the range of load, size of tire, and tire pressure tested.

Comparison

When the surface-treated items were compared to similar items having no surfacing, there was significant improvement in the performance of the surface-treated items. Data for unsurfaced items trafficked by the simulated MX load cart are given in Table 1. As can be seen, item 3 of Lane 1 contained Blend II material at the surface and sustained 1.93 in. of rutting; whereas, item 3 in Lane 3 contained the double surface treatment on Blend II material and sustained only 1.1 in. of rutting. Also, item 4 of Lane 1 had Blend I at the surface and sustained 4.61 in. of rutting; whereas, item 4 of Lane 3 containing a single surface treatment sustained only 1.0 in. of rutting. There was also significant movement of the soil in items 3 and 4 of Lane 1 from underneath the tire to the sides of the traffic lane; this did not occur in the surface-treated items. The important implication of these results is that the application of a surface treatment on the in-place soils at the MX deployment area may be sufficient to carry the anticipated heavy loads and provide an adequately paved road.

CONCLUSIONS

The following conclusions resulted from this analysis:

1. Adequate compaction of soil layers is important to prevent densification.
2. Surface treatments performed satisfactorily under heavy loads.
3. Rutting of soil layers was reduced by the application of surface treatments.

REFERENCES

Closely with both theoretical and experimental computer program (l). The program is relatively simple and inexpensive to use and, as reported by Barber (1), also occur at the bottom of the concrete pavement slab.

The initial phase of the analysis consisted of determining the magnitude of the tensile stresses in the concrete pavement for single and tandem axles at four load positions. The axle configurations examined were as follows: Case I, a single axle with dual 10-in. tires; Case II, a single axle with single 16-in. tires; Case III, tandem axles with 10-in. dual tires; and Case IV, tandem axles with single 13-in. tires. Four load positions were analyzed:

1. At the joints with the vehicle centered in the lane;
2. At the joints with the right wheel at the pavement edge;
3. At the midpoint of the slab with the right wheel at the pavement edge; and
4. At the midpoint of the slab with the right wheel 12 in. from the pavement edge.

The results clearly showed that the mid-panel edge loadings caused the most stress and that maximum tensile stress was located at the bottom edge of the mid-panel slab. The mid-panel edge loadings, shown in Figure 2, were selected for use in this study.

A single axle, mid-panel edge load, 9-in. pavement, and a modulus of subgrade reaction of 100 psi/in. were selected for the analysis of the sensitivity of load-related stresses to variations in tire pressure, single tire width, and joint spacing. These were varied as follows:

1. Tire contact pressures of 70, 80, 90, and 100 psi were analyzed for both 10-in. dual tires and 16-in. single tires. The results, shown in Figure 3, indicate a definite relationship between tire pressure and joint spacing.

2. The effects of tire width were analyzed using a 20-kip single axle load with 10-, 12-, 14-, 16-, and 18-in. wide single tires. The results, shown in Figure 4, indicate a definite relationship between tire width and pavement stresses.

3. The effects of tire pressure were analyzed using a 20-kip single axle load with 10-, 12-, 14-, 16-, and 18-in. wide single tires. The results, shown in Figure 5, indicate a maximum variation of less than 3 percent.

Based on the preceding a decision was made to use a tire contact pressure of 80 psi and a single tire width of 10 in. for dual tires, 16 in. for single tires on single axles, and 13 in. for single tires on tandem axles. These tire widths were based on the regulatory requirements for maximum tire load. Because the loaded pavement area modeled in the program is a rectangle, the transverse dimension was the tire width and the longitudinal dimension varied depending on the axle load. The tire contact pressure was 80 psi.

To evaluate warping stresses, the temperatures at the top and bottom surfaces of a concrete slab will cause the slab to warp. The weight of the slab and its contact with the subgrade restricts the movement of the slab and stresses are developed. Measurements by Teller and Southerland (2) show that the temperature difference between the pavement layers is much larger during the day than during the night. Furthermore, during the day the temperature of the upper surface of the concrete slab is higher than the temperature at the bottom of the slab placing tensile stresses at the bottom of the slab. This is important, because the maximum load-related tensile stress also occur at the bottom of the concrete pavement slab.

To evaluate warping stresses, the temperatures at the top and bottom of the slab were computed from Weather Bureau data using a procedure developed by Barber (1). Maximum pavement temperatures were cal-

Figure 1. Study approach.

1. Tire contact pressures of 70, 80, 90, and 100 psi were analyzed for both 10-in. dual tires and 16-in. single tires. The results, shown in Figure 3, indicate that the variation in edge stress is about 1 percent for tire contact pressures between 70 and 100 psi.

2. The effects of tire width were analyzed using a 20-kip single axle load with 10-, 12-, 14-, 16-, and 18-in. wide single tires. The results, shown in Figure 4, indicate a definite relationship between tire width and pavement stresses.

3. Joint spacings of 13, 15, and 20 ft were analyzed to determine the effect of joint spacing on pavement edge stress. The results, shown in Figure 5, indicate a maximum variation of less than 3 percent.

Based on the preceding a decision was made to use a tire contact pressure of 80 psi and a joint spacing of 13 ft in this analysis of pavement stresses.

Warping Stresses

Differences in temperature between the top and bottom surfaces of a concrete slab will cause the slab to warp. The weight of the slab and its contact with the subgrade restricts the movement of the slab and stresses are developed. Measurements by Teller and Southerland (2) show that the temperature difference between the pavement layers is much larger during the day than during the night. Furthermore, during the day the temperature of the upper surface of the concrete slab is higher than the temperature at the bottom of the slab placing tensile stresses at the bottom of the slab. This is important, because the maximum load-related tensile stress also occur at the bottom of the concrete pavement slab.

To evaluate warping stresses, the temperatures at the top and bottom of the slab were computed from Weather Bureau data using a procedure developed by Barber (1). Maximum pavement temperatures were cal-
Single Axle - Dual Tires

Tandem Axle - Dual Tires

Single Axle - Single Tires

Tandem Axle - Single Tires

Figure 2. Loading cases used in the finite-element analysis of concrete pavement.

Figure 3. Effect of variations in tire pressure on edge stress.

Figure 4. Effect of the width of a single tire on edge stress.

culated for 7-, 9-, 10-, and 12-in. slabs in eastern and western Washington. Temperatures were calculated for each slab thickness, and the difference in gradients between eastern and western Washington was only about 5 percent. Therefore, to reduce the number of computations, only the western Washington pavement temperatures were used for the analysis.

To determine the maximum combined load and warping stresses, the warping stresses were calculated at the bottom center of the longitudinal pavement edge. This was where the maximum load-related edge stresses were found. Two methods for computing warping stress were considered: a procedure presented by Bradbury (5), which is based on Westergaard's work, and a set of regression equations developed by Darter (6) using data developed from a finite-element analysis.

The two methods were compared using pavement temperatures for July, which was the month with the highest temperature gradient. The following variables were used in the analysis: moduli of subgrade reaction (K) of 50, 100, 200, and 300 psi/in. and pavement thicknesses of 7, 9, and 12 in. Figure 6 shows the stresses calculated for a 9-in. pavement. For higher K-values the Bradbury analysis gave much...
higher stresses than the Darter equations. However, the warping stresses calculated by the Bradbury procedure were generally higher than the measured stress because full restraint of the slab is assumed. Whereas, the finite-element program used by Darter allows the slab to curl in a weightless condition, then the restraining weight of the slab is added.

Based on a comparison of the two procedures and a review of previous work, the Darter equations, subject to the conditions in the following discussion, were selected to compute edge-warping stresses for this study. It was noted that above a modulus of subgrade reaction of approximately 200 psi/in., the warping stress tended to decrease. Majidi, Ilves, and McComb (13) reported that when analyzing warping stresses using a coupled finite-element and elastic-multilayer subgrade program, no appreciable differences in warping stresses were noted for changes in subgrade support conditions. It was concluded that Darter’s equations would be used to compute warping stresses for subgrades with K-values of 200 psi/in. and below. For K-values above 200 psi/in., the warping stress calculated for 200 psi/in. would be used. This assumed that for very weak subgrades, the subgrade yields as the slab warps. This provides uniform support over the length of the slab and reduces stress.

Fatigue Analysis

The fatigue relationship used was the one proposed by Vesic (8): 

$$ N_{2.5} = 225,000 \left( \frac{MR}{a} \right)^4 $$

(1) 

where 

$$ N_{2.5} = \text{load repetitions to a serviceability index of 2.5}, $$

$$ MR = \text{modulus of rupture of the concrete, psi, and} $$

$$ a = \text{tensile stress, psi.} $$

The tensile stress was the combined load and warping stress. The fatigue analysis assumed that load repetitions were uniformly distributed over the year. The mean maximum monthly warping stress was used, which assumes that the load repetitions occurred during the day. It was felt that this assumption was adequate for comparison of tire sizes and configurations. Allowable repetitions for a specific axle load and pavement section was based on the following relationship:

$$ \sum \frac{n}{N_i} = 1 $$

(2) 

where 

$$ n = 1/12 \text{ of the total load repetitions, and} $$

$$ N_i = \text{the allowable number of load applications for each month, based on the combined load stress and warping stress for that month.} $$

Figure 7 shows the fatigue relationships developed for single axles on a 9-in. pavement.

Equivalency Relationships

The fatigue curves were used to determine the percent of a dual tire axle load that an axle with a specific width of single tire could carry and have an equivalent number of repetitions to a serviceability index of 2.5. It was found that each pavement depth and modulus of subgrade reaction had an individual relationship. These are shown in Figure 8.

Equivalent wheel-load factors were developed for dual tires on single axles and 10-, 12-, 14-, 16-,
and 18-in. wide single tires on single axles. The factors were developed for 7-, 9-, and 12-in. pavements with subgrade $K$-values of 100 and 300 psi/in. The following relationship was used to develop the equivalent wheel-load factors:

$$F_i = \frac{N_{18}}{N_i}$$

where

- $F_i$ = equivalent wheel load factor, 18-kip dual-tire, single axles;
- $N_{18}$ = repetitions to a serviceability index of 2.5 for an 18-kip dual-tire, single-axle load; and
- $N_i$ = repetitions to a serviceability index of 2.5 for the axle load being evaluated.

The equivalent wheel-load factors for single axles with single tires on a 9-in. pavement with a subgrade $K$-value of 100 psi/in. are given in Table 1.

**ANALYSIS OF FLEXIBLE PAVEMENTS**

The use of currently available analysis procedures to compare the effects of various widths of single tires with dual tires on flexible pavement performance presents an interesting problem. This is because the various elastic-layer and finite-element analysis procedures developed for flexible pavements use uniform circular loads. As a result, the width of the tire being modeled is a function of tire contact pressure and load. In a previous study, Terrel and Rimsritong (9) compared the relative damaging...
Table 1. Traffic equivalence factors for single axles with single tires, rigid pavement 9-in. thick, and modulus of subgrade reaction = 100.

<table>
<thead>
<tr>
<th>Axle Load (kips)</th>
<th>Single Tire Width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 in.</td>
</tr>
<tr>
<td>10</td>
<td>0.4251</td>
</tr>
<tr>
<td>12</td>
<td>0.6922</td>
</tr>
<tr>
<td>14</td>
<td>1.0453</td>
</tr>
<tr>
<td>16</td>
<td>1.4939</td>
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<td>18</td>
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<td>22</td>
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</tr>
<tr>
<td>40</td>
<td>17.3146</td>
</tr>
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</table>

The following three techniques were used for modeling tire widths.

1. Constant Radius-Variable Pressure Method. This procedure was the method used by Terrel and Rimsritong. Three single tire widths were evaluated, 10, 15, and 18.5 in. The width of each dual tire was 10 in. The tire widths were maintained by varying the tire pressures. The maximum horizontal strains at the bottom of the asphalt pavement layer were determined and the fatigue life for various axle loads on the three pavement sections calculated. Figure 9 shows the relationship developed between axle loads and repetitions to failure for a 6-in. asphalt pavement section.

2. Double Circle-Constant Pressure Method. This method and the single circle-constant pressure method, to be discussed next, use the assumption that the axle load versus repetitions to failure curves for various single tire widths are parallel to the curve for dual tires. To determine the slope of the fatigue curves, curves were developed for dual tires using two methods: applying the wheel load through a circle with a constant radius and applying the load using a constant contact pressure of 80 psi. The slopes of the two curves were very close for the 9.5-in. asphalt pavement. However, the difference in slopes increased as the depth of the asphalt pavement section decreased.

It was concluded that the average slope would be an adequate representation of the slope of the fatigue curve. For dual tires, the average curve was fit through the intersection of the constant contact pressure and constant radius lines. An example of these curves for a 6-in. pavement section is shown in Figure 10. It is interesting to note that the intersection of these curves lies between 20- and 25-kip axle loads, which is in the load range commonly analyzed using the elastic layer programs.

To model tire width using the double circle method, two adjacent loading circles with a contact pressure of 80 psi were used. The radius of the circle was chosen so that four times the radius equaled the desired tire width. The total area of two circles, was calculated and multiplied by the
contact pressure. This represented the simulated load on the single tire. The maximum horizontal strain at the bottom of the pavement layer was determined and the repetitions to failure calculated. The point representing axle load versus number of repetitions to failure was plotted and a fatigue curve fit through the point. Calculations were made for simulated tire widths of 10, 12, 14, 16, and 18 in. The resulting relationship for a 6-in. asphalt pavement section is shown in Figure 11.

3. Single Circle—Constant Pressure Method: This method is similar to the double circle method. In this case, the diameter of the circle was chosen to equal the width of the tire to be simulated. The

Figure 9. Axle load repetitions to failure for single axles on a 6-in. asphalt concrete pavement over an 8-in. crushed aggregate base—constant radius method.

Figure 10. Fatigue relationship for single axles with dual tires (6-in. asphalt concrete pavement over 8 in. of crushed aggregate base).

Figure 11. Axle load repetitions to failure for single axles on a 6-in. asphalt concrete pavement over an 8-in. crushed aggregate base—double circle method.
wheel load was equal to the area of the circle times the contact pressure, which was held constant at 80 psi. The maximum horizontal strain at the bottom of the asphalt pavement section was determined and repetitions to failure calculated. A fatigue curve was then fit through the point using the same method as in the double circle method. Fatigue curves were developed for 10-, 12-, 14-, 15-, and 18-in. wide tires. The curves for a 6-in. asphalt pavement section are shown in Figure 12.

Equivalency Relationships

For each method and pavement thickness, the percent of dual axle load that an axle with single tires could carry and have an equivalent fatigue life was determined. The equivalency relationships for a 6-in. asphalt concrete pavement are shown in Figure 13. Because of the wide range between the double-circle and the two single-circle methods, a comparison with actual field measurements was needed.

There have been only a limited number of investigations to measure the actual effects of dual tires versus single tires on pavement performance. At the AASHO Road Test an investigation was conducted to determine the performance and deflections for a number of pavement sections under loadings of several pieces of military transport equipment (12). These included the study of the use of low pressure, low-cut tires (LPLS) on tractor and semitrailer units and the effects of the use of the GOER, a self-propelled cargo or fluid transporter resembling a conventional two-axle tractor scraper. Both the LPLS and GOER tires were approximately the same width as the dual tires used for comparison.

Zube and Forsyth (13) reported on a study by the California Division of Highways in 1963 to determine the single-wheel, single-axle loading that would produce the same destructive effect as a dual-wheel, single-axle loading of 18,000 lb. The width of the single tire was approximately 12 in. At one test site they measured the horizontal strain at the bottom of the pavement section under both dual and single tire loadings.

Based on an analysis of the data from the AASHO Road Test and the California study it was concluded that an axle with a single tire equal in width to the dual tires on a 3-in. asphalt pavement section should be able to carry 120 percent of a dual tire axle load and have an equivalent destructive effect in fatigue, whereas an axle with 12-in. wide tires on a 3-in. asphalt pavement section should be able to carry 62 percent of a dual-tire axle load. Figure 14 shows these points connected with a straight line on a plot of the equivalency relationships developed for single versus dual tires on a 3-in. pavement. The line appeared to fall midway between the single and double circle lines. Therefore, an average relationship was developed between the single methods and the double-circle method.

The results shown in Figure 15 indicate that the average single-tire to dual-tire equivalency is close to the equivalency developed using available...
field data. For this reason, it was decided to use an average between the single-circle and double-circle equivalencies for all three pavement sections. These are shown in Figure 16. Admittedly, there is little data to support the use of the average relationship; and field studies will be undertaken to improve this relationship. These studies will include measurements of deflections under axles with single and dual tires using extensometers installed in the pavement structure.

The fatigue curves for dual tires and the equivalency relationships in Figure 16 were used to develop equivalent wheel-load factors for 10-, 12-, 14-, 16-, and 18-in. wide tires on flexible asphalt concrete pavement (ACP) sections with approximate AASHO structural numbers of 2, 4, and 6. The equivalency factors were calculated using the relationship in Equation 3. The equivalency factors for a pavement section with an SN of 4 are given in Table 2.

CONCLUSIONS

Load equivalency relationships have been developed that can be used to determine the effects of axle loads, with various widths of single tires, on both rigid and flexible pavements. These relationships can be used to evaluate regulations relating to tire width and axle loading configurations. They also permit conversion of mixed traffic, including axles with single tires, to equivalent 18-kip dual-tire, single-axle load applications for use in pavement design and evaluation.

A summary of size and weight limits published by the American Trucking Associations (14) indicate that at least 24 states have regulations that control maximum tire loads. Ten additional states have regulations that limit the load on axles with single tires. Of the states having regulations limiting the maximum tire load, 19 permit tire loads in excess of 550 lb/in. of tire width. This includes six states that permit tire loads of 800 lb/in. of width. The relative effects of single versus dual tires on pavement performance were compared with the regulations for maximum tire loads.
This comparison for a 20,000 lb dual-tire axle load is shown in Figure 17. The comparison supports the requirement of 550 lb/in. of tire width. However, tire loads above 550 lb/in. of tire width are not supported. For example an axle with 14-in. single tires on a 9-in. concrete pavement with a subgrade \( K = 100 \) can carry approximately 82 percent of a dual-tire axle load or a maximum of 16,400 lb for an equivalent fatigue life, whereas regulations permitting 660 lb/in. of tire width would allow an axle load of 18,400 lb and regulations permitting 800 lb/in. of tire width would allow the maximum 20,000 lb axle load.

**Figure 17.** Comparison of the regulatory requirements for maximum tire loads with the dual and single tire relationships for equivalent fatigue life where the dual tire axle load equals 20,000 lb.

**ACKNOWLEDGMENT**

This work was sponsored by the Washington Department of Transportation in cooperation with FHWA.

**REFERENCES**


The contents of this paper reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the views or policies of the Washington State Transportation Commission, U.S. Department of Transportation, or the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.