INFLUENCE OF TIRE DESIGN ON PAVEMENT DESIGN AND VEHICLE MOBILITY

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SYNOPSIS

A RATIONAL APPROACH to the design of bituminous paving mixtures described in an earlier paper is reviewed. This approach is based upon: (1) c and ϕ values for the paving mixture as measured by the triaxial test, (2) lateral support of the pavement adjacent to the loaded area, (3) frictional resistance between pavement and tire and between pavement and base, (4) pavement thickness, (5) shape of the curve of tire pressure distribution on the contact area, and (6) whether the wheel loads are standing, moving at uniform speed, or exerting severe braking or acceleration stresses. This study was undertaken to investigate the design requirements for bituminous pavements capable of supporting tire pressures of 300, 400, 500 psi., etc., under consideration for future aircraft, and in particular to attempt to determine the minimum c and ϕ values required by bituminous mixtures to support these high tire pressures.

By flattening the slope of the curve of tire pressure distribution near the edge of the contact area, it appears that high tire pressures could be supported by bituminous pavements having relatively low c and ϕ values. This flatter slope may be difficult to obtain with current tires, but it is shown that it would result from the use of multicompartment tires of more or less concentric construction in which the outermost compartment would be inflated to the lowest pressure and the innermost compartment to the highest.

By employing multicompartment tires, it is shown that the mobility of vehicles over shallow layers of soft soil underlain by firm soil should be greatly improved. For good vehicle mobility over soft soils of great depth, on the other hand, single-compartment tires inflated to apply a pressure not greater than the bearing capacity of the soil are indicated. Multicompartment tires, or closely spaced single-compartment tires inflated to different pressures, may provide more effective soil compaction. A close interrelationship seems to exist between tire design, pavement design, vehicle mobility, and soil compaction.

While this paper presents an essentially theoretical study of certain problems in pavement design, vehicle mobility, and soil compaction, it is based upon generally accepted principles of soil mechanics, and with respect to bituminous pavement design, at least, it provides conclusions that are in agreement with the observed field performance of bituminous pavements.

IN THREE PAPERS published about two years ago (*1*, *2*, *3*) the writer outlined a rational approach to the design of bituminous paving mixtures based upon data provided by the triaxial test. While these papers resulted very largely from a theoretical analysis of the problem of the stability of bituminous pavements, it was shown that the conclusions derived agree at least qualitatively with the observed field performance of these pavements. Furthermore, this approach furnishes a reasonable explanation for a number of puzzling features about service behavior that cannot be provided on the basis of any data obtained from the empirical tests, such as Hubbard-Field, Hveem, and Marshall, currently utilized for bituminous-pavement design.

It was pointed out very briefly in one of these papers (*2*) that this approach might be usefully employed to modify the design of pneumatic tires for two principal purposes: (1) to enable the much higher tire pressures of 300, 400, 500 psi., etc., under consideration for future aircraft to be supported by bituminous pavements with much lower c and ϕ values (lower stabilities) than would be possible with current tire design, and (2) to improve the mobility of vehicles over soft ground.

The present paper is devoted to a more detailed study of what appears to be a close interrelationship between tire design, pavement design, and vehicle mobility, and indicates that this relationship might also be applied to the more effective compaction of soils.

PAVEMENT DESIGN

It is essential first of all to summarize some of the important subject matter from these earlier papers which described a rational approach to the design of bituminous-paving mixtures.

It was assumed, Figure 1, that the thickness of base course and surface was adequate to prevent subgrade failure, and that the base-course material itself would not fail under the shearing stresses imposed by any of the applied loads. The problem under consideration, therefore, was the development of a rational method for designing bituminous paving mixtures that would have sufficient strength or stability to resist failure (being squeezed out from between tire and base course) under the wheel loads and tire pressures to which they were to be subjected. These paving mixtures were assumed to have been properly designed in every other respect, such as workability, density, durability.

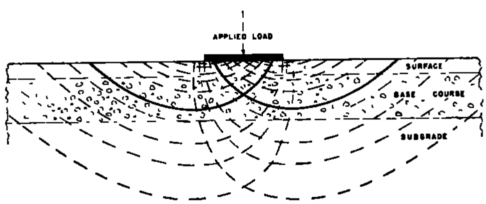

Figure 1. Shear planes under a loaded area.

It was pointed out that the stability requirements for a bituminous paving mixture depend upon whether the applied wheel load is (1) static or moving very slowly, *e.g.*, parking areas, taxiways; (2) moving rapidly at uniform speed, *e.g.*, rural highways or the central portion of airport runways; or (3) subjecting the pavement to severe braking or acceleration stresses, *e.g.*, stop lights, bus stops.

The assumption was made that the strength characteristics of a bituminous paving mixture are indicated by the magnitudes of the values of cohesion c and angle of internal friction ϕ, given by the Mohr diagram based upon triaxial test data for the mixture (Fig. 2). It was demonstrated that an increase in the rate of strain employed in the triaxial test results in an increase in the value of cohesion c, due to the viscous resistance of the paving mixture, but has little or no effect on the value of the angle of internal friction ϕ. This provides a rational explanation for the greater stability shown by bituminous-paving mixtures under rapidly moving as compared with static or slowly moving wheel loads that has been demonstrated by field experience.

The objective of a rational method of design for bituminous-paving mixtures on the basis of the triaxial test is to determine the smallest corresponding values of c and ϕ required to provide a stable bituminous pavement for the loading conditions anticipated throughout its lifetime. The smaller the corresponding values required for c and ϕ, the wider is the range of aggregates from which a selection may be made to provide a bituminous pavement of adequate stability. This in turn tends to lower the cost of bituminous pavement construction.

It was assumed that the stresses involved when a loaded tire rests on a bituminous pavement are equivalent to those of a strip load of great length. Since it was shown that the pavement under a loaded tire develops more stability in the direction of the longitudinal than the transverse axis of the contact area, this assumption is not unreasonable. However, because the actual length of the tire contact area on a pavement is relatively short, this assumption leads to somewhat conservative design.

It was shown that, all other factors being equal, the stability of a bituminous pavement appears to depend very materially upon: (1) the lateral support of the pavement adjacent to the loaded area, L_S; (2) the frictional resistance between pavement and tire and between pavement and base, which can be expressed as an equivalent lateral support L_R, and (3) the shape of the curve of pressure distribution over the contact area.

On the basis of the geometry of the Mohr diagram (Fig. 2), the maximum vertical load V that a bituminous pavement can support is given by the following equation:

$$V = L\left(\frac{1+\sin\phi}{1-\sin\phi}\right) + 2c\sqrt{\frac{1+\sin\phi}{1-\sin\phi}} \qquad (1)$$

where c = cohesion c obtained directly from the Mohr diagram,

ϕ = angle of internal friction ϕ obtained directly from the Mohr diagram.

L = the total effective lateral support from all sources that can be mobilized to react against the lateral thrust of the prism of pavement immediately under the loaded area.

One source of lateral support L is quite obviously provided by the pavement immedi-

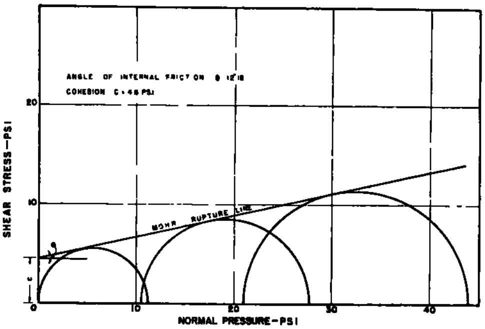

Figure 2. Typical Mohr diagram for triaxial-compression test.

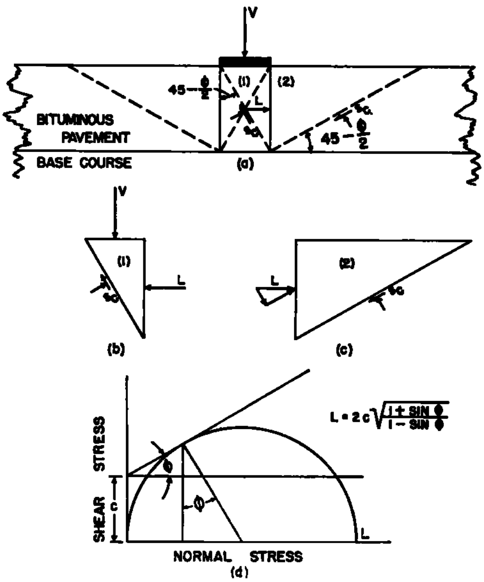

Figure 3. Lateral Support L provided by the portion of a bituminous pavement surrounding the loaded area is given by

$$L = 2c\sqrt{\frac{1 + \sin\phi}{1 - \sin\phi}}.$$

ately adjacent to and surrounding the contact area. This portion of the total effective lateral support L is designated by L_S. As previously explained (*1, 2, 3*), and as illustrated by Figure 3, the unconfined compressive strength of the bituminous paving mixture can be taken as a conservative measure of the lateral support L_S provided by the pavement immediately adjacent to the loaded area; that is (from the Mohr diagram),

$$L_S = 2c\sqrt{\frac{1 + \sin\phi}{1 - \sin\phi}} \qquad (2)$$

If this value for L_S is substituted for L in Equation 1 the following equation results after substitution and simplification,

$$V = \frac{4c}{1 - \sin\phi}\sqrt{\frac{1 + \sin\phi}{1 - \sin\phi}} \qquad (3)$$

The Mohr diagram illustrating the value of V in Equation 3 is shown in Figure 4, wherein the Mohr circle on the left represents the unconfined compressive strength.

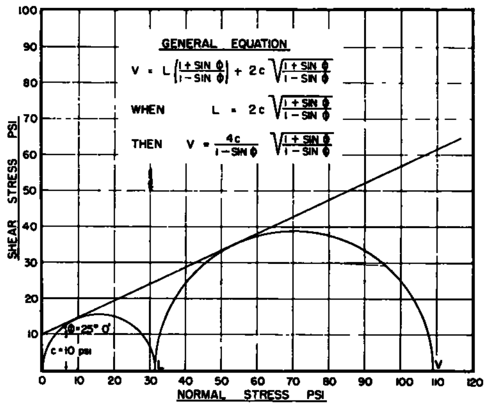

Figure 4. Maximum vertical load V that can be carried by a bituminous pavement when lateral support L is equal to the unconfined compressive strength of the material.

Figure 5 provides a graphical representation of Equation 3 for a wide range of tire pressures. It should be emphasized that Figure 5 illustrates a diagram for the design of bituminous-paving mixtures on the basis that the only source of lateral support is that provided by the portion of the pavement adjacent to the loaded area, and that L is equal to the unconfined compressive strength of the paving mixture in each case.

It was indicated previously that due to several other sources of resistance, the actual value of the lateral support L_S provided by the pavement surrounding the loaded area is probably greater than the unconfined compressive strength of the paving mixture. It was sug-

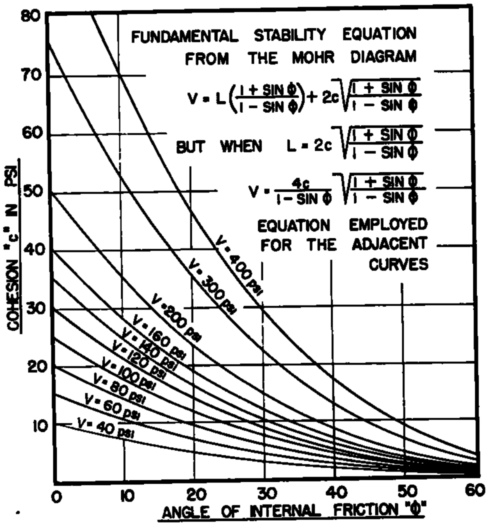

Figure 5. Design chart for bituminous mixtures based on triaxial test and values of lateral support $L = 2c\sqrt{\frac{1 + \sin\phi}{1 - \sin\phi}}$.

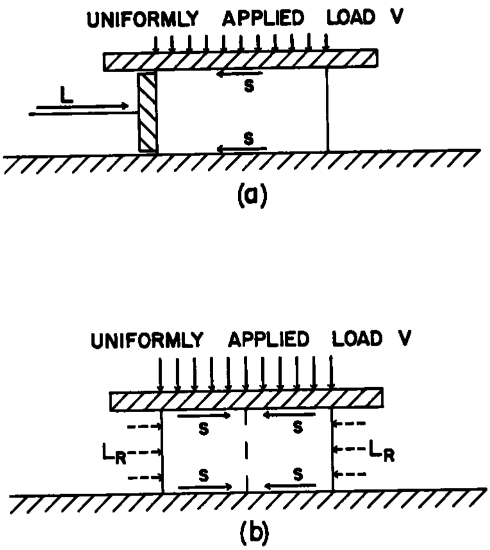

Figure 6. Friction between tire and pavement and between pavement and base is equivalent to additional lateral support for the section of pavement under a loaded area.

gested that these additional sources of resistance outside of the loaded area could be taken into account by making L_S equal to the unconfined compressive strength multiplied by a factor K, when it would become

$$L_S = 2cK\sqrt{\frac{1 + \sin\phi}{1 - \sin\phi}} \tag{4}$$

The substitution of the right hand side of Equation 4 for L in Equation 1 and simplifying gives the following:

$$V = 2c\sqrt{\frac{1 + \sin\phi}{1 - \sin\phi}} \left(\frac{K(1 + \sin\phi) + (1 - \sin\phi)}{1 - \sin\phi}\right) \tag{5}$$

which reduces to Equation 3 when K is taken equal to unity. $K = 1$ might be a conservative value for K, and it is assumed to have this value in the equations and diagrams em-

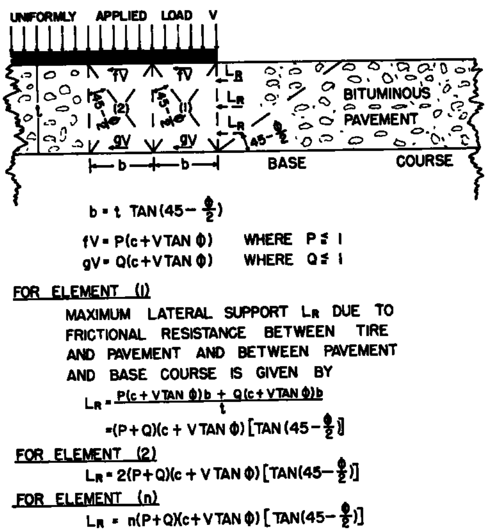

Figure 7. Magnitude of the lateral support L_R equivalent to the frictional resistance developed between tire and pavement and between pavement and base, under the loaded area.

ployed to illustrate the principles under discussion in the present paper. Later on, as more data become available, K can be evaluated more definitely. It might turn out that the appropriate value for K is less than unity.

The three previous papers pointed out that the frictional resistance between pavement and tire and between pavement and base seem to provide an additional major source of pavement stability. Figure 6 illustrates the nature and location of these two frictional resistances, and Figures 6(a) and 7 indicate that they can be represented mathematically by an equivalent additional lateral support L_R.

Values of the coefficient of friction f between pavement and tire have been measured by Moyer (*4*) and Lee (*5*), who report values of f up to 1.0 for stationary or slowly moving vehicles, although 0.8 is a more normal top value. No data seem to be presently available concerning the value of g, the coefficient of friction between pavement and base. For a rational method of design, values for f and g must be either determined or assumed for pavement design for each individual project.

Figure 7 illustrates a method for evaluating the total frictional resistance between pavement and tire and between pavement and base in terms of the equivalent lateral support L_R, and for expressing the maximum value of L_R that can be developed as a simple mathematical equation,

$$L_R = n(P + Q)(c + V \tan \phi) \left[\tan\left(45 - \frac{\phi}{2}\right)\right] \tag{6}$$

Figure 7 explains that the factor P in Equation 6 indicates that the maximum frictional resistance fV that can be developed between pavement and tire cannot exceed the shearing resistance of the bituminous pavement itself, which is given by the Coulomb equation $s = c + V \tan \phi$, where V is the pressure applied by the tire to the contact area. The factor Q is of similar significance with respect to the frictional resistance gV between pavement and base. As shown by Figure 7, the highest value that either P or Q can have individually is unity, and the lowest value is zero. Therefore, the maximum value for $P + Q = 2$, and the minimum value is zero.

In actual practice it may be found that either P or Q can develop a larger value than unity. However, since there is no present reason for expecting this, it is assumed that neither P or Q can have values greater than unity.

Equation 6 can be rewritten in terms of f and g, rather than P and Q, when it becomes,

$$L_R = nV(f + g) \left[\tan\left(45 - \frac{\phi}{2}\right)\right] \tag{7}$$

It is apparent that the total effective lateral support L developed by a bituminous pavement can be expressed as

$$L = L_S + L_R \tag{8}$$

from which it follows that Equation 1 can be rewritten as

$$V = 2c\sqrt{\frac{1 + \sin\phi}{1 - \sin\phi}} + L_S\left(\frac{1 + \sin\phi}{1 - \sin\phi}\right) + L_R\left(\frac{1 + \sin\phi}{1 - \sin\phi}\right) \tag{9}$$

Equation 9 makes it clear that the stability of a bituminous pavement consists of three principal parts:

(1) The stability due to unconfined compressive strength of the pavement represented by the first term on the right hand side $2c\sqrt{\frac{1 + \sin\phi}{1 - \sin\phi}}$. This might be referred to as the inherent strength of the pavement in the complete absence of lateral support from the surrounding material, and of frictional resistance between pavement and tire and between pavement and base.

(2) Stability due to the lateral support L_S provided by the portion of the pavement adjacent to the loaded area, and expressed by the term:

$$L_S\left(\frac{1 + \sin\phi}{1 - \sin\phi}\right).$$

(3) Stability due to a lateral support L_R equivalent to the frictional resistance between pavement and tire and between pavement and base, and represented by the term:

$$L_R\left(\frac{1 + \sin\phi}{1 - \sin\phi}\right).$$

In addition, a further source of stability in the form of arching action, particle interference, etc., due to their composition and thickness, may exist in certain bituminous pavements. This could be referred to as structural stability. Where it exists, structural stability might be evaluated as the difference between the total stability developed, and the stability calculated on the basis of Equations 10 or 11.

Since L_S has already been evaluated by

Equation 4, and L_R by Equation 6, and remembering that the pressure exerted by a tire is not uniform, but varies across the contact area (6, 7), *e.g.*, Figure 10, Equation 9 can be written as follows:

$$V = 2c\sqrt{\frac{1+\sin\phi}{1-\sin\phi}} + 2cK\sqrt{\frac{1+\sin\phi}{1-\sin\phi}}\left(\frac{1+\sin\phi}{1-\sin\phi}\right) + n(P+Q)(c+V'\tan\phi)\left[\tan\left(45-\frac{\phi}{2}\right)\right]\left(\frac{1+\sin\phi}{1-\sin\phi}\right) \quad (10)$$

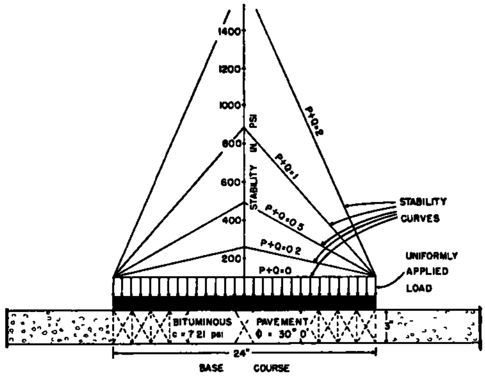

Figure 8. Relationships between applied load and stability of bituminous pavements at varying distances from edge under the loaded area and for different degrees of frictional resistance developed between pavement and tire and between pavement and base (pavement stability equal to applied load for edge conditions; aeroplane tire).

where V = stability in psi. developed by the bituminous pavement at any point on the contact area,

c = unit cohesion in psi. obtained from the Mohr diagram,

ϕ = angle of internal friction obtained from the Mohr diagram,

K = a constant, which may be taken equal to unity for conservative design,

P = ratio of frictional resistance fV between pavement and tire to the shearing resistance of the pavement represented by the Coulomb equation $s = c + V\tan\phi$, and, therefore, has a maximum value of unity,

Q = ratio of frictional resistance gV between pavement and base to the shearing resistance of the pavement $c + V\tan\phi$, and has a maximum value of unity,

n = the number of elements, each of width equal to $t\,[\tan(45 - \phi/2)]$, measured from the edge of the contact area to the point on the contact area where the value of stability V is required, where t is the thickness of pavement,

V' = the average vertical pressure exerted by the tire between the edge and the point on the contact area at which the value of stability V is required.

When L_R is represented by Equation 7 instead of Equation 6, Equation 10 becomes

$$V = 2c\sqrt{\frac{1+\sin\phi}{1-\sin\phi}} + 2cK\sqrt{\frac{1+\sin\phi}{1-\sin\phi}}\left(\frac{1+\sin\phi}{1-\sin\phi}\right) + nV'(f+g)\left[\tan\left(45-\frac{\phi}{2}\right)\right]\left(\frac{1+\sin\phi}{1-\sin\phi}\right) \quad (11)$$

where f = coefficient of friction between pavement and tire,

g = coefficient of friction between pavement and base,

and the other symbols have the significance previously defined for them.

That the frictional resistance fV between pavement and tire and the frictional resistance gV between pavement and base may be an important source of stability for bituminous pavements, is illustrated by Figure 8, in which the straight line stability curves for various values of $P + Q$ and $f + g$ indicate a rapid increase of pavement stability when proceeding from the edge toward the center of the contact area. For Figure 8 it was assumed that a uniform tire pressure of 100 psi. was applied to the contact area, and that the stability of the pavement was exactly 100 psi. at the edge of the contact area, due to the first two terms on the right hand side of Equations 9, 10, and 11. The increase in stability of the pavement underlying the loaded area when proceeding from the edge to the center of the contact area, illustrated by the stability curves in Figure 8, was calculated by means of the third term on the right hand side of Equation 10 for the $P + Q$ curves, and by means of the third term on the right hand side of Equation 11 for the stability curves labelled with $f + g$ values. Figure 8 demonstrates that even a low value for $f + g = 0.325$ raises the stability of the pavement near the center of the contact area to more than four times its stability at the edge, for the particular conditions pertaining to this diagram.

Other evidence of the considerable influence of frictional resistance between pavement and tire and between pavement and base on the stability of bituminous mixtures is provided by the fact that Jurgenson (*8*) designed a test for measuring the shearing resistance of clay, by squeezing it between two rough surfaces, *e.g.*, Figure 6. In this case, too, the maximum shear is developed at each of the two interfaces.

As a further check on the importance of these two frictional resistances, load was applied to a layer of plasticine (a modeling clay) 0.75 in. thick and resting on a large steel plate, by means of steel bearing plates 3, 6, 9, and 12 in. in diameter. Some very preliminary results are shown graphically in Figure 9 for a vertical deformation of 0.05 in. in each case. They indicate that due to the greater distance between center and edge over which the two frictional resistances are acting as the bearing plate diameter is increased, the load carried by the 12 in. plate, 57.5 psi., is over two and one half times the load carried by the 3-in. plate, 22.4 psi. It will be recalled that for load tests at the surface of a great depth of clay, the unit pressure supported at any given deflection *decreases* with increasing diameter of the bearing plate, and that the curve of unit pressure versus plate diameter would slope down from the 3-in. plate, instead of sloping upward as in Figure 9. Consequently, the influence of the frictional resistances between the plasticine and the upper and lower bearing surfaces on the ability of the plasticine to support load is even greater than Figure 9 may indicate as a first impression. It should be emphasized again that Figure 9 represents the results of some very preliminary tests, which will be repeated much more carefully at an early date.

Many fine examples of the important influence of good frictional resistance between pavement and base on pavement stability have been provided by field experience. An otherwise well designed paving mixture, when

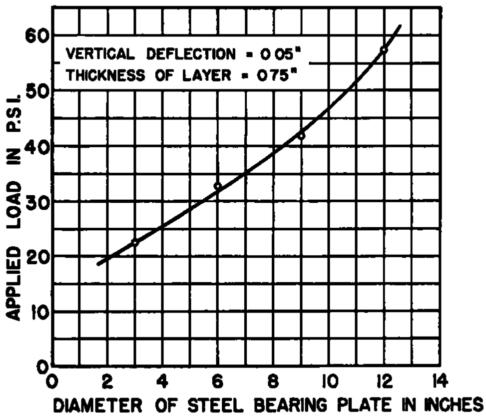

Figure 9. Increase in supporting value of plasticine layer with increase in diameter of bearing plate.

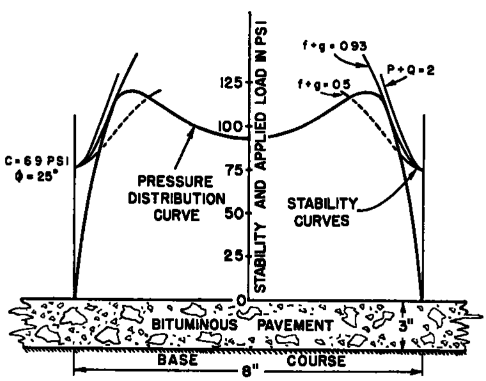

Figure 10. Influence of typical pressure distribution over the contact area, and of various degrees of frictional resistance between pavement and tire and between pavement and base in terms of $f + g$ values on the design of the underlying bituminous pavement (truck tire).

laid on a smooth base, or on a base to which it is poorly bonded or not at all, will quickly develop indications of instability under traffic, quite often in the form of large tension cracks of well recognized pattern.

Figure 10 illustrates the application of Equations 10 and 11 to the actual design of a bituminous-paving mixture. The heavy continuous curve represents the actual pressure applied to the pavement by the tire at all points across the transverse axis of the contact area (*6, 7*). The two peaks are considered to be due to the influence of the tire walls. The pressure curve rises from zero pressure at the edge of the contact area to a maximum at these two peaks, and diminishes somewhat from them toward the center. Very few measurements have been made of the pressures applied by tires to their contact areas on pavements and it is not known how much tires vary in this respect. More carefully obtained information concerning this factor would be very valuable.

The short curves on the right and left hand sides of Figure 10 are stability curves for different values of $f + g$ for a given paving mixture

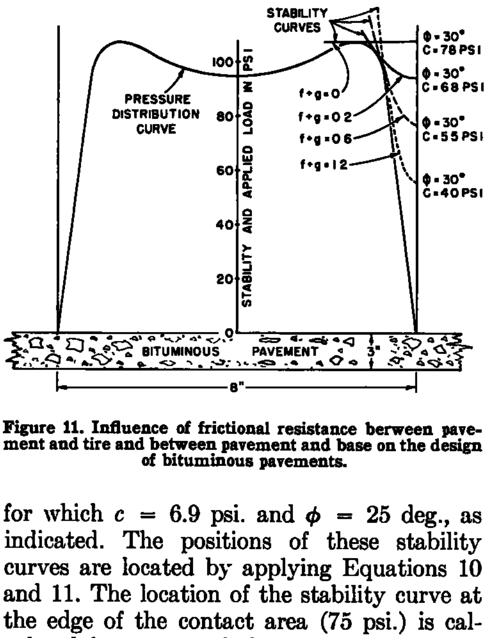

Figure 11. Influence of frictional resistance berween pavement and tire and between pavement and base on the design of bituminous pavements.

for which $c = 6.9$ psi. and $\phi = 25$ deg., as indicated. The positions of these stability curves are located by applying Equations 10 and 11. The location of the stability curve at the edge of the contact area (75 psi.) is calculated by means of the first two terms of Equations 9 and 10; that is, on the basis that the only source of pavement stability is the unconfined compressive strength of the pavement (the first term of Equations 10 and 11), plus the stability due to the lateral support provided by the pavement adjacent to the loaded area (the second term of Equations 10 and 11). The location of the stability curve at the edge of the loaded area, 75 psi., can also be read directly from Figure 5, employing the coördinates $c = 6.9$ psi. and $\phi = 25$ deg., or can be calculated by means of Equation 3. The increase in stability with increasing distance inward from the edge of the contact area indicated by the stability curves of Figure 10 is due to the frictional resistance between pavement and tire and between pavement and base, and is calculated by means of the third term in Equations 10 and 11, Equation 10 being employed for the $P + Q = 2$ curve and Equation 11 for the $f + g = 0.93$ and $f + g = 0.5$ curves. These stability curves indicate that because of the influence of these two frictional resistances, the pavement can sustain a higher and higher vertical load as the center of the contact area is approached from the edge; that is, its stability increases with increasing distance inward from the edge of the loaded area.

The ordinate axis in the center of the diagram indicates values for both tire pressure exerted on the contact area and pavement stability. If it is assumed that the stability of the pavement must be not less than the pressure applied by the tire at any point on the contact area, then it is apparent that the stability curve must not cut through the pressure curve at any point. It is equally clear that the critical stability curve is the one that is just tangent to the pressure curve. In Figure 10, the stability curve for $f + g = 0.5$ cuts through the pressure curve, indicating that the pavement would be unstable for the portion of the contact area for which the stability curve lies below the pressure curve. The stability curve for $f + g = 0.93$ is just tangent to the pressure curve, and indicates the lowest value of $f + g$ for which this particular paving mixture ($c = 6.95$ psi., $\phi = 25$ deg.) would be stable at all points on the contact area. The stability curve labelled $P + Q = 2$, on the other hand, indicates the highest $f + g$ values that could be developed for this paving mixture, since any $f + g$ stability curve lying above this $P + Q = 2$ curve would represent a value of frictional resistance between pavement and tire or between pavement and base, or both, that was greater than the shearing resistance of the bituminous pavement. It is apparent that the pavement would fail in shear before such a high value for f or g or $f + g$ could be developed.

The importance of frictional resistance between pavement and tire and between pavement and base on bituminous-pavement design is emphasized in Figure 11, in which stability curves for $f + g = 0$, $f + g = 0.2$, $f + g = 0.6$, and $f + g = 1.2$ are shown on the right-hand side. These stability curves demonstrate very clearly the decrease in values of c and ϕ that is possible as the $f + g$ values are increased. For example, when f + g = 0, a paving mixture with $c = 7.8$ psi. and $\phi = 30$ deg. developing a stability of 107 psi. at the edge of the contact area is required, while for $f + g = 1.2$ a bituminous mixture with $c = 4.0$ psi. and $\phi = 30$ deg. developing a stability of only 54 psi. at the edge of the contact area is adequate; that is, by increasing the $f + g$ value from 0 to 1.2, the stability requirements for the paving mixture in terms of c and ϕ values have been reduced by one half.

In the field of airport-runway design, one of the important current problems is presented by the increased tire pressures for landing wheels. Figure 12 demonstrates that on the basis of present tire designs, as the tire pressure is increased, the stability of the paving mixture must be increased. The solid pressure-curve in Figure 12 is for an average tire pressure of 100 psi., while the dashed pressure-curve corresponds to an average tire pressure of 200 psi., the total load being 8,000 lb. in each case. If $f + g = 1.0$ in both cases, the stability curves of Figure 12 indicate that the values of c and ϕ must be increased from $c = 4.5$ psi. and $\phi = 30$ deg. to $c = 9.0$ psi. and $\phi = 30$ deg. to give approximately double the pavement stability as the tire pressure is increased from 100 psi. to 200 psi. This shows that many existing bituminous pavements will be unstable if tire pressures are increased to 300, 400, 500 psi., etc., as sometimes suggested for future aircraft. In addition, as these tire pressures increase, the c and ϕ values of paving mixtures must be further increased to provide the necessary pavement stability. This, in turn, means that fewer and fewer aggregates would have the properties needed to produce bituminous pavements with the increased stability required. Furthermore, the design of stable bituminous pavements for these proposed high tire pressures might be a serious problem in areas where only inferior aggregates occur.

On the basis of the subject matter that has just been presented, a rational method of design for bituminous pavements requires that (1) the shape of the most critical curve of distribution of tire pressure on the contact area must be known, (2) the coefficients of friction between pavement and tire, f, and between pavement and base, g, must be known, (3) values for c and ϕ for the bituminous mixture must be determined, (4) the pavement thickness must be specified, (5) the stability curve must be drawn using Equations 10 or 11, and (6) the stability curve should be tangent to or above the pressure distribution curve for all points on the contact area, to provide the minimum stability required.

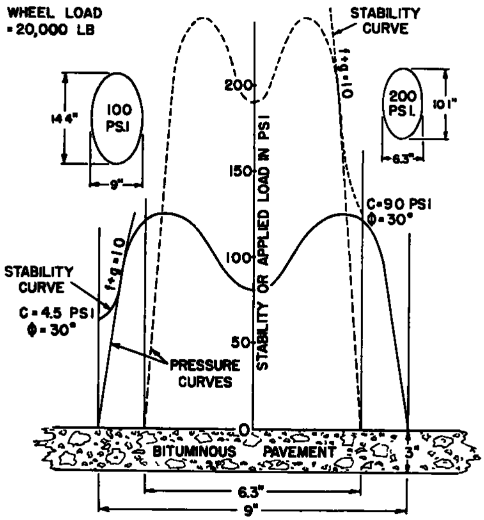

Figure 12. Increased pavement stability required when tire pressure is increased from 100 to 200 pounds per square inch.

INFLUENCE OF TIRE DESIGN

On the basis of Figure 12, if the tire pressure is increased, the stability of the paving mixtures that are to carry these higher tire pressures must also be increased. This is the only solution to the problem of pavement design for higher tire pressures that can be offered by the current empirical methods for bituminous mixture design, such as Hubbard-Field, Hveem, Marshall.

On the other hand, while the rational approach to the design of bituminous paving mixtures that has just been outlined indicates that paving mixtures of greater stability is one answer to the problem of higher tire pressures, it also suggests another possible solution.

Instead of constructing pavements of higher and higher stability, it indicates that by certain modifications in the design of tires, many existing pavements might continue to be stable in spite of much higher tire pressures. In addition, these high tire pressures might be safely carried by new pavements of moderate stability.

The objective to be achieved by the modifications in tire design suggested by this rational approach consists of flattening the slope of the curve of tire-pressure distribution near the edge of the contact area, as illustrated in Figure 13. The solid tire-pressure-distribution curve shown in Figure 13 is representative of that for an average current tire, and has a steep slope near the edge of the contact area. The dashed tire-pressure-distribution curve illustrates the much flatter slope near the edge of the loaded area that would be obtained by means of a modified tire-design. The stability curves tangent to these two pressure distribution curves demonstrate the large decrease in pavement stability (c and ϕ values) that is possible by decreasing the slope of the tire pressure curve near the edge of the contact area. Both stability curves are drawn for a value of $f + g = 0.65$. The stability curve tangent to the steeper, solid tire-pressure curve indicates that a bituminous pavement for which $c = 7.35$ psi. and $\phi = 25$ deg., providing a stability of 80 psi. (Equation 3) at the edge of the contact area (due to the pavement surrounding the loaded area) is required, while the stability curve tangent to the dashed-line pressure-curve of flatter slope demonstrates that a bituminous pavement for which $c = 1.75$ psi. and $\phi = 25$ deg., providing a stability of only 19 psi. at the edge of the contact area, is needed. That is, by decreasing the slope of the tire-pressure curve near the edge of the contact area (Fig. 13), the stability requirement for the paving mixture in this particular case is reduced from 80 psi. to 19 psi.

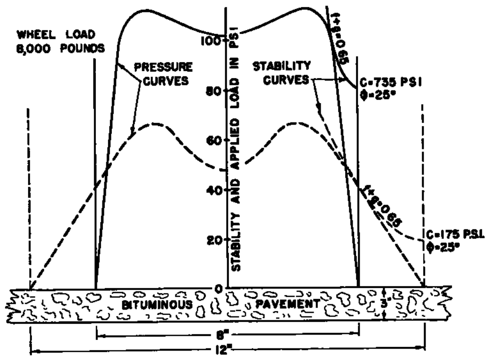

Figure 13. Influence of shape of pressure distribution curve across the contact area on bituminous pavement design.

It is apparent, therefore, that by flattening the slope of the tire-pressure-distribution curve near the edge of the contact area, very much higher tire pressures could be supported by many existing bituminous pavements, or by new pavements of relatively low stability (low c and ϕ values).

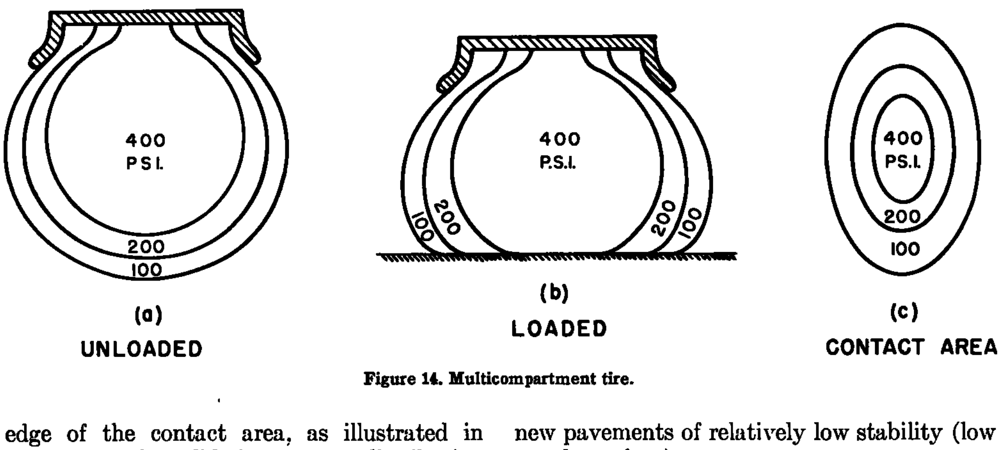

Figure 14. Multicompartment tire.

Tire manufacturers may be able to produce ordinary tires for which the slope of the pressure-distribution curve is much flatter near the edge of the contact area than is the case with present tires. However, Figure 14 demonstrates that there is a more positive approach to this problem, by utilizing a tire containing two or more compartments, more or less concentric, each inflated to a different pressure. Figure

14(a) illustrates such a tire consisting of three compartments inflated to 100, 200, and 400 psi., from outermost to innermost compartments, respectively. Figure 14(b) indicates the action of such a tire when loaded, while Figure 14(c) shows the principal pressure contours on the contact area of this tire. Other pressures could be employed for the compartments than those shown in Figure 14, and it should be clear that many variations of this principle are possible, in some of which rubber of different hardness or softness, etc. might replace one or more of the gas-filled compartments of the tire.

The multicompartment type of tire illustrated in Figure 14 has two important advantages over existing single-compartment tires designed to carry the same total load on the same contact area: (1) the flatter slope of the pressure-distribution curve near the edge of the contact area lowers the c and ϕ values (stability requirements) needed for a stable paving mixture and (2) the applied pressure is higher toward the center of the contact area, where Figures 8 to 13 have already demonstrated the greatest pavement stability seems to be developed.

Figure 15 illustrates the advantage of a two-compartment versus a single-compartment tire for a wheel load of 20,000 lb. The contact areas for both tires are exactly the same. The stability curve in Figure 15(a) that is just tangent to the pressure-distribution curve for a single-compartment tire inflated to about 200 psi., indicates that a bituminous-paving mixture would be required for which $c = 9$ psi. and $\phi = 30$ deg. developing a stability of about 125 psi. at the edge of the contact area (due to the lateral support of the pavement surrounding the loaded area, Equation 3). Figure 15(b) illustrates a two-compartment tire inflated to 100 psi. in the outer compartment and to 400 psi. in the inner compartment. Because of the overall flattening of the slope of the pressure curve near the edge of the contact area, the stability curve in Figure 15(b) indicates that a bituminous-paving mixture would be required for which $c = 4.5$ psi. and $\phi = 30$ deg., and developing a stability of only about 62 psi. at the edge of the contact area (due to the lateral support of the portion of the pavement surrounding the loaded area, Equation 3). For both Figure 15(a) and Figure 15(b), the stability curves are based upon $f + g = 1.0$. Figure 15 demonstrates, therefore, that by going from a single-compartment to a two-compartment tire, the stability of the paving mixture required to carry a wheel load of 20,000 lb. on the contact area shown might be reduced to about one half, *e.g.*, from about 125 psi. to about 62 psi.

Figure 16 illustrates the reduction in the stability requirement for the bituminous pavement that is possible for supporting a wheel load of 50,000 lb. on a given contact area, when a triple-compartment tire inflated to 60 psi. in the outer compartment, to 150 psi. in the intermediate compartment, and to 300 psi. in the inner compartment, is substituted for a single-compartment tire inflated to 200 psi. The stability curve for Figure 16(a) shows that for the single-compartment tire, a bituminous pavement for which $c = 9$ psi. and $\phi = 30$ deg., and developing a stability of about

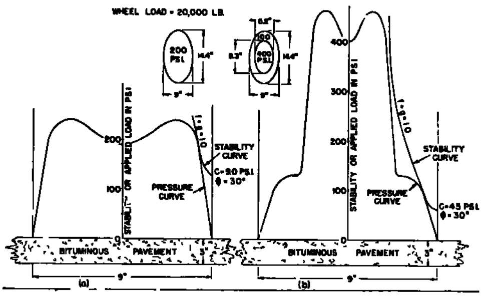

Figure 15. Influence of tire design on the design of bituminous pavements for a wheel load of 20,000 lb.

125 psi. at the edge of the contact area (Equation 3) is required. On the other hand, the stability curve for Figure 16(b) indicates that with a triple-compartment tire inflated as shown, the same total load could be carried on the same contact area by a bituminous pavement for which $c = 2.9$ psi. and $\phi = 30$ deg., and which developed a stability of only about 41 psi. at the edge of the contact area. In this case, by substituting a triple-compartment tire for the single-compartment tire, a reduction of about two thirds in the stability requirement for the bituminous-paving mixture could be made.

Figures 13, 15, and 16 demonstrate that by flattening the slope of the curve of pressure distribution near the edge of the contact area, many existing bituminous pavements would be stable, even if the average tire pressure were greatly increased above present values.

Furthermore, by this modification in tire design, bituminous pavements with relatively low c and ϕ values could be designed and constructed that would have quite adequate stability under average tire pressures of several hundred psi.

Comments and Qualifications. First, the rational approach to the design of bituminous pavements that has just been described is based entirely on stress factors, and no direct mention has been made of the strains developed in a pavement subjected to these stresses. Very little information is available concerning the magnitude of the strains a bituminous pavement can withstand without damage. If either the Hveem Stabilometer method, or the triaxial method described in the Asphalt Institute's hot-mix manual (*9*), actually subject test specimens to failure conditions as usually claimed for them, the strain at which the failure stress occurs must be very small.

It is clear that some strain must be developed in the prism of pavement immediately under the loaded area, before it can begin to mobilize lateral support from the adjacent pavement. Also, some strain must occur before the pavement can mobilize the frictional resistances between pavement and tire and between pavement and base. That repeated strains of some magnitude under traffic loads are beneficial to bituminous pavements rather than detrimental is indicated by the often repeated and thoroughly substantiated statement to the effect that bituminous pavements require the kneading action of traffic to keep them in good condition.

It is common practice in North America to measure the strength of test specimens of bituminous mixtures at 140 F., which is frequently quoted as the maximum pavement temperature developed under the summer sun on this continent. Consequently, if the pavement is sufficiently stable to support traffic loads when its temperature is 140 F., it has a large safety factor at much lower temperatures as far as strength is concerned. However, more information must be obtained before it can be determined what factor of safety should be selected for both stress and strain under service conditions at the critical temperature of 140 F.

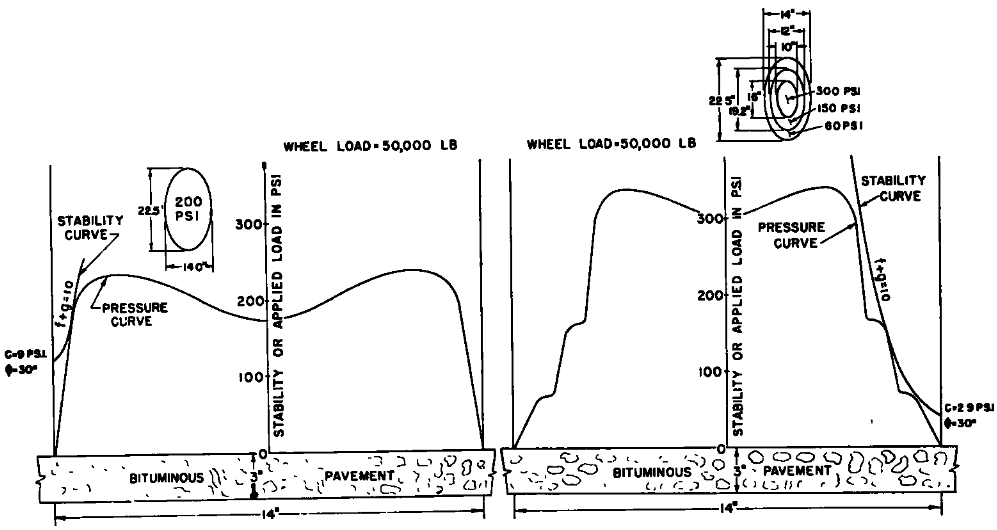

Figure 16. Influence of tire design on the design of bituminous pavements for a wheel load of 50,000 lb.

It should be observed that all present design methods, Hubbard-Field, Marshall, Hveem, and triaxial, test specimens of bituminous mixtures to failure and report stability at failure as the strength of the mixture. If the strain corresponding to the failure stress is greater than could be permitted for a pavement under traffic loads, any factor of safety with respect to strain which is being unwittingly introduced into the actual design and construction of bituminous pavements at the present time is also effective with respect to stress, and vice versa.

Consideration of a maximum permissible strain less than that corresponding to failure conditions would not eliminate any of the stress items on which the rational method of design outlined here is based, but would have the effect of applying a factor of safety to each of them.

Second, it should be carefully noted that the possible advantages of a multicompartment tire for simplifying pavement design for high tire pressures are dependent upon the fact that frictional resistance between pavement and tire and between pavement and base appears to be an important source of pavement stability. If due to considerations of limited permissible maximum strain within the pavement under service conditions, it should be necessary to apply an appreciable factor of safety to these two frictional resistances, the advantages of a multicompartment over a single-compartment tire would be reduced, and if this factor of safety were large enough, these advantages would disappear, insofar as their being of any practical value is concerned.

Third, to simplify its presentation, it was assumed at the beginning of this paper that the base course would not fail under the shearing stresses imposed by any load applied at the surface of the bituminous pavement. Nevertheless, it should be pointed out that the pressure applied by the innermost compartment of a multicompartment tire may be quite high, *e.g.*, Figure 15, and that it may be the cause of very high shearing stresses in the underlying base course. Consequently, in actual design, two criteria of failure must be investigated: (1) the tendency of the bituminous pavement to be squeezed out between the tire and the base course, and (2) the tendency of failure to occur along some failure curve extending into the base, *e.g.*, Figure 20. The first of these two criteria of failure has just been considered in this paper, and some reference to the nature of the second will be made in connection with vehicle mobility over a layer of soft soil in a later section.

VEHICLE MOBILITY

Vehicle mobility might be defined as the ease with which vehicles can move or be moved over either natural terrain or prepared surfaces. The problem of improving the mobility of vehicles and of making them more independent of the nature of the medium over which they are to travel is one of great economic consequence, since it applies to every industry and activity where materials or persons must be transported on equipment fitted with wheels, tracks, skids, etc. It is a particularly important problem to those individuals and organizations whose vehicles must travel for at least part of the time over natural ground (which in Canada may include snow and muskeg). It is with the problem of the mobility of wheeled vehicles over soft terrain that the present section of this paper is principally concerned.

The gradual large-scale displacement of horses and other beasts of burden by farm tractors in recent years has delayed the start of spring seeding, because the land must be drier to enable tractors to operate than was the case with horses. This means that crops mature later in the fall than formerly, and in western Canada, and probably in the more northerly states of the great plains of the western United States, the danger of serious frost damage is thereby increased. Late seeding and early frost resulted in the loss of many millions of dollars in the form of damage to the grain crop in western Canada in 1950. The fall of 1951 was quite wet and seriously interfered with harvesting operations. There were many short periods of fine weather when the grain itself was in a satisfactory condition for harvesting, but the land was so wet that the tractors, combines, and trucks could not operate in the fields. As a result, according to our Dominion Bureau of Statistics, 285,000,000 bushels of wheat, oats, and barley are passing this winter buried under the snow in western Canada, and again, even if conditions should be very favorable for spring harvesting, the losses due to unrecovered grain and deterioration of quality may be many tens of millions of dollars. It should be emphasized that a great deal of this loss can be attributed directly to the lack of mobility of present agricultural equipment on soft ground.

Contractors lose many days of work each year because of wet weather, and the poor mobility of construction equipment on soft ground. Operations depending upon vehicles employed by petroleum, mining, logging, and pulp and paper industries, and by public utilities, etc., are frequently delayed because of poor vehicle mobility over soft ground. Vehicles of all kinds very often have poor mobility on sand.

Serious economic loss occurs, therefore, in many industries because of the poor mobility of equipment over natural terrain, or on roads in a low state of development. In addition, the improved mobility of vehicles over soft ground is an important objective in connection with military operations.

Everything else being equal, vehicle mobility is dependent upon two factors: (1) available tractive effort and (2) rolling resistance. Available tractive effort is the maximum reaction between the tire and the surface on which it is resting or moving that can be utilized to propel the vehicle. Rolling resistance is the reaction that the surface opposes to either the forward or reverse motion of the vehicle. In soft soils, rolling resistance is high when the tires cut deeply, and available tractive effort is low because the maximum reaction that can be developed between normal tires and such soils for propelling the vehicle is relatively small. With certain exceptions, whatever is done to decrease rolling resistance also tends to increase available tractive effort and thereby promotes better vehicle mobility. Rolling resistance on soft soil would be decreased if tires could be designed to travel over the surface of these soils without cutting into them deeply; that is, if the tires were designed to ride over the soil, instead of squeezing it out (lateral displacement), or consolidating it greatly, or both. The present section of this paper considers the important factor of improving vehicle mobility by designing tires that will tend to travel over the surface of soft soils without cutting into them deeply and displacing them.

The soft ground that is so frequently the cause of poor vehicle mobility can be divided into two principal categories: (1) the soft layer extends from the surface of the ground to a shallow depth at which firmer soil exists (frequently the case after rains) and (2) the soft ground extends from the surface to great depth, or at least to a depth that is large relative to the width of the tires on the vehicle.

It should be apparent that the first category above grades into the second category and that the dividing line between the two is relative rather than absolute, since the action of a narrow tire on a thin layer of soft soil could be roughly similar to that of a wide tire on a much thicker layer of the same soft soil.

In each of the two categories listed, the soil can vary from cohesionless sand or gravel to cohesive soils that develop either both c and ϕ or only cohesion c in the quick triaxial test. It is recognized that actual soil can vary from being relatively homogeneous to largely heterogeneous in both categories, but to simplify the presentation in this section of the paper, it is considered to be either a shallow soft layer of one homogeneous soil on a great depth of another firmer homogeneous soil (Category 1), or to consist of a soft homogeneous soil extending from the surface to a great depth (Category 2).

VEHICLE MOBILITY OVER SOFT SOIL OF SHALLOW DEPTH

First of all, improved vehicle mobility for the conditions listed above in Category 1 will be considered. The layer of soft soil is relatively shallow and is underlain by a great depth of firm soil. Good vehicle mobility will result in this case if the tires can be made to ride over the surface of the soft layer instead of cutting into it deeply as usually occurs at the present time. The problem consists essentially of determining the maximum load that can be placed on a tire without squeezing out the soft layer of soil on which it is resting. This problem is quite similar to that considered in a previous section, where the stability required by a bituminous pavement to prevent it from being squeezed out between tire and base course was investigated. In the latter case a multicompartment tire was indicated to have some advantages over a single-compartment tire. It will be shown that a multicompartment tire also permits a much greater wheel load to be supported on a shallow layer of soft soil underlain by firm soil. Three cases of shallow layers of soft soils will be considered, a soft cohesive soil for which $\phi = 0$ deg., a soft cohesive soil for which $\phi = 10$ deg., and a cohesionless soil for which $\phi = 30$ deg.

Soft Layer of Cohesive Soil for which $\phi = 0$ deg. Since the maximum frictional resistance between soft layer and tire, and between soft layer and underlying firm soil is to be developed, Equation 10 will be employed. Because the angle of internal friction $\phi = 0$, Equation 10 in this case reduces to

$$V = 4c + nc\,(P + Q) \qquad (12)$$

The maximum frictional resistance between soft layer and tire, and between soft layer and the firm soil below that can be developed is the shearing resistance of the soil. Therefore, $P + Q = 2$, and Equation 12 becomes

$$V = 4c + 2nc \tag{13}$$

The first term $4c$, on the right hand side of Equation 13, represents the strength of the soft layer if its stability were influenced solely by lateral support from the portion of the layer adjacent to the loaded area, Figure 17. The second term, $2nc$, represents the added stability due to the frictional resistance between soft layer and tire, and between soft layer and underlying firm soil. This additional stability is gradually mobilized as increasing load on the tire tends to squeeze out the soft layer.

Text books on soil mechanics indicate that $c = 3$ psi. is a low value for a cohesive soil, and represents a very soft clay. Substituting this value for c in Equation 13 gives

$$V = 12 + 6n \tag{14}$$

which is the equation of stability or strength for this soft layer when $c = 3$ psi. Equation 14 is indicated graphically by the straight line stability curve in Figure 17.

To avoid squeezing out the soft layer of soil between the tire and firm soil below, it is clear that the curve representing the distribution of tire pressure on the contact area must not be above the stability curve at any point. If the maximum-permissible load is to be carried by the tire, the stability curve should also be the tire-pressure-distribution curve. This would require a tire with an infinite number of more or less concentric compartments inflated to successively higher pressures from outermost to innermost compartments, which is, of course, impractical. Figure 17, therefore, illustrates a three-compartment tire inflated to 12.5 psi. in the outer compartment, to 16.0 psi. in the intermediate, and 20 psi. in the inner compartment. This provides a tire-pressure-distribution curve that follows the stability curve quite closely.

Since Figure 17 applies strictly to a strip loading, the pressures shown should be somewhat conservative for an elliptical contact area, although, as previously pointed out, the elliptical prism of soft soil immediately under the loaded area tends to develop greater stability in the direction of the major than of the minor axis of the contact area. Assuming that the pressures shown in Figure 17 apply to an elliptical contact area for which the minor axis is 24 in. and the major axis is 1.6 times this, or 38.4 in., the maximum load that could be applied to the soil through the medium of the three-compartment tire without causing the soil to be squeezed out is 11,145 lb.

It is worth while to examine the additional load-carrying capacity of the tire as a result

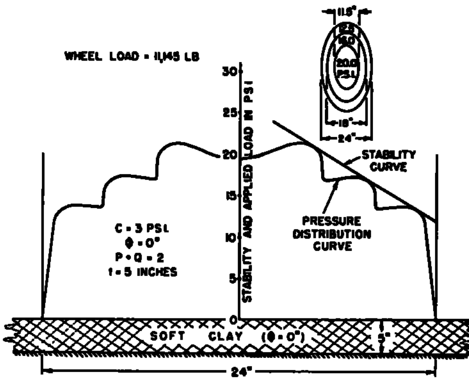

Figure 17. Tire design for vehicle mobility over a layer of soft clay ($\phi = 0$ deg.) of limited thickness.

of employing a three-compartment rather than a single-compartment tire.

Load carried by a single compartment tire inflated to 12.5 psi. = (3.142) (1.6) (12) (12) (12.5) = 9,050 lb.

Additional load carried by second compartment = (3.142) (1.6) (9) (9) (16.0 − 12.5) = 1,420 lb.

Additional load carried by third compartment = (3.142) (1.6) (5.75) (5.75) (20.0 − 16.0) = 675 lb.

Total additional load carried by second and third compartments = 2,095 lb.

For the conditions illustrated in Figure 17, the additional load carried as a result of the second and third compartments is only 2095 lb. more than the load supported by a single-compartment tire inflated to 12.5 psi. Therefore, a multicompartment tire might not be justified in this particular case. However, if the thickness of the soft clay layer were 2.5 instead of 5 in., the slope of the stability curve would be twice as steep as that shown in Figure 17, and both the unit pressures in the second and third compartments, and the total additional load carried by the tire as a result of the use of the two extra compartments would be considerably greater than is the case for Figure 17.

Soft Layer of Cohesive Soil for which ϕ = 10 deg. The void space in soil near the surface of the ground is normally filled partly or largely with air, when the water table is at some depth, and it is unlikely that this air is entirely displaced even after prolonged rains. Consequently, it seems reasonable to expect that the angle of internal friction ϕ of a layer of soft soil at the ground surface will not often be zero as indicated in the first case immediately above, but will ordinarily have some positive value when subjected to a quick triaxial test. The quick triaxial test would ordinarily seem to be applicable in this situation, since moving traffic loads are applied for such short periods of duration that little or no drainage from the soil under so fleeting a load would be expected. This case, therefore, considers vehicle mobility over a layer of soft cohesive soil for which the angle of internal friction ϕ is greater than zero, as illustrated in Figure 18.

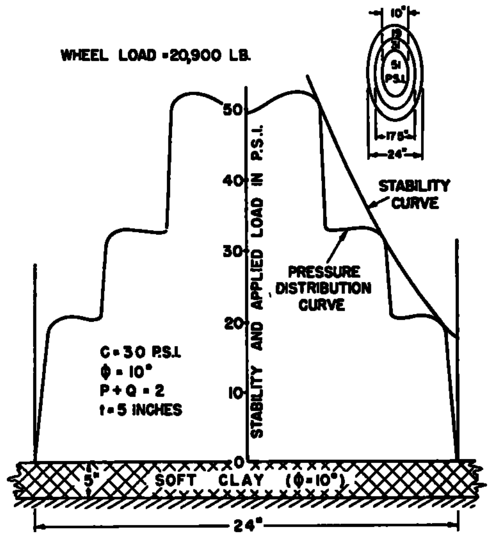

Figure 18. Tire design for vehicle mobility over a layer of soft clay (ϕ = 10 deg.) of limited thickness.

The problem in this case, as in the first case, is the design of a tire, and the determination of its most-effective inflation pressure, so that squeezing out the layer of soft soil between the tire and the firm soil below will be avoided. A rational solution to this problem is demonstrated in Figure 18.

The stability curve shown is obtained by applying Equation 10 and employing the value $P + Q = 2$, which indicates that the maximum frictional resistance equal to the shearing resistance of the soft soil is developed between soft layer and tire and between soft layer and the firm soil below. At the edge of the contact area, the stability developed is that due to the lateral support provided by the soft layer adjacent to the contact area. The increase in stability shown by the stability curve when proceeding along the minor axis from the edge of the contact area toward the center is due to the influence of the frictional resistance between soft layer and tire, and between the soft layer and the firm soil below.

To avoid the squeezing out of the soft layer by the tire, the curve representing the distribution of tire pressure across the minor axis of the elliptical contact-area must not be above the stability curve at any point. Figure 18 shows the pressure-distribution curve for a three-compartment tire. When the layer of soft soil has a positive value for the angle of internal friction ϕ, the location of the stability curve varies somewhat with the position of the pressure distribution curve. Consequently, it is necessary to determine both the stability curve and the pressure-distribution curve shown in Figure 18 by a process of trial and error, for which Equation 10 is employed. The simultaneous adjustment of the location of both curves until they are just tangent to each other can be accomplished quite rapidly by this method.

Assuming that the major axis of the elliptical contact-area is 1.6 times the minor axis, and that the latter is 24 in., Figure 18 indicates that the maximum load that could be carried by a three-compartment tire inflated as shown, and for the other conditions that apply, is 20,900 lb. This load is the largest that could be carried by this tire without causing the layer of soft soil to be squeezed out between the tire and the firm soil below. While the size of tire is the same in both Figures 17 and 18, it will be noted that the maximum load that can be exerted by the tire in the latter case is nearly 10,000 lb. larger than for the former (20,900 lb. versus 11,145 lb.). This is due to the fact that the angle of internal friction ϕ = 10 deg.

for the soft layer illustrated in Figure 18, while $\phi = 0$ for the soft layer in Figure 17. The cohesion $c = 3$ psi. in both cases. The difference between the maximum tire loads shown in Figures 17 and 18 illustrates the important influence that even a relatively small angle of internal friction ϕ for the soft layer can have.

The additional load-carrying capacity of the tire due to the use of three compartments, rather than a single compartment for the conditions illustrated in Figure 18, can be demonstrated.

Load carried by a single compartment tire inflated to 19 psi. = (3.142) (1.6) (12) (12) (19) = 13,800 lb.

Additional load carried by second compartment = (3.142) (1.6) (8.75) (8.75) (31 − 19) = 4,600 lb.

Additional load carried by third compartment = (3.142) (1.6) (5) (5) (51 − 31) = 2,500 lb.

Total additional load carried by second and third compartments = 7,100 lb.

For the conditions represented by Figure 18, the additional load carried by the tire as a result of the second and third compartments is 7,100 lb. more than could be supported on a single-compartment tire. In those cases where maximum tire-loading is desirable, therefore, Figure 18 demonstrates the advantages of the multicompartment tire inflated to the proper pressures for providing better vehicle mobility.

Soft Layer Consisting of Cohesionless Soil for which ϕ = 30 deg. In Figure 19, the design of a tire required to obtain large load-carrying capacity when operating on a layer of cohesionless soil, for which the angle of internal friction $\phi = 0$, having a thickness of 5 in., and underlain by much firmer soil, is illustrated. As in the first two cases, the problem consists of determining the design and proper inflation for a tire to avoid squeezing out the layer of cohesionless soil between the tire and the firm soil below. The principles involved for the solution of this are generally similar to those for the first two, and reference will be made only to the slightly different approach employed.

The stability curve shown in Figure 19 indicates a stability value of 10 psi. at the edge of the contact area, due to the lateral support of the layer of cohesionless soil adjacent to the loaded area. This stability value of 10 psi. was arbitrarily selected as being intermediate between the theoretical value indicated by the method described by Barber (*10*) based upon a logarithmic spiral failure curve, and the experimental values for the bearing capacity of cohesionless soil under a long, narrow (24 in. by 1 in.) bearing area published by Davis and Woodward (*11*) and supported in principle by Housel's (*12*) study of the stability of granular materials. The value of 10 psi. indicated for the layer of cohesionless sand at the edge of the contact area is, therefore, probably conservative. The increase in stability occurring between the edge and center of the contact

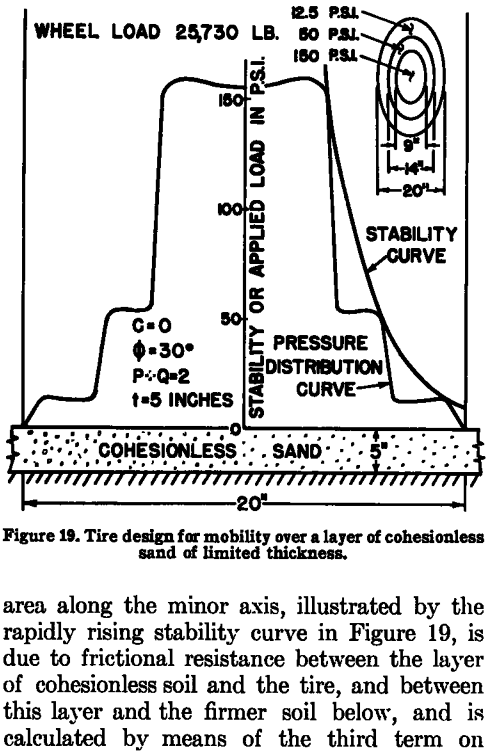

Figure 19. Tire design for mobility over a layer of cohesionless sand of limited thickness.

area along the minor axis, illustrated by the rapidly rising stability curve in Figure 19, is due to frictional resistance between the layer of cohesionless soil and the tire, and between this layer and the firmer soil below, and is calculated by means of the third term on the right hand side of Equation 10,

$$n(P + Q)(c + V' \tan \phi) \left[\tan\left(45 - \frac{\phi}{2}\right)\right]\left(\frac{1 + \sin \phi}{1 - \sin \phi}\right) \quad (15)$$

The stability curve rises rapidly in Figure 19, because of the relatively high angle of internal friction ϕ = 30 deg. of the layer of cohesionless soil. The positions of the stability curve and the pressure-distribution curve were determined quickly by trial and error on the basis of Equation 15, and the stability curve is just tangent to the pressure-distribution curve.

The maximum load of 25,730 lb. that can be applied to the soil layer by the three-compartment tire illustrated in Figure 19 is obtained when the outer compartment is inflated to 12.5 psi., the intermediate compartment to 50 psi., and the inner compartment to 150 psi.

That the utilization of a three-compartment tire greatly increases the load-carrying capacity of the sand layer, as compared with the use of a single-compartment tire for the conditions illustrated in Figure 19, can be easily shown.

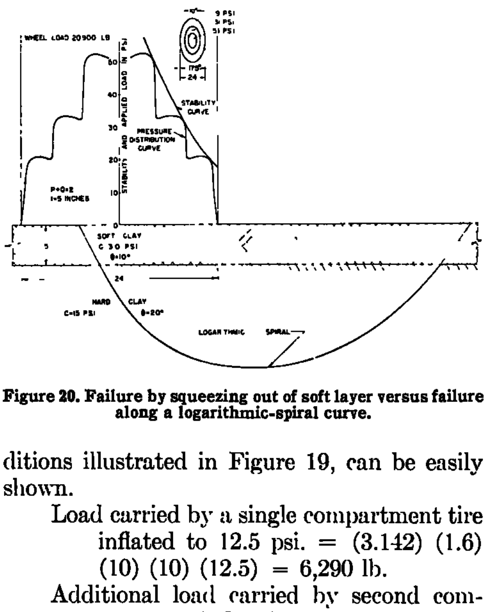

Figure 20. Failure by squeezing out of soft layer versus failure along a logarithmic-spiral curve.

Load carried by a single compartment tire inflated to 12.5 psi. = (3.142) (1.6) (10) (10) (12.5) = 6,290 lb.

Additional load carried by second compartment inflated to 50 psi. = (3.142) (1.6) (7) (7) (50 − 12.5) = 9,240 lb.

Additional load carried by third compartment inflated to 150 psi. = (3.142) (1.6) (4.5) (4.5) (150 − 50) = 10,200 lb.

Total additional load carried by the second and third compartments = 19,440 lb.

Since the additional load carried by the tire is 19,440 lb. as a result of the use of the intermediate and inner compartments, Figure 19 demonstrates the advantage of multicompartments for enabling a tire to carry a large load over a relatively shallow layer of cohesionless soil.

Comments and Qualifications. First, it should be apparent in Figures 17, 18, and 19, that two criteria of failure for the soil under the applied load must be considered. These are illustrated in Figure 20. Failure may occur as a result of the soft layer being squeezed out between the tire and the firm soil below. Failure may also develop because the shearing resistance of the underlying soil is exceeded along a critical failure curve represented by the logarithmic spiral shown in Figure 20, where the curve of failure is shown extending through the soft layer and into the firm soil underneath. Both criteria of failure must be investigated before the tire pressures to be employed in the multicompartment tires illustrated in Figures 17, 18, and 19 can be finalized. For example, in Figure 20, the c and ϕ values shown for the soft layer are assumed to be $c = 3$ psi. and $\phi = 10$ deg., while for the underlying firm soil they are assumed to be $c = 15$ psi. and $\phi = 20$ deg. The position of the most critical logarithmic spiral curve of failure shown in Figure 20, and the maximum inflation pressure that could be applied to the inner compartment before failure along this curve would occur, can be determined by means of the method and tables published by Barber (*10*). Barber's method is based upon balancing load and reaction moments about the origin of the critical logarithmic spiral. It is roughly similar to the Swedish-circle method employed for determining the stability of embankments. The critical logarithmic spiral is the one along which the shearing stress is greatest, and its origin must be determined by trial and error. The calculations are rather lengthy in each case and are therefore not reproduced here. For the conditions shown in Figure 20, Barber's method indicates that failure along the critical logarithmic spiral shown would not develop until the inflation pressure of the inner compartment reached about 200 psi. Figures 18 and 20, however, show that this inflation pressure would squeeze out the soft layer, since the pressure curve would be above the stability curve. Consequently, on the basis of Figure 20, the tendency of the soft layer to be squeezed out between tire and firm soil below is greater than its tendency to fail along the critical failure curve represented by the logarithmic spiral, and the inflation pressures shown in Figures 18 and 20 could be safely employed for the conditions represented by these two figures.

Second, in Figures 17, 18, 19, and 20, a sharp line of demarcation between the soft layer and the underlying firm soil is assumed. In the case of cohesive soils in the field, there would tend to be a more gradual transition from one to the other. This would tend to complicate the stability analysis, but it emphasizes the need for investigating both of the criteria of failure just described.

Third, Figures 17, 18, and 19 illustrate why ordinary tires inflated to pressures of from 40 to 90 psi. usually cut through shallow layers of soft soil and displace them. The curves of tire-pressure distribution on the contact areas for these tires are far above the stability curves for the soft layer in each case over much or all of the contact area. Consequently, the applied pressure on part or all of the contact area is greater than the stability that can be developed by the soft layer, and it is, therefore, squeezed out between the tire and the firm soil below.

Fourth, while Figures 17, 18, and 19 indicate that the inflation pressure in the outer compartment must be kept relatively low, nevertheless these outer compartments assist greatly in keeping the soft layer of soil from being squeezed out laterally, and make possible the use of relatively high inflation pressures for the inner compartments. The net result is a reasonably high permissible loading for the tire as a whole.

Fifth, Figures 17, 18, and 19 demonstrate the importance of employing large single tires in place of either dual or tandem tires for improving vehicle mobility over shallow layers of soft soils. The wider the contact area between the tire and the soft soil, the higher is the stability of the soft layer towards the center of the loaded area. The width of the contact area under each of two dual tires is ordinarily much less than that of the contact area under a large single tire carrying the same total load. Consequently, for the same total loaded area, a much greater load could be applied to a large single tire than to dual or tandem tires without squeezing out the soft layer.

Sixth, in the calculations on which Figures 17, 18, 19, and 20 are based, it has been assumed that the soft layer of soil can be subjected to the strain that occurs when its ultimate strength is developed. This enables the full shearing resistance of the soft soil to be employed as frictional resistance between soft layer and tire and between soft layer and the firm soil below. If strains of this magnitude should be found undesirable for any reason, it would be necessary to apply a safety factor to the soil's shearing resistance, and to employ the resulting value as the frictional resistance between soft layer and tire and between soft layer and the underlying firm soil.

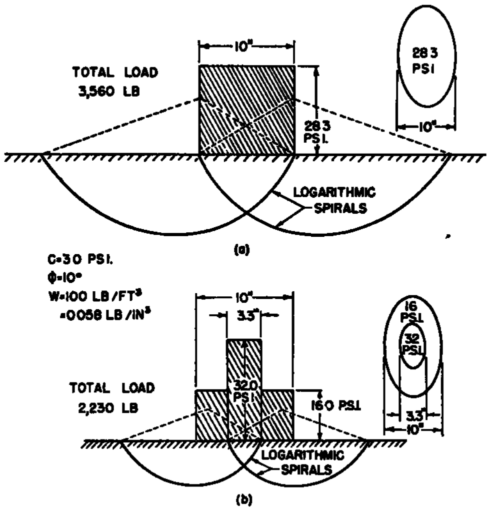

Figure 21. Single-compartment tire exerting a uniform pressure over the contact area equal to the bearing capacity of the soil provides a higher tire loading for vehicle mobility over soft soils of great depth than a multicompartment tire with the same contact area.

VEHICLE MOBILITY OVER SOFT SOIL OF GREAT DEPTH

In the previous section, it was shown that a multicompartment tire would facilitate vehicle mobility over a shallow layer of soft soil underlain by firm soil. Figure 21, on the other hand, demonstrates that for vehicle mobility over soft soils of great depth a single-compartment tire would be superior to a multicompartment tire.

Figure 21(a) indicates that a soft soil of great depth, for which $c = 3$ psi. and $\phi = 10$ deg., can support a maximum unit pressure of 28.3 psi. in the form of a strip load 10 in. wide. This value is determined by the method and tables given by Barber (*10*) on the basis that the curve of failure is a logarithmic spiral.

Assuming that a tire can apply this same maximum pressure on an elliptical contact area, the total load that the tire can support without causing failure of this soil along the logarithmic spiral failure curve is 3,560 lb.

By means of Barber's method, the maximum load that can be applied by the pressure arrangement illustrated for strip loading in Figure 21(b) can also be calculated. The overall width of 10 in. has been divided into three sections each 3.3 in. wide. Utilizing the load on the two outer sections as surcharge, the maximum pressure that could be applied to the center section without causing failure of this particular soil to occur along one or both of the logarithmic spirals was investigated. With the outer sections carrying a load of 16 psi. it was found that a pressure of 32 psi. is the maximum that could be applied to the center section without causing failure in this soil.

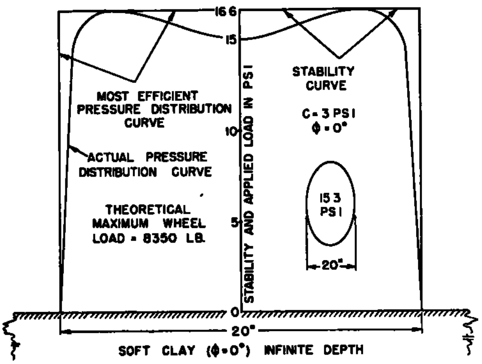

Figure 22. Tire design for vehicle mobility over soft clay (ϕ = 0 deg.) of great depth.

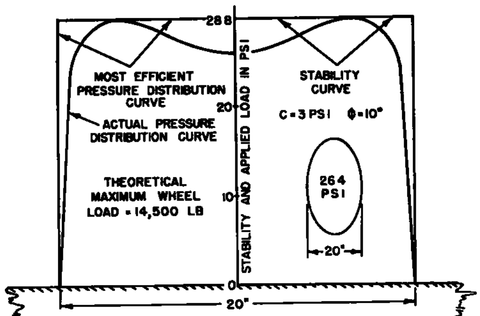

Figure 23. Tire design for vehicle mobility over soft clay (ϕ = 10 deg.) of great depth.

Assuming that the data of Figure 21, which were calculated for strip loading, can be utilized without serious error for elliptical tire-contact areas (the resulting conclusions should be conservative), Figure 21 demonstrates that the maximum pressure, 32.0 psi., that could be applied by the inner compartment of a two-compartment tire without causing failure of the underlying soil is only 13 percent higher than the maximum uniform pressure, 28.3 psi., that could be applied to a single-compartment tire. Furthermore, the maximum total load that could be applied by a two-compartment tire inflated to 16.0 psi. in the outer compartment and to 32.0 psi. in the inner compartment (Figure 21), without causing failure of this particular soil, is 2,230 lb.

Insofar as vehicle loading is concerned, the most effective tire design for a given contact area is the one that enables the largest load to be carried without causing the soil on which it is travelling to fail. On the basis of the conditions illustrated in Figure 21, it is apparent that a single-compartment tire inflated to apply a uniform pressure of 28.3 psi. could carry a total load of 3,560 lb., whereas a two-compartment tire inflated to 32 psi. in the inner compartment, and to 16 psi. in the outer, could carry a total load of only 2,230 lb., the contact areas of both tires being the same. While some error is introduced by applying the results of calculations based on strip loading, directly to an area of relatively short length, such as an elliptical contact area, there seems to be little doubt that the more complicated calculations associated with elliptical contact areas would only indicate that a still greater load could be carried by a single-compartment tire than by a multicompartment tire on soft soils of great depth, without causing them to fail.

It should be noted that because of the larger logarithmic spiral failure curve, there is more resistance by the soil to failure in the direction of the longitudinal axis of the contact area than in the direction of the transverse axis. On this basis, the critical load supported by a tire is somewhat similar to that for a stripload of relatively short length.

By means of calculations similar to those for Figure 21(a), the diagram for Figure 22 illustrates that the maximum inflation pressure for a tire width of 20 in. on a soft clay of great depth, for which c = 3 psi. and ϕ = 0 deg., is 16.6 psi., which is the bearing capacity of the soil under a strip load 20 in. wide. For the same tire width on a soft clay for which c = 3 psi. and ϕ = 10 deg., Figure 24, the maximum inflation pressure is 28.8 psi. (the bearing capacity of the soil). When the soft ground consists of cohesionless sand, for which c = 0 and ϕ = 30 deg., Figure 23, the maximum inflation pressure for a tire width of 20 in. is 22.3 psi., which is this soil's bearing capacity.

In Figures 22, 23, and 24, the stability curves are horizontal lines having ordinate values equal to the bearing capacity of the soil in each case. The stability curves are horizontal because the soft soil is too deep for the frictional resistance between soil and tire to have any influence on the measured bearing capacity of the soil. The most effective tire-pressure-distribution curve would be the top and two sides of the rectangle having the width of the contact area and with the sides equal to the ordinate value of the soil bearing capacity in each figure. However, actual tire-pressure-distribution curves do not have this rectangular shape and, as illustrated by Figures 22, 23, and 24, the maximum load carried by the tire will be somewhat less than the theoretical if the tire-pressure-distribution curve is not to exceed the stability curve at any point of the contact area.

Comments and Qualifications. First, it is clear that the maximum permissible tire-inflation pressures indicated for the conditions illustrated in Figures 22, 23, and 24 are considerably less than those normally employed for trucks, tractors, and other vehicles. Since the normal inflation pressures for tires on these vehicles are much greater than those permitted by the stability curves for Figures 22, 23, and 24, it can be readily understood why the tires cause the underlying soil to fail and to develop deep ruts, which facilitate stalling even when the vehicles are loaded lightly.

Second, whenever the angle of internal friction ϕ of the soil has a value greater than zero, the logarithmic spiral method for determining the supporting value of the soil (*10*) indicates that its bearing capacity varies directly but not necessarily proportionately with the width of the loaded area. On this basis, and with all other factors equal, a large single tire would tend to be more effective for supporting a given load than dual or tandem tires for the same total contact area, although this conclusion does not seem to be in keeping with plate-bearing tests on cohesive soils, which tend to show that for any given deflection smaller bearing plates can support a higher unit pressure than larger bearing plates.

The rate of change of bearing capacity with width of contact area, as indicated by the logarithmic-spiral method (*10*), is relatively small for cohesive soils, but is quite large in the case of cohesionless soils. The latter is in keeping with practical experience, for it has long been common practice to materially reduce the tire pressure when vehicles are crossing a desert, in order to obtain better vehicle mobility by decreasing the tendency of the tires to cut into the sand. Figure 24 clearly indicates why this procedure is effective. Due to partial deflation, the tire-pressure curve is lowered to approach the stability curve for the

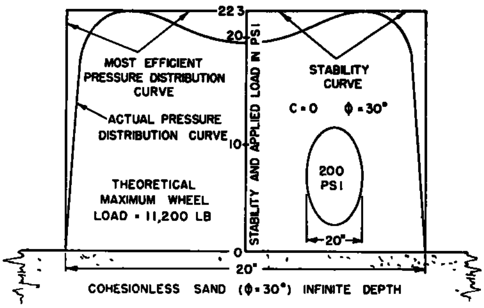

Figure 24. Tire design for vehicle mobility over cohesionless sand (ϕ = 30 deg.) of great depth.

sand. In addition, the contact area is enlarged when the tire pressure is reduced, and as already pointed out, the logarithmic-spiral method on which Figure 24 is based indicates that the bearing capacity of cohesionless soils increases quite rapidly as the size of the loaded area is increased.

Third, as has been already indicated, there is a close relationship between vehicle mobility and the nature of the ground over which the vehicle travels. The ground must be able to support the weight of the vehicle as applied by tires, tracks, skids, etc. In addition, the traction between the tires or tracks and the ground must be large enough to propel the vehicle. The section of this paper on vehicle mobility has dealt almost exclusively with the first of these two factors, and has said very little about the second. However, it should be obvious that the ability of the tires to support the vehicle without exceeding the bearing capacity of the soil is not in itself enough to ensure good vehicle mobility. It must also be possible to develop sufficient traction between the tires and the ground to put the vehicle into motion, and to keep it moving at reasonable speed over sloping as well as flat terrain. This available tractive effort depends upon the friction between the tire and the ground, the shearing resistance of the soil, the manner in which the soil-shearing resistance is developed, the size of the contact area, etc. Obtaining adequate traction is frequently a difficult matter when vehicles are to move over soft clay soils or snow. A great deal of information regarding the various factors on which tractive effort depends can be found in published technical literature, and this portion of the vehicle-mobility problem is outside the scope of the present paper.

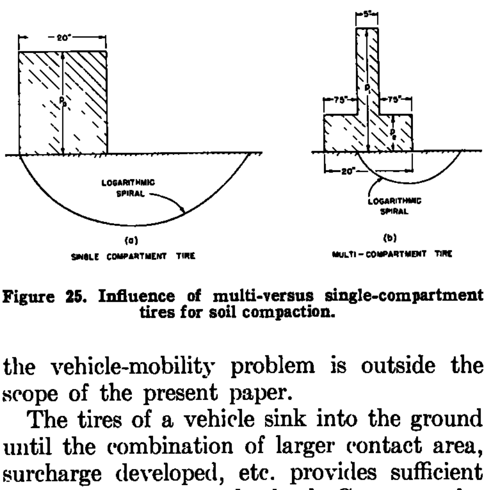

Figure 25. Influence of multi-versus single-compartment tires for soil compaction.

The tires of a vehicle sink into the ground until the combination of larger contact area, surcharge developed, etc. provides sufficient reaction to support the load. Consequently, with present tires, and over soft terrain, a large portion of the horse power developed by the engine is required for merely squashing down the ground under the tires, and the rolling resistance may be very high. By decreasing the tendency of the tires to sink into soft soil, the rolling resistance is ordinarily materially reduced, and vehicle mobility thereby tends to be improved. It is with this phase of the vehicle-mobility problem that this section of the paper has been concerned.

Fourth, because the first wheels over soft terrain may utilize considerable horsepower for merely squashing down the ground, several investigators have pointed out the advantage of having all wheels on each side of a vehicle travel in the same path. That is, better vehicle mobility is obtained if the front and all following wheels on each side track. From this it follows that if for any reason either a dual or tandem assembly is to be substituted for single wheels in any given situation, the tandem arrangement will ordinarily result in less rolling resistance and therefore better vehicle mobility over soft ground.

Fifth, some of the principles developed in this section for application to wheeled vehicles might be usefully applied to obtain better mobility for tracked vehicles. They might also be employed to obtain improved mobility for both types of vehicles over snow and muskeg.

SOIL COMPACTION

In soil compaction, a layer of loose soil is rolled until it reaches the density specified, when its density and strength are approximately the same as those for the layers of soil below that were previously compacted. It is a practical objective of soil compaction to attain the specified density with a minimum number of passes of the roller.

In general, with pneumatic-tired rollers, the compaction of layers of soil is speeded up by increasing the tire-inflation pressure. However, if the tire-inflation pressure exceeds the bearing capacity of the soil, the soil tends to squeeze out under the tires of the roller instead of compacting. It is probable, therefore, that either soil compaction could be speeded up, or higher soil densities could be obtained, if it were possible to employ higher inflation pressures without exceeding the bearing capacity of the soil undergoing compaction, than can be attained by the use of current single-compartment tires. Figure 25 indicates that this result might be obtained by means of multi-compartment tires.

Figure 25 (a) shows that a uniform unit pressure p_0 is the maximum that could be applied to a strip load 20 in. wide, without exceeding the bearing capacity of the underlying soil. On a strip load of the same width, for which the outer 7.5 in. on each side functions to some extent as a surcharge, Figure 25(b) indicates that the unit pressure p_1 on the center 5 in. could be increased above the maximum unit pressure p_0 possible for the uniform loading represented by Figure 25(a).

The ratio of p_1 from Figure 25(b) to p_0

from Figure 25(a) is listed in Table 1 for several soils with different c and ϕ values. The values shown for these ratios are based upon strip loading and a logarithmic spiral is assumed for the failure curve. The tables given by Barber *(10)*, and the method of balancing moments were employed for the calculations.

For soils with the values of c and ϕ listed on the left-hand side in the first four rows in Table 1, the data in the right-hand column indicate that the unit pressure on the central 5 in. of the loaded area of Figure 25(b) could be increased to about 20 percent above the maximum unit pressure that could be applied to the uniformly loaded area of Figure 25(a). By the use of a multicompartment tire, therefore, it appears that an appreciably higher pressure could be applied to part of the contact area, than is possible with current single-compartment tires. This higher pressure should provide higher density within the layer of soil with which it is in contact.

TABLE 1
RATIOS OF $p_1:p_0$ FOR SOILS WITH DIFFERENT VALUES OF c AND ϕ

c psi	ϕ deg	p_0 psi	p_1 psi.	p_2 psi.	$p_1:p_0$
5	10	47.3	57.1	17.1	1.21
10	10	94	114	34	1.22
7	20	126	151	45	1.20
15	20	265	321	96	1.21
2	30	102	107	32	1.05
0	30	22.3	14.0	0	.629
0	30	22.3	13.1	5.24	.588

At the same time, because of the narrower width over which this higher pressure is acting, it may not be as effective for compacting soil at depth as a somewhat lower uniform pressure acting over a larger contact area. On the other hand, it should be remembered that the pressures shown in Table 1 have been calculated on the basis of strip loading for Figures 25(a) and (b). Similar data calculated on the basis of the elliptical contact areas that actually occur under loaded tires would probably indicate considerably higher values for the ratio $p_1:p_0$ than those listed in Table 1. If this should be the case, the multicompartment tires might be quite effective for obtaining either higher densities or more rapid compaction.

The values for the ratio $p_1:p_0$ for the bottom three rows in Table 1 indicate that a multicompartment tire would be inferior to a single-compartment tire for compacting soils with high values for the angle of internal friction ϕ and low values for cohesion c. When c = 2 psi. and ϕ = 30 deg. (third last row), the ratio $p_1:p_0$ is only 1.05. That is, the pressure p_1 on the center 5 in. of the loaded area, Figure 25(b), is only slightly greater than the pressure p_0 uniformly applied over the entire contact area of Figure 25(a). Over the balance of the contact area of Figure 25(b) the pressure p_2 is only about one third of either p_0 or p_1. When c = 0 and ϕ = 30 deg. (two bottom rows), the ratio $p_1:p_0$ is approximately 0.6. This shows that a multicompartment tire inflated as in Figure 25(b) would be decidedly inferior to a single-compartment tire for compacting cohesionless soils. The indicated poor performance of multicompartment tires for compacting cohesionless soils is due to the fact that the critical loaded area in Figure 25(b) is only 12.5 in. wide, whereas this width is 20 in. in Figure 25(a). As pointed out earlier, the supporting value of a cohesionless soil of considerable depth varies greatly with the width of the loaded area.

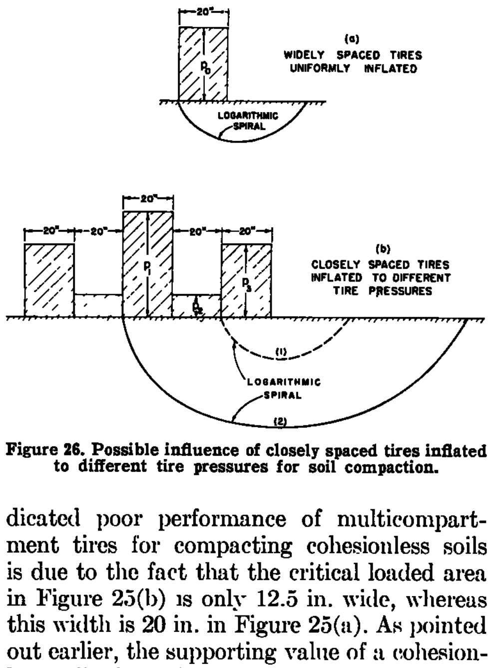

Figure 26. Possible influence of closely spaced tires inflated to different tire pressures for soil compaction.

A variation of the multicompartment tire concept for soil compaction is illustrated in Figure 26(a). It consists of several closely spaced individual single-compartment tires on the same axle inflated to different pressures. In this case, the outer tires act as a surcharge and make it possible to increase the inflation pressure of the central tire, Figure 26(b), without causing failure in a transverse direction along either of the logarithmic-spiral failure curves.

The maximum inflation pressure p_0 that can be applied to the widely spaced single tires on some present pneumatic tired rollers, without causing failure of the underlying soil to occur, is illustrated in Figure 26(a). Consequently, the maximum inflation pressure p_3 that can be employed for the outer tires of Figure 26(b) without causing failure of the underlying soil along Curve 1 is also p_0. That is, $p_3 = p_0$ is the maximum surcharge that can be applied by the outer tire. The next problem is to determine the maximum pressure p_1 that can be applied by the central tire without causing failure of the underlying soil along Curve 2. This can be solved by Barber's method (*10*) previously referred to. The inflation pressure for the tire or tires between the central and outermost tires must also be considered in this problem. It is assumed that the tires are so closely spaced that the underlying soil will not fail by being squeezed up between them.

TABLE 2

RATIOS OF $p_1 \cdot p_0$ FOR SOIL COMPACTION WITH CLOSELY SPACED TIRES INFLATED TO DIFFERENT PRESSURES

c psi.	ϕ deg.	p_0 psi.	p_1 psi.	p_2 psi.	p_3 psi.	$p_1 : p_0$
10	10	94	134	23	47	1.43
10	10	94	140	18	70	1.49
10	10	94	149	0	94	1.59
10	10	94	133	30	94	1.43
7	10	66	95	17	33	1.44
7	10	66	99	13	50	1.50
7	10	66	105	0	66	1.59
7	10	66	95	20	66	1.44
0	30	22.3	66.9	6 69	22.3	3.0
0	30	22.3	65.3	22.3	22.3	2.92

In Table 2, values are listed for p_0, p_1, p_2, and p_3 in Figure 26 that have been calculated for three different soils for which $c = 10$ psi. and $\phi = 10$ deg. in one case, for which $c = 7$ psi. and $\phi = 10$ deg. in another, and for which $c = 0$ psi. and $\phi = 30$ deg. in the third.

For soils with the c and ϕ values listed on the left-hand side in the first eight rows of Table 2, the data in the right-hand column demonstrate that by the close spacing of individual single-compartment tires inflated to different pressures as illustrated in Figure 26(b), the inflation pressure of the central tire might be increased to from 40 to 50 percent above the maximum pressure that could be applied to the same tires if they were widely spaced, Figure 26(a), as is normally the case with present pneumatic tired rollers. The somewhat higher ratios for $p_1 : p_0$ for the two cases where $p_2 = 0$ are of little practical significance, since in actual practice some positive value for p_2 would be required in the form of surcharge.

For cohesionless soils for which $\phi = 30$ deg., the data in the bottom two rows of Table 2 indicate ratios of $p_1 : p_0 = 3$ (approximately) for the tire arrangement shown in Figure 26(b). Ratios of $p_1 : p_c$ approaching 3 may be difficult to obtain in actual practice for the reason given in the next paragraph. Nevertheless, to whatever extent a high ratio for $p_1 : p_0$ is possible, the tire arrangement illustrated in Figure 26(b) may be found appreciably more effective than that of current pneumatic rollers for the compaction of cohesionless subgrade and base course materials, and may make higher densities possible.

It is realized that in Figure 26(b) consideration has been given to the stability of the underlying soil in the transverse direction only (in the direction of the axle), and that there would ordinarily be no similar surcharge effect at the front or rear of the central tire in the longitudinal direction (the direction of travel). The stability of the soil under a tire tends to be somewhat greater in the longitudinal than in the transverse direction, and in addition, if there were a tendency for the soil to fail in the longitudinal direction ahead of or behind the central wheel, actual failure would be arrested by an automatic shifting of load to the adjacent tires, since considerable consolidation must usually occur before actual failure develops.

The principal conclusion indicated by the theoretical studies on which Figure 26 and Table 2 are based, is that by the use of closely spaced individual single-compartment tires inflated to different pressures as illustrated in Figure 26(b), the inflation pressure of the central tire (or tires) might be increased by the order of from 40 or 50 to more than 100 percent above the maximum inflation pressure possible for the same tires when widely spaced, as is usually the case with present pneumatic-tired rollers, Figure 26(a). However, before it can be definitely established that any such marked difference in tire pressures is possible in actual practice, and whether or not this arrangement would result in either higher densities or increased efficiency of compaction, considerable experimental work must be undertaken.

COMMENTS AND QUALIFICATIONS

The condition of a layer of soil undergoing compaction in a fill normally progresses from a layer of soft soil underlain by a considerable depth of firm, thoroughly consolidated soil just as rolling begins, to a layer of firm soil underlain by the same firm soil when rolling is complete. For a layer of soft soil underlain by a great depth of much firmer soil, it was shown in the earlier section of this paper on vehicle mobility (Figs. 17, 18, and 19) that a properly inflated multicompartment tire could be loaded much more heavily than a single-compartment tire before causing the soft soil to fail by being squeezed out between the tire and the firm soil below, the contact areas being the same. The heavier loading on a multicompartment tire should provide more rapid consolidation of a layer of soft soil during the earlier stages of the rolling operation. This would apply to cohesive and cohesionless soils alike.

As the layer of soil undergoing compaction approaches the firm condition of the previously compacted underlying soil, the situation gradually changes from compacting a layer of soft soil over a firm soil to compacting the top portion of a great depth of firm homogeneous soil. This latter condition is probably approached during more than half of the rolling operation. That is, the rate of increase of soil density is rapid during the first passes of the roller but much slower during the final passes. The later stages of compaction were chiefly considered in the foregoing section on soil compaction.

It seems not unlikely, therefore, that the most effective procedure for compacting layers of soil could be developed on the basis of the approach illustrated in Figures 17, 18 ,19, and 20 for the early and intermediate stages, and on the basis of the approach illustrated by Figures 25 and 26 for the final stages. Since the bearing capacity of the soil layer ordinarily increases as compaction proceeds, rollers with the lowest optimum arrangement of tire pressures would be employed for initial compaction. These would be followed by rollers carrying a higher optimum arrangement of tire pressures for the intermediate compaction stage, while rollers with tires inflated to the highest optimum arrangement of tire pressures would concentrate on the final compaction of each layer.

While the principles of soil mechanics appear to be able to indicate the general direction to be taken in tire (and roller) design for more effective soil compaction, considerable experimentation will be required to establish the practical usefulness of the conclusions arrived at by this method and to determine their optimum application for this purpose.

CONCLUSION

The subject matter of this paper consists very largely of the results of a theoretical study in which well-established principles of soil mechanics have been applied to the solution of certain problems in bituminous-pavement design, vehicle mobility, and soil compaction. One of the major conclusions from this study is that solutions to a number of these problems are materially influenced by the design of the tires which transmit wheel loads to the pavement, or to the surface of the natural ground, etc. It has been shown that a very close interrelationship appears to exist between tire design, pavement design, vehicle mobility, and soil compaction.

One of the more important possibilities developed in the paper is that by the use of multicompartment pneumatic tires (or any other method that will provide an overall flattening of the slope of the tire-pressure-distribution curve near the edge of the contact area), bituminous-pavement design may be simplified for the much higher tire pressures under consideration for future aircraft, vehicle mobility over shallow layers of soft soils may be materially improved, and soil compaction may be performed more effectively.

Some of the calculations on which this paper is based have just been completed, and there has not yet been time to discuss with representatives from the rubber industry how difficult the fabrication of these multicompartment tires may be. Regardless of this, however, it has been one of the objectives of this paper to demonstrate that the application of several well-known principles of soil mechanics to certain problems in the fields of bituminous-pavement design, vehicle mobility, and possibly, soil compaction appear to point directly to the multicompartment tire or its equivalent as a possible useful solution.

It is realized that there are often serious discrepancies between the conclusions indicated by theoretical soil mechanics, and the practical results obtained when the same principles are applied in the field. Consequently, experimental work may indicate that some of the theoretical findings presented in the paper are altogether too optimistic and cannot be duplicated in practice. On the other hand, it is not improbable that the results found in practice may in some cases be considerably better than the theoretical indications seemed to promise. For example, in connection with Figures 15, 16, 17, 18, 19, 22, 23, and 24, it has been assumed that the tire-pressure-distribution curve must be either tangent to or below the stability curve for all points on the contact area. Actual practice may indicate that the tire-pressure-distribution curve may exceed the stability curve over part of the contact area without serious detriment, because either the excessive load is of short duration or the excess of stress in the locally overstressed area or areas can be relieved without injury by plastic flow toward sections that are understressed. To the extent, if any, that this is found to be possible, the theoretical approach outlined would be more conservative in this respect than actual practice indicated to be necessary.

While the subject matter of this paper is presented quantitatively, it is clearly realized that other theoretical equations could be employed or developed which would provide somewhat different quantitative values than those that have been shown in the tables and in a number of the diagrams. Nevertheless, it should be emphasized that it has been the primary purpose of this paper to outline certain principles or concepts that might be usefully applied to bituminous-pavement design, vehicle mobility, and soil compaction, rather than to stress the precise nature of the equations to be employed to evaluate these principles or concepts quantitatively.

Finally, it should be pointed out again that this paper consists essentially of the results of a theoretical study of certain problems in pavement design, vehicle mobility, and soil compaction, and it should be recognized that the evaluation of several of the factors it has shown to be important for the quantitative solution of these problems will require extensive laboratory and field investigation.

SUMMARY

A rational approach to the design of bituminous paving mixtures is reviewed.

This rational approach is based upon the c and ϕ values for the bituminous mixture measured by the triaxial test, the lateral support of the pavement adjacent to the loaded area, the frictional resistance between pavement and tire and between pavement and base, the thickness of pavement, the shape of the most critical curve of tire-pressure distribution on the contact area, and whether the wheel loads are standing, moving at a uniform speed, or exerting severe braking or acceleration stresses.

The study leading to this rational approach to the design of bituminous paving mixtures was undertaken in an attempt to determine the minimum c and ϕ values required by bituminous-paving mixtures for supporting the tire pressures of 300, 400, 500 psi., etc., under consideration for future aircraft.

By decreasing the slope of the curve of tire pressure distribution near the edge of the contact area, it is shown that much higher tire pressures could be supported by paving mixtures having relatively low c and ϕ values.

The most positive method for decreasing the slope of the curve of tire-pressure distribution near the edge of the contact area appears to consist of the use of multicompartment tires in which the outermost compartment is inflated to the lowest pressure and the innermost compartment to the highest.

By employing multicompartment tires, it is shown that the mobility of vehicles over shallow layers of soft soil underlain by firmer soil, could be materially improved.

For good vehicle mobility over soft soils of great depth, single-compartment tires inflated to apply a pressure not greater than the bearing capacity of the soil are indicated.

It is shown that the use of multicompartment tires, or closely spaced single-compartment tires inflated to different pressures may provide more effective soil compaction.

A close interrelationship between tire design, pavement design, vehicle mobility, and soil compaction is demonstrated.

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