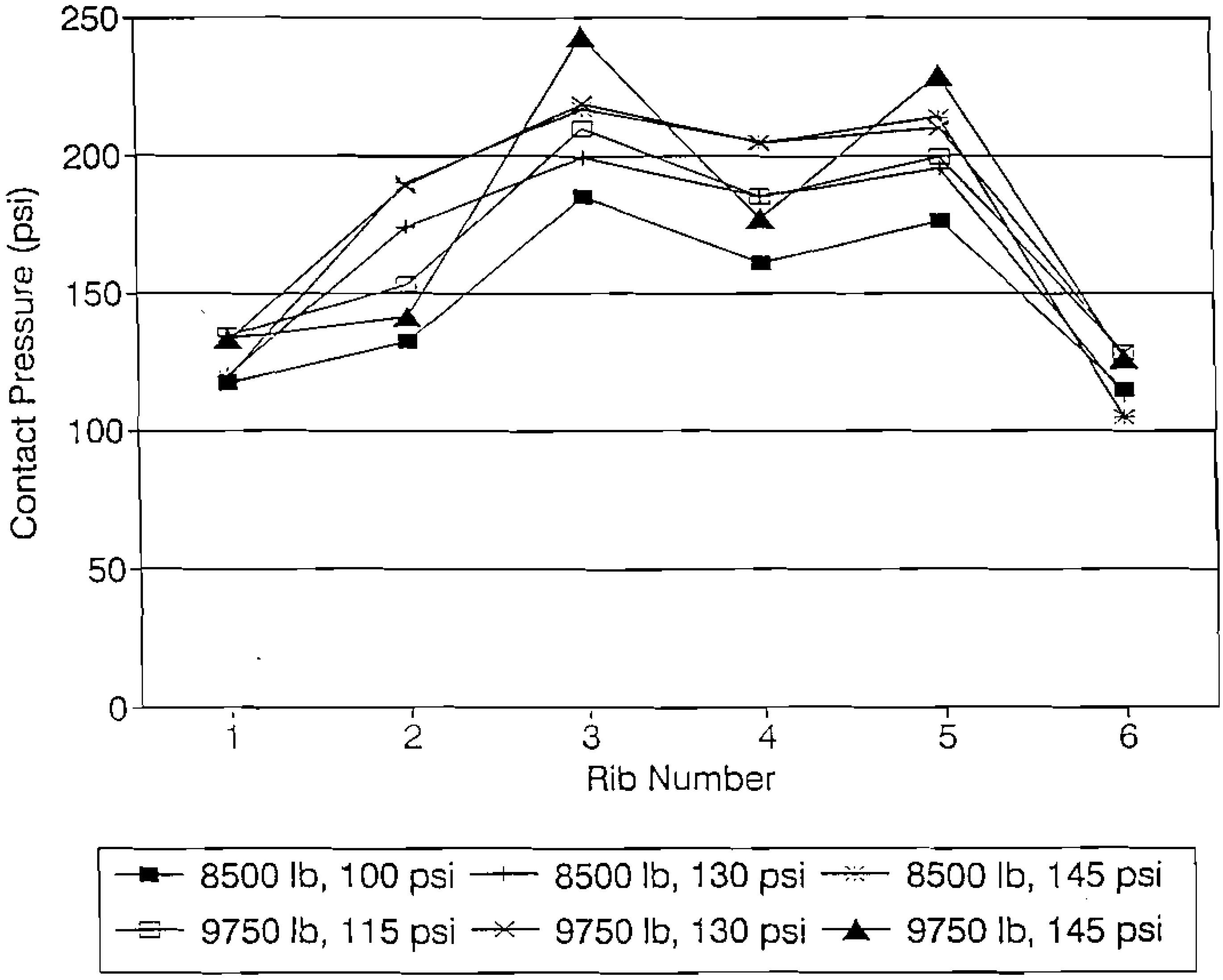

Figure 20. Contact stress distribution for the 425/65R22.5 single tire, 8500 and 9750 lb/tire load.

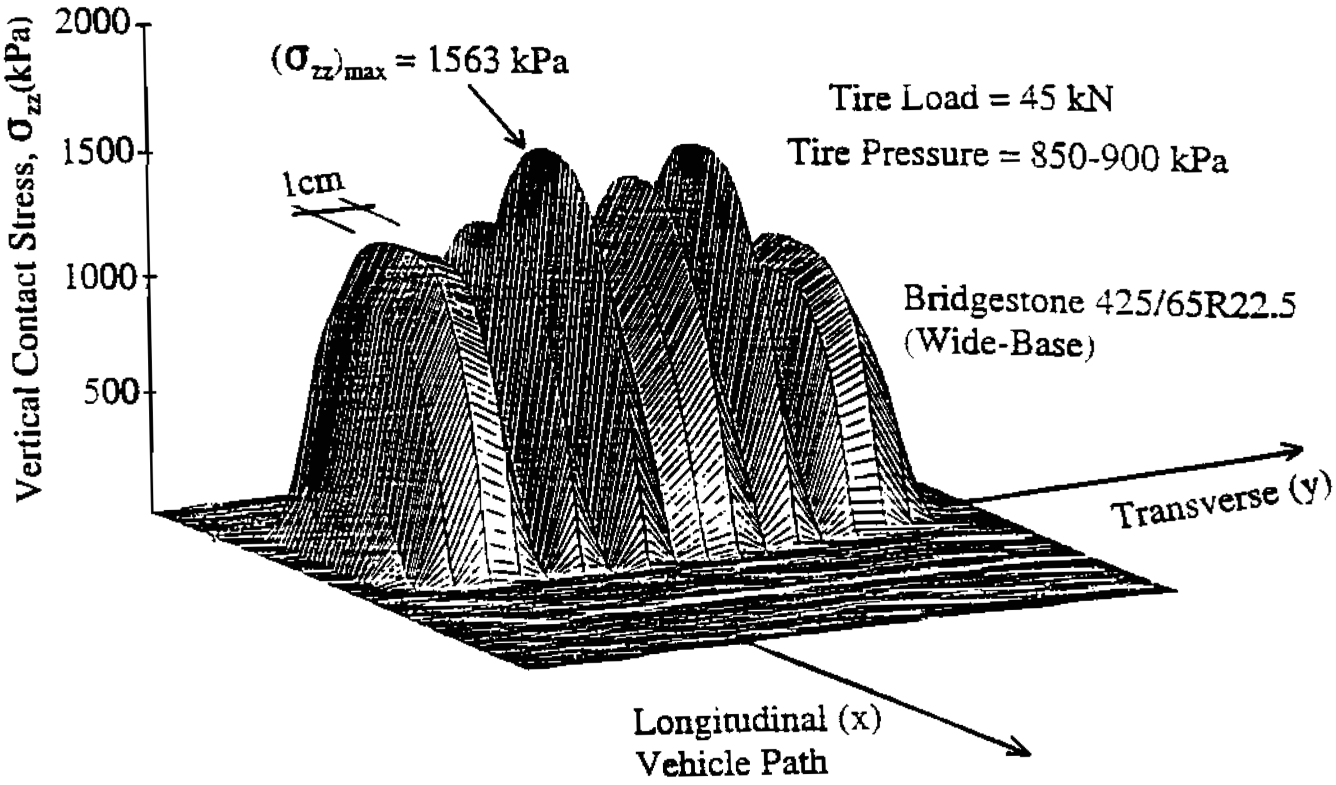

Figure 21. Vertical pressure distribution at the tire/pavement interface measured by the VRSPTA device.

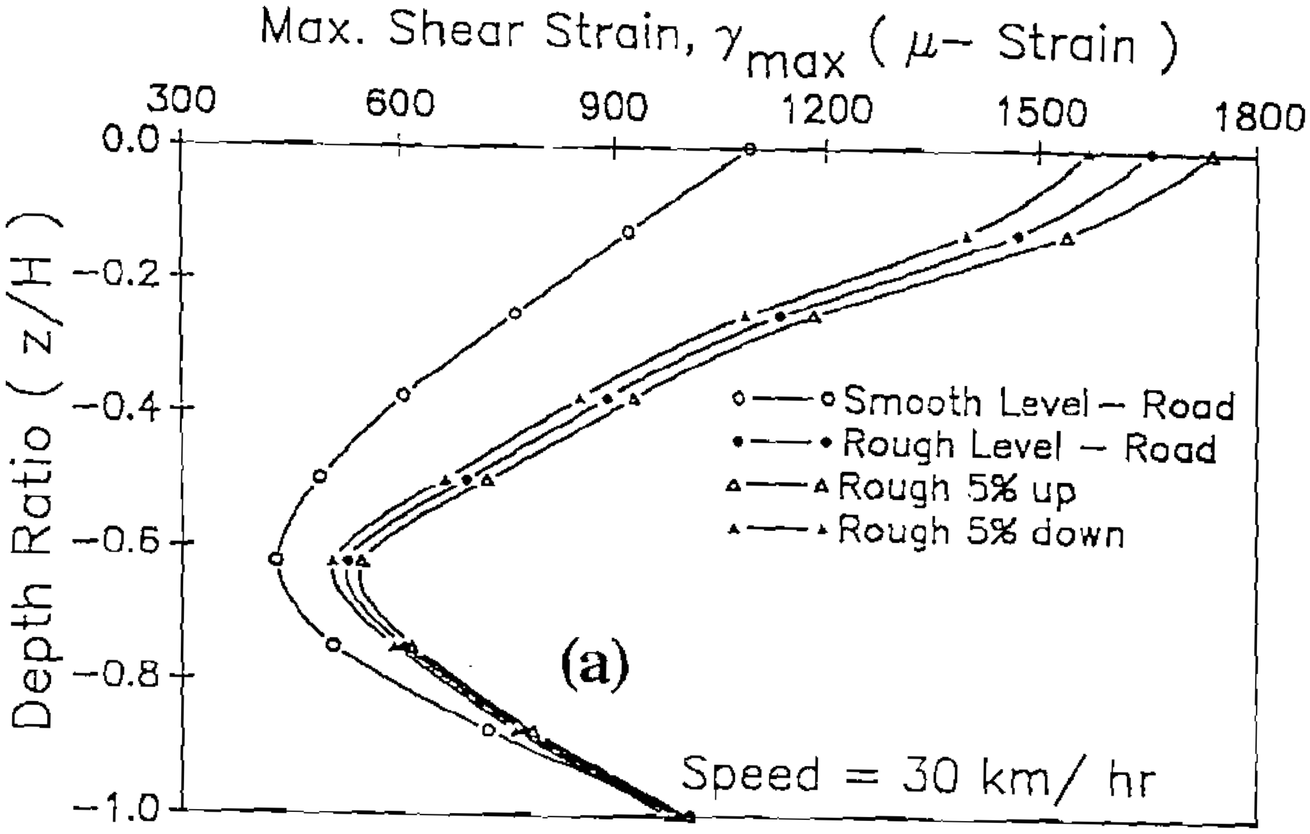

Figure 22. Distribution of maximum shear strain in the AC layer at speed of 30 km/h.

project (28). The VRSPTA device was used to measure the stress distribution at the tire/pavement interface under various levels of axle load and tire inflation pressure. With the appropriate approval from the FHWA's COTR, the measured stress distributions can be directly used in the Phase II of this research. It should be noted that the tires evaluated in the FHWA project are the same ones recommended in the test plan for this project.

It is common knowledge that the loads generate by the moving traffic are highly dynamic. The previous sections have also emphasized this fact and showed the various factors that influence the magnitude of these dynamic loads. Several field studies have shown that dynamic loads generate pavement responses which are significantly influenced by vehicle speed. Figure 23 shows the influence of truck speed on the measured surface deflections of flexible pavements at the AASHO Road Test (29). The AASHO Road Test data showed that an increase from creep speed to 48 Kph (30 mph) would reduce the surface deflection by fifty percent.

Sebaaly et al. Measured the impact of vehicle speed on the tensile strain at the bottom of the AC layer at the Penn State Test Track as part of an FHWA research project (30). Figure 24 summarizes the impact of vehicle speed on the measured tensile strains under single and tandem axles. The data in Figure 24 shows that vehicle speed has a significant impact on the measured tensile strain at the bottom of the AC layer, especially under the intermediate and full load levels for both single and tandem axles. By varying the vehicle speed from 32 to 80 km/h (20 to 50 mph), the measured strains under the intermediate and fully loaded axles decreased by 50 percent. By looking at the fatigue life-strain relationships discussed earlier, it can be seen that a 50 percent reduction in the strain can significantly increase the predicted fatigue life. Therefore, vehicle speed will play a major role in the damage caused by super-single and

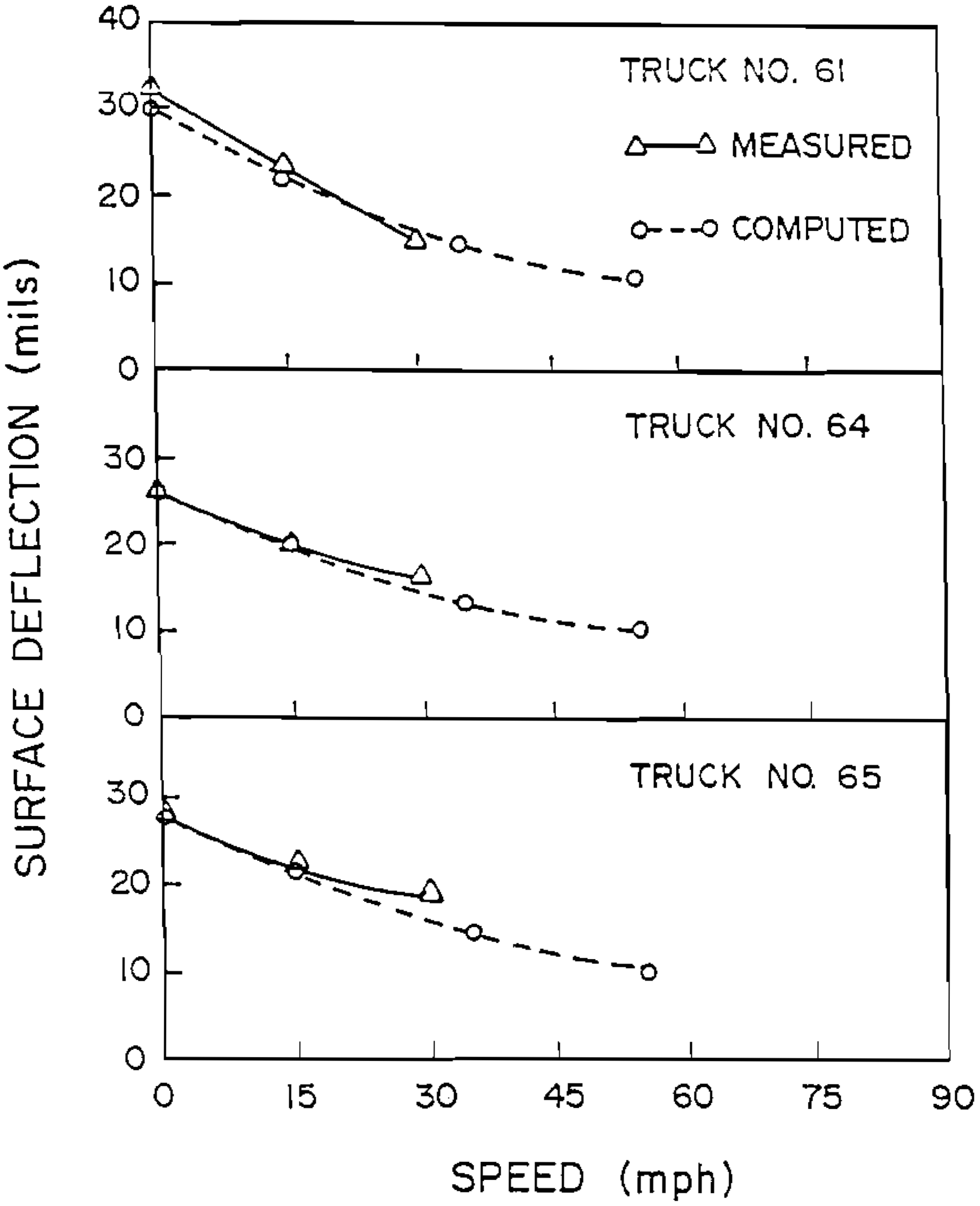

Figure 23. Measured and computed surface deflections under various speed at the AASHTO Road Test.

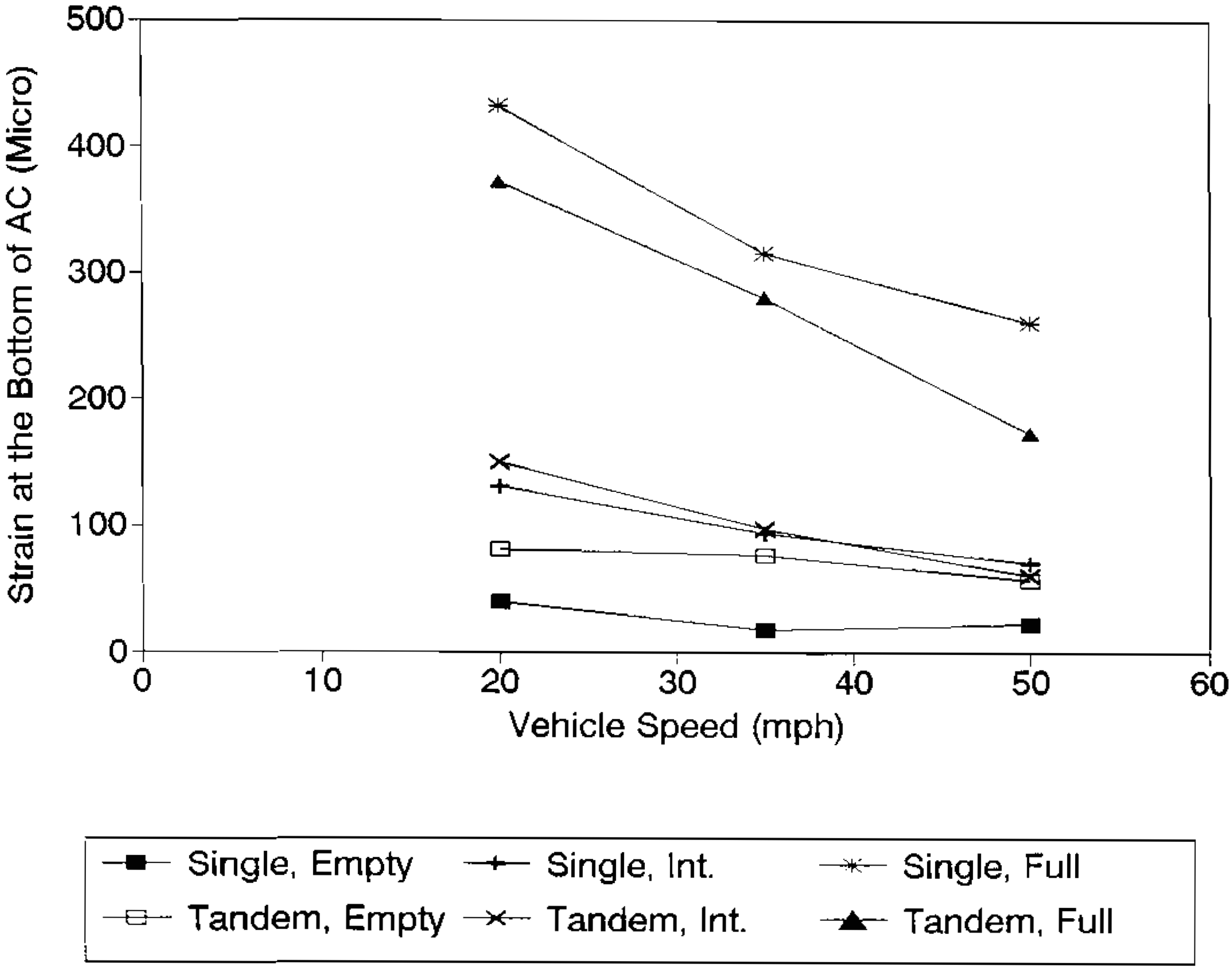

Figure 24. Effect of vehicle speed on the measured tensile strain at the bottom of AC layer.

singled-out tires relative to dual tires.

In order to satisfy the above listed criteria, a recently developed dynamic-based pavement response model is recommended to be used in Phase II of this research project as part of the analytical procedure to evaluate the relative damage of flexible pavement caused by single tires as compared with dual tires (31). This model accounts for the rate-dependent material properties and also the dynamic effects of the moving load such as inertia, resonance, etc. It is based on Fourier transform of the loaded area and is much more computationally efficient than the moving-load models based on the finite element method. It can handle nonuniform tire print pressure distribution (normal and shear). The computer code DYNPAVE has been subjected to verification using a number of test cases for which classical solutions (e.g., Boussinesq's solutions) are available (31). Such observations include the dependency of the longitudinal AC strain $\epsilon_{AC}$, on vehicle speed, the complex interaction between the loaded areas present in the tandem and tridem axle configurations, and the presence of a substantial compressive strain component in the measured time histories of $\epsilon_{AC}$.

### *Sensitivity Analysis*

Using the validated analytical approach, the researchers will conduct an extensive sensitivity analysis to identify the critical pavement factors which impact the damage caused by super-single and singled-out tires relative to dual tires. The sensitivity analysis will include the following factors:

|  |  |  |  |  |
|---|---|---|---|---|
| - Flexible Pavement Structures: | AC-Layer: | 100 | 150 | 200 mm |
|  | Crushed Agg. Base : | 100 | 150 | 200 mm |

Cement Treated Base: 100 150 200 mm
Granular Subbase : 100 150 200 mm

- Axle Configuration: Single Tandem and Tridem
- Vehicle Speed: 25, 50, 80, and 105 km/h
- Tire Inflation Pressures: Manufacturer recommended +/- 20%
- Materials Factors: Materials properties will be selected to represent weak, medium, and strong pavement structures. The type of material properties will depend on the selected pavement response model.

Once the above sensitivity analysis is conducted, the significant factors will be identified and the final analysis will be conducted using more refined levels of the critical factors.

*Approaches to Control Single Tires Damage*

It is anticipated that the sensitivity analysis conducted would indicate that the relative damage of single-tire configurations versus dual tire configurations is a function of the following critical factors:

1. axle load
2. tire pressure
3. thickness of structural section
4. stiffness of structural layers
    a. material types used for subgrade, subbase, base and surface course
    b. temperature of pavement layers
        1). frozen subgrade, subbase, base
        2). loss of stiffness of HMA at high temperatures
    c. moisture content of pavement layers
5. joint design and load transfer across joints
6. axle configuration

This task will identify the various combinations of the above critical factors which must be considered. A TEF for fatigue and a TEF for rutting will be evaluated for each combination of critical factors. The levels of the critical factors will be selected to represent the widest ranges possible. The research team recognizes that at least six distinct climatic zones exist in the U.S. as defined by the *AASHTO Design Guide*. These climatic zones will impact the selection of materials properties for the weak, medium, and strong pavement structures. Therefore, the database will be divided along the boundaries of the AASHTO recommended climatic zones and each zone will have its own set of TEF's. The database will include different combinations of pavement structures, i.e. pavements with and without subbases and different layers thicknesses. In the case of traffic conditions, the selection of a wide range of axle load configurations, i.e., single, tandem, and tridem, and axle load levels will ensure the applicability of the database to a wide range of road facilities.

The information in the TEF database will be analyzed to identify the various scenarios by which the pavement damage resulting from the use of single tires can be controlled. This analysis will be conducted on the following premise:

> For a given pavement section located in a given climatic zone, identify the most effective way(s) to control or reduce the pavement damage resulting from the single tire use. The following suggestions or a combination of these could result.

- Recommend a better AC material to resist the added damage.
- Use thicker structural sections to resist the added damage.
- Allow single tires above a certain speed level.
- Allow single tires below a certain level of axle load.

For example, on a flexible pavement located in the wet freeze-thaw cycling zone, the TEF database showed the following:

TEF at 80 km/h = 1.02

TEF at 24 km/h = 2.00

Therefore, one of the scenarios will be to allow single tires only where the higher speed can be maintained.

## THE ALTERNATIVE EVALUATION PLAN

This evaluation plan is being recommended as an alternative to the pavement-response plan that was recommended above. The objective of this alternative plan is the combine actual pavement performance with theoretical analyses to evaluate the flexible pavement damage caused by single tires as compared to dual tires. The following is a description of the major elements of the alternative plan:

- Collect field performance measurement on the Westrack pavement testing facility. The Westrack Pavement testing facility has an inside lane which has not been loaded as part of the cureent FHWA research project. This inside lane is a mirror image of the test lane having twenty-six sections of HMA mixtures with different volumetric properties. Table 49 summarizes the properties of the twenty-six sections and Figure 25 shows their locations. The Westrack pavement testing facility will be loaded with four tractor-trailer combination vehicles where each of the vehicles will be fitted with dual tires on one side of the axle and with super-single or singled-out tires on the other side of the axle.

Table 49. Properties of the Westrack test sections.

| Section | Gradation | Mix Designation | Target %AC | Target %AV |
|---|---|---|---|---|
| 01 | Fine | MM1 | M | M |
| 02 | | LM | L | M |
| 03 | | LH1 | L | H |
| 04 | | ML | M | L |
| 14 | | HM | H | M |
| 15 | | MM2 | M | M |
| 16 | | LH2 | L | H |
| 17 | | MH | M | H |
| 18 | | HL | H | L |
| 19 | Fine Plus | MM1 | M | M |
| 20 | | MH | M | H |
| 21 | | HL1 | H | L |
| 22 | | LM | L | M |
| 09 | | HL2 | H | L |
| 10 | | LH | L | H |
| 11 | | MM2 | M | M |
| 12 | | ML | M | L |
| 13 | | HM | H | M |
| 05 | Coarse | MM1 | M | M |
| 06 | | MH | M | H |
| 07 | | HM | H | M |
| 08 | | LM | L | M |
| 23 | | ML | M | L |
| 24 | | MM2 | M | M |
| 25 | | HL | H | L |
| 26 | | LH | L | H |

L = Low, M = Medium, H = High

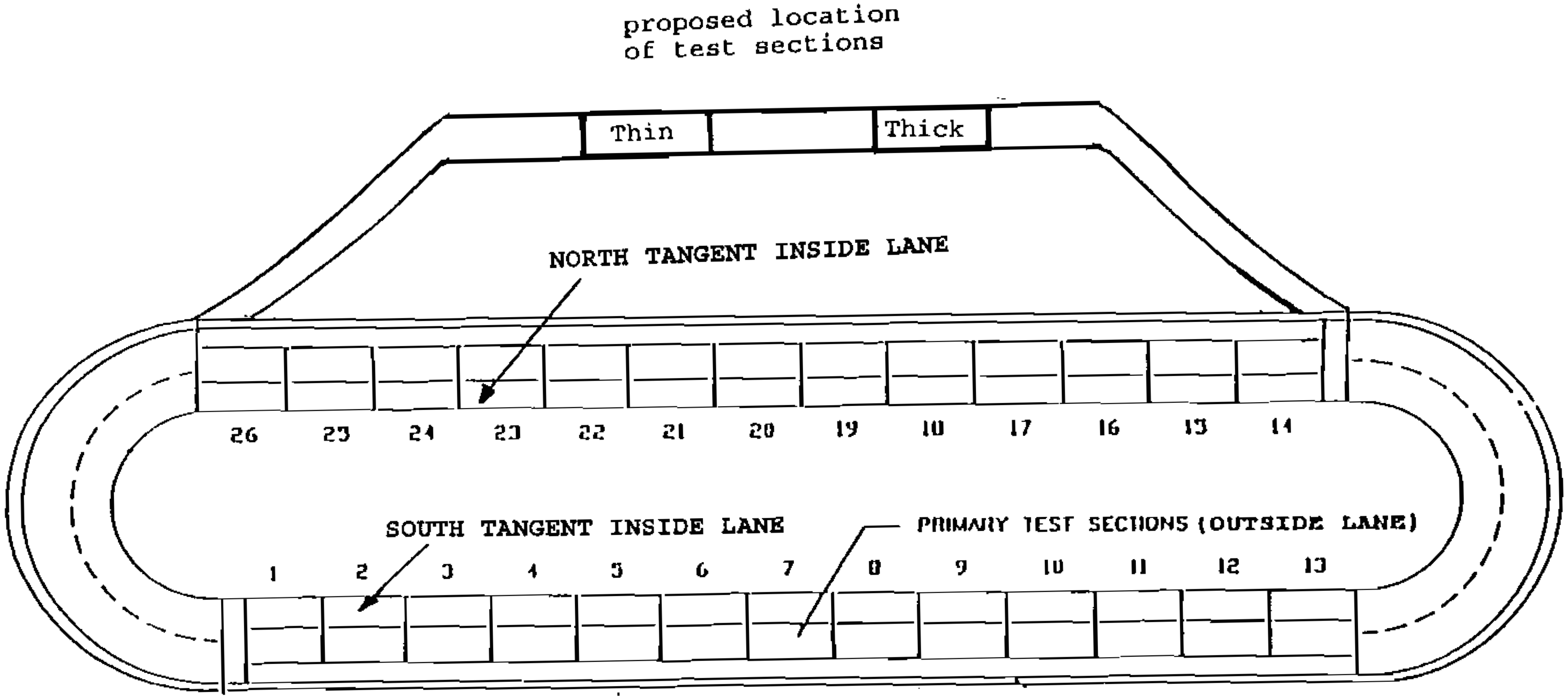

Figure 25. Location of north and south tangents and inner lane sections proposed for the test program.

During the first part of the field testing, the sections located on the south tangent (sections 1-13, Figure 25) will be loaded with vehicles fitted with dual tires on one side and super-single tires on the other. Each single axle will be loaded with 89 KN (20,000 lb) which would provide a total of 360,000 ESALs for each month of loading. The location of the loads will be shifted to achieve equal load levels on both sides of the axles. The four vehicles will run on the inside lane while traveling on the south tangent and then shift onto the outside lane while traveling on the north tangent. The performance of the south tangent sections will be monitored for 2-3 month. It is anticipated that a 2-3 month of continuous loading during the hot summer will produce signigficant performance data. The relative damage of the super-single tire will be evaluated by comparing the performance of the wheel track on the south tangent loaded with dual tires with the one loaded with the super-single tire.

During the second part of the field testing, the sections located on the north tangent (sections 14-26, Figure 25) will be loaded with vehicles fitted with dual tires on one side and singled-out tires on the other. Each single axle will be loaded with 89 KN (20,000 lb) which would provide a total of 360,000 ESALs for each month of loading. The location of the loads will be shifted to achieve equal load levels on both sides of the axles. The four vehicles will run on the inside lane while traveling on the north tangent and then shift onto the outside lane while traveling on the south tangent. The performance of the north tangent sections will be monitored for 2-3 month. It is anticipated that a 2-3 month of continuous loading during the hot summer will produce signigficant performance data. The relative damage of the singled-out tire will be evaluated by comparing the performance of the wheel track on the north tangent loaded with dual tires with the one loaded with the singled-out tire.

- Retrofit instrumentation into one pavement section on the south tangent and one section on the north tangent. The retrofitted instrumentation will include: 1) a multi-depth deflectometer (MDD), 2) strain gauges at the bottom of the AC layer, and 3) thermocouples throughout the depth of the AC layer. Collect pavement response data from the instrumented sections during the performance testing of both tangents. The collected pavement response data will be used to validate the pavement dynamic load model described under the Main Evaluation Plan described earlier.

- Use the collected pavement performance data to evaluate the relative damage of single tires as compared to dual tires for the axle type and load level that were included in the experiment, i.e. single axle with 89 KN (20,000 lb) load under a single speed of 64 km/h (40 mph) and one tire inflation pressure.

- Use the collected pavement performance data to validate rutting and fatigue performance models. The validated performance models will then be used with the validated dynamic load model to expand the evaluation into the conditions described earlier under the sections entitled: "*Field Test Program.*"

- Use the validated pavement performance models and pavement response model to conduct the *Sentivity Analysis* and to develop *Approaches to Control Single Tires Damage* as described under the main evaluation plan.

**Advantages and Disadvantages**

The above described alternative evaluation plan has some advantages and some disadvantages. Its advantages can be summarized as follow:

1. It provides actual pavement performance data on several pavement test sections.
2. It provides actual pavement performance data to validate rutting and fatigue performance models to be used in the expanded analyses.
3. It allows one-to-one comparison of single tires with dual tires under highway speed.

Its disadvantages can be summarized as follows:

1. The application of 360,000 ESALs per month on a single lane using four trucks following each other at short distances does represent an accelerated mode of loading which may not represent actual field conditions.
2. The collected performance data will be limited to just single axle with one level of load, inflation pressure, and vehicle speed. Eventhough the validated model will still be used to expand the study to other levels.
3. The field performance experiment will have to be conducted during the summers of 1998 and 1999 which will require changing the end date of the project beyond the current end date of July 1999.
4. Additional funds will be required to complete the proposed field performance plan.

## COMPARISON OF THE MAIN AND ALTERNATIVE PLANS

As can be seen from the above recommendation, the main and alternative evaluation plans have different approaches. The following paragraphs compare the concept of each one and summarize the corresponding deliverables.

The concept of the main evaluation plan is based on the fact that pavement responses can be effectively used to evaluate the relative pavement damage caused by single tires as compared with dual tires. This concept is strongly supported by the findings of the ALF experiment and the comparison of the ALF data with several response type studies. The deliverables of the main evaluation plan can be summarized as follow:

1. A database of relative pavement damages caused by single tires verified by pavement responses under a wide range of pavement structure, axle type, axle load, tire type, tire inflation pressure, vehicle speed, and environmental conditions.
2. An analytical procedure validated using pavement responses under a wide range of pavement structure, axle type, axle load, tire type, tire inflation pressure, vehicle speed, and environmental conditions.
3. A software package which can be used to evaluate the relative damage of single tires on flexible pavements for cases that are not covered by the developed database.

The concept of the alternative evaluation plan is based on the fact that pavement performance should be used to evaluate the relative pavement damage caused by single tires as compared with dual tires. The deliverables of the alternative evaluation plan can be summarized as follow:

1. A database of relative pavement damages caused by single tires on twenty-six sections of the Westrack pavement Testing Facility. The database is limited to single axle with 89 KN (20,000 lb) load under 64 km/h (40 mph) vehicle speed.

2. An analytical procedure validated using pavement responses and performance under a limited combination axle type, tire type, inflation pressure, and environmental conditions.

3. A database of relative pavement damages caused by single tires as compared with dual tires developed using the analytical procedure that was validated in step 2.

## BUDGET AND TIME REQUIREMENTS

Table 50 summarizes the task-by-task budget for the Main Evaluation Plan while Table 51 summarizes the task-by-task budget for the Alternative Evaluation Plan.

The Main Evaluation Plan will have the following requirements:

| | |
|---|---|
| Phase I Expenditures: | \$ 62,500.00 |
| Phase II Expenditures: | \$ 337,500.00 |
| Total Budget: | \$ 400,000.00 |
| Additional Funds Needed: | \$ 0.00 |
| Completion Date: | July 31, 1999 |

The Alternative Evaluation Plan will have the following requirements:

| | |
|---|---|
| Phase I Expenditures: | $ 62,500.00 |
| Phase II Expenditures: | $ 411,412.00 |
| Total Budget: | $ 473,912.00 |
| Additional Funds Needed: | $ 73,913.00 |
| Completion Date: | July 31, 2000 |

Table 50. Budget for the Main Evaluation Plan.

| Category/Name | Role in Study | % Time | Hr. Rate($) | Task 6 | | Task 7 | | Task 8 | | Total Hours | Total Cost ($) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Hrs. | $ | Hrs. | $ | Hrs | $ | | |
| University of Nevada<br>A. Salaries | | | | | | | | | | | |
| P.E. Sebaaly | PI | 20 | 48.48 | 562 | 27,246 | 479 | 23,222 | 100 | 4,848 | 1,141 | 55,316 |
| J. A. Epps | Research Eng. | 10 | 73.28 | 81 | 5,936 | 292 | 21,398 | 50 | 3,664 | 423 | 30,998 |
| R. Siddharthan | Research Eng. | 8 | 51.60 | 34 | 1,754 | 288 | 14,861 | 30 | 1,548 | 352 | 18,163 |
| Grad. Student | Research Asst. | 20 | 11.25 | 122 | 1,373 | 688 | 7,740 | 50 | 563 | 860 | 9,676 |
| Secretary | | 5 | 12 | 0 | 0 | 0 | 0 | 165 | 1,980 | 165 | 1,980 |
| Total of Salaries | | | | 799 | 36,309 | 1,747 | 67,221 | 395 | 12,603 | 2,941 | 116,133 |
| B. Fringe Benefit | | | | | 1,065 | | 1,877 | | 1,002 | | 3,944 |
| C. Operating | | | | | 14,921 | | 488 | | 529 | | 15,938 |
| D. Travel | | | | | 1,600 | | | | | | 1,600 |
| Subtotal for UNR | | | | | 53,895 | | 69,586 | | 14,134 | | 137,615 |
| UNR OVERHEAD | | | | | | | | | | | |
| A. 44.3% 1st $25,000 of NATC Subcontract | | | | | 11,075 | | | | | | 11,075 |
| B. 44.3% UNR Subtotal | | | | | 23,875 | | 30,826 | | 6,261 | | 60,962 |
| Total UNR Overhead | | | | | 34,950 | | 30,826 | | 6,261 | | 72,037 |
| Total for UNR | | | | | 88,845 | | 100,412 | | 20,395 | | 209,652 |

| Category/Name | Role in Study | % Time | Hr. Rate ($) | Task 6 | | Task 7 | | Task 8 | | Total Hours | Total Cost ($) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Hrs | $ | Hrs | $ | Hrs | $ | | |
| **Nevada Auto. Test Center**<br>**A. Salaries** | | | | | | | | | | | |
| **C. Ashmore** | Research Eng. | 8 | 32.49 | 260 | 8,448 | 100 | 3,249 | 80 | 2,599 | 440 | 14,296 |
| **J. Keany** | Comput. Spec. | 1 | 38.86 | 100 | 3,886 | | | | | 100 | 3,886 |
| **D. White** | Vehicle Tech. | 4 | 14.83 | 240 | 3,559 | | | | | 240 | 3,559 |
| **E. Brown** | Vehicle Oper. | 10 | 8.92 | 560 | 4,995 | | | | | 560 | 4,995 |
| **G. Works** | Inst. Tech. | 2 | 10.74 | 80 | 860 | 30 | 322 | 40 | 430 | 150 | 1,612 |
| **Secretary** | | 3 | 8.11 | 290 | 2,356 | | | | | 290 | 2,356 |
| **Direct Labor** | | | | | 24,104 | | 3,571 | | 3,029 | | 30,704 |
| **Labor Escalation (1.5%)** | | | | | 362 | | 54 | | 45 | | 461 |
| **Total Labor Cost (TLC)** | | | | | 24,462 | | 3,625 | | 3,074 | | 31,161 |
| **B. Fringe Benefit (46% TLC)** | | | | | 11,253 | | 1,668 | | 1,414 | | 14,335 |
| **C. Overhead 20% (TLC+B)** | | | | | 7,143 | | 1,059 | | 898 | | 9,100 |
| **D. Facilities Cap. Cost of Money 5.5%(TLC+B)** | | | | | 1,964 | | 291 | | 247 | | 2,502 |
| **E. Operating** | | | | | 33,460 | | | | | | 33,460 |
| **F. Test Section Construct.** | | | | | 20,000 | | | | | | 20,000 |
| **G. Fee 7%(TLC+B+C+E+F)** | | | | | 6,742 | | 445 | | 377 | | 7,564 |
| **H. General and Admin Cost 9%(TLC+B+C+E+F)** | | | | | 8,669 | | 572 | | 485 | | 9,726 |
| **Total for NATC** | | | | | 113,693 | | 7,660 | | 6,495 | | 127,848 |
| **GRAND TOTAL (UNR+NATC)** | | | | | $ 202,538 | | $108,072 | | $ 26,890 | | $ 337,500 |

Table 51. Budget for the Alternative Evaluation Plan.

| Category/Name | Role in Study | % Time | Hr. Ra($) | Task 6 | | Task 7 | | Task 8 | | Total Hours | Total Cost ($) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Hrs. | $ | Hrs. | $ | Hrs | $ | | |
| **University of Nevada**<br>**A. Salaries** | | | | | | | | | | | |
| **P.E. Sebaaly** | **PI** | 20 | 48.48 | 350 | 16,968 | 400 | 19,392 | 100 | 4,848 | 850 | 41,208 |
| **J. A. Epps** | **Research Eng.** | 10 | 73.28 | 40 | 2,931 | 120 | 8,794 | 50 | 3,664 | 210 | 15,389 |
| **R. Siddharthan** | **Research Eng.** | 8 | 51.60 | 50 | 2,580 | 150 | 7,740 | 30 | 1,548 | 230 | 11,868 |
| **Grad. Student** | **Research Asst.** | 20 | 11.25 | 700 | 7,875 | 400 | 4,500 | 50 | 563 | 1150 | 12,938 |
| **Secretary** | | 5 | 12 | 0 | 0 | 0 | 0 | 165 | 1,980 | 165 | 1,980 |
| **Total of Salaries** | | | | 724 | 30,354 | 1,070 | 40,426 | 395 | 12,603 | 2,605 | 83,383 |
| **B. Fringe Benefit** | | | | | 769 | | 1,132 | | 1,002 | | 2,903 |
| **C. Operating** | | | | | 1,000 | | 500 | | 529 | | 2,029 |
| **D. Travel** | | | | | 2,000 | | | | | | 2,000 |
| **Subtotal for UNR** | | | | | 34,123 | | 42,058 | | 14,134 | | 90,315 |
| **UNR OVERHEAD** | | | | | | | | | | | |
| **A. 44.3% 1st $25,000 of NATC Subcontract** | | | | | 11,075 | | | | | | 11,075 |
| **B. 44.3% UNR Subtotal** | | | | | 15,117 | | 18,632 | | 6,261 | | 40,010 |
| **Total UNR Overhead** | | | | | 26,192 | | 18,632 | | 6,261 | | 51,085 |
| **Total for UNR** | | | | | 60,315 | | 60,690 | | 20,395 | | 141,400 |

| Category/Name | Role in Study | % Time | Hr. Rate ($) | Task 6 | | Task 7 | | Task 8 | | Total Hours | Total Cost ($) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Hrs | $ | Hrs | $ | Hrs | $ | | |
| Nevada Auto. Test Center<br>A. Salaries | | | | | | | | | | | |
| C. Ashmore | Research Eng. | 8 | 32.49 | 600 | 19,494 | 30 | 975 | 100 | 3,249 | 730 | 23,718 |
| J. Keany | Comput. Spec. | 1 | 38.86 | 100 | 3,886 | | | | | 100 | 3,886 |
| D. White | Vehicle Tech. | 4 | 14.83 | 1000 | 14,830 | | | | | 1000 | 14,830 |
| E. Brown | Vehicle Oper. | 10 | 8.92 | 1000 | 8,920 | | | | | 1000 | 8,920 |
| G. Works | Inst. Tech. | 2 | 10.74 | 40 | 430 | | | | | 40 | 430 |
| Secretary | | 3 | 8.11 | 100 | 811 | | | | | 100 | 811 |
| Direct Labor | | | | | 48,371 | | 975 | | 3,249 | | 52,595 |
| Labor Escalation (1.5%) | | | | | 726 | | 15 | | 49 | | 790 |
| Total Labor Cost (TLC) | | | | | 49,097 | | 990 | | 3,298 | | 53,385 |
| B. Fringe Benefit (46% TLC) | | | | | 22,585 | | 455 | | 1,517 | | 24,557 |
| C. Overhead 20% (TLC+B) | | | | | 14,336 | | 289 | | 963 | | 15,588 |
| D. Facilities Cap. Cost of Money 5.5%(TLC+B) | | | | | 3,943 | | 79 | | 265 | | 4,287 |
| E. Operating | | | | | 135,000 | | | | | | 135,000 |
| F. Test Section Construct. | | | | | 0 | | | | | | |
| G. Fee 7%(TLC+B+C+E+F) | | | | | 15,747 | | 121 | | 405 | | 10,273 |
| H. General and Admin Cost 9%(TLC+B+C+E+F) | | | | | 20,246 | | 156 | | 520 | | 20,922 |
| Total for NATC | | | | | 260,954 | | 2,090 | | 6,968 | | 270,012 |
| GRAND TOTAL (UNR+NATC) | | | | | $ 321,269 | | $ 62,780 | | $ 27,363 | | $ 411,412 |

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