RELATIONSHIP BETWEEN TIRE INFLATION PRESSURE AND MEAN TIRE CONTACT PRESSURE

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Contact pressure is important to the design engineer because it determines the intensity of loading. However, it is not as easily monitored as tire inflation pressure. Therefore, a study was made of the relationship between tire inflation pressure and tire contact pressure. Various commercial truck tires were tested in the laboratory under various combinations of load and inflation pressures; the corresponding average contact pressures were determined by the "dirty print" approach. It was found that (a) under normal conditions of wheel load and inflation pressure the average contact pressure between the tire and the road will be less than the tire inflation pressure; (b) tire contact pressure is a function of both inflation pressure and wheel load and is a constant depending on the type of tire; and (c) the relationship between tire inflation pressure and contact pressure lies within a narrow band for the tires tested; for the combination of wheel load and tire pressures recommended by the manufacturers, an average relationship of contact pressure in kilopascals = 0.61 inflation pressure + 145.

•PRESSURE on the contact between the vehicle tire and road pavement is important to the design engineer because it determines intensity of loading. For every vehicle tire, there is a fixed relationship among the internal inflation pressure, the contact pressure on the road, and the mass carried by the tire. An increase in tire contact pressure is associated with an increase in stresses in the upper layers of the pavement, which, in turn, results in greater fatigue and deformation. Pavement design engineers are interested in contact pressure, not inflation pressure, but only the latter can be monitored easily. Thus, a study was conducted to find the relationship between internal (inflation) pressure and contact pressure. Paterson (8) showed that a variation in contact pressure across the tire exists, but only the average contact pressure is discussed in this paper. All work was done statically. Lister and Nunn (7) showed that, at speeds of 8 km/h and higher, contact pressure was reduced by 2 to 5 percent. However, work done by Green, McRae, and Murphy (3) indicated that this effect is very much a function of the type of tire and that the contact pressure of the rolling wheel can be more or less than that of the static case.

THEORETICAL CONSIDERATIONS

Many pavement design engineers such as Ahlvin (1) assumed the contact pressure between the tire and the pavement to be equal to the internal pressure, that is to say, the relationship between the area of contact, A, the wheel load, W, and internal pressure, p, is

$$A = \frac{W}{p}$$

Freeme (2) concluded that this relationship is not valid and that area of contact is given more accurately as

Publication of this paper sponsored by Committee on Surface Properties-Vehicle Interaction.

$$A = \frac{W}{p+S} + A_o$$

where

A_o = additional area arising because the road is not infinitely stiff but deflects under W, and
S = stiffness factor of the tire walls.

Because a certain percentage of the load is carried to the pavement by the stiffness of the tire walls, the contact area will be smaller than that calculated by $A = \frac{W}{p}$.

The principle of the stiffness factor has been used previously; for example, Yoder (11, p. 343) assumed that, because of tire stiffness, contact pressure would be 10 percent more than inflation pressure. Other researchers found the stiffness factor not to have a constant value and that contact pressure can sometimes be more and sometimes be less than inflation pressure. Lawton (5), in a study of aircraft tires, said, "At rated tire load and an inflation pressure of 7½ psi per ply, the average contact pressure and the inflation pressure are equal. For inflation pressures higher than 7½ psi per ply, the contact pressure is less than the inflation pressure. For inflation pressures less than 7½ psi per ply, the reverse is true." Ladd and Ulery (4) also pointed to a transition but they found it to be approximately at 1000 kPa. A transition point exists, but at what pressure it will occur depends on the type of tire.

Initial tests to determine the relationship between contact pressure and inflation pressure for various truck tires led to confusing results. It was soon apparent that the 10 percent assumption was completely unacceptable. The contact pressure was often as much as 30 percent lower than the inflation pressure instead of 10 percent higher. Depending on the type of tire, tire load, and inflation pressure, contact pressure may vary from much less than the inflation pressure to much more. Other researchers such as Lister and Nunn (7) and Ledbetter, Ulery, and Ahlvin (6) have studied contact pressures and have had similar experiences.

When explaining the 10 percent assumption of Yoder (11), it is customary to indicate that a certain portion of the total load is carried through the stiff tire walls to the supporting pavement. The actual contact area is smaller than that calculated by dividing the load by the inflation pressure; the contact pressure is more than the inflation pressure. A balloon normally is used as an example of an object with no wall stiffness in which the contact pressure equals exactly the inflation pressure.

Contact Pressure of a Balloon With No Stiffness

Physical determination of inflation pressure and contact pressure of a balloon indicated that the contact pressure was always lower than the inflation pressure, sometimes by as much as 50 percent. Typical results are shown in Figure 1. The forces acting on the contact between the balloon and the pavement indicated that the contact pressure should be lower than the inflation pressure.

Figure 2 shows a balloon in contact with a smooth surface and the forces acting on it: internal pressure, external contact pressure, and tension in the balloon. Equilibrium of forces requires that

$$pA = qA + Tl \sin\theta \quad (1)$$

where

q = average contact pressure,
T = tension per unit length (at the edge of the contact),
θ = angle between T and the horizontal,
l = circumference of A, and
D = contact diameter.

Figure 1. Relationship between inflation pressure and contact pressure for a balloon.

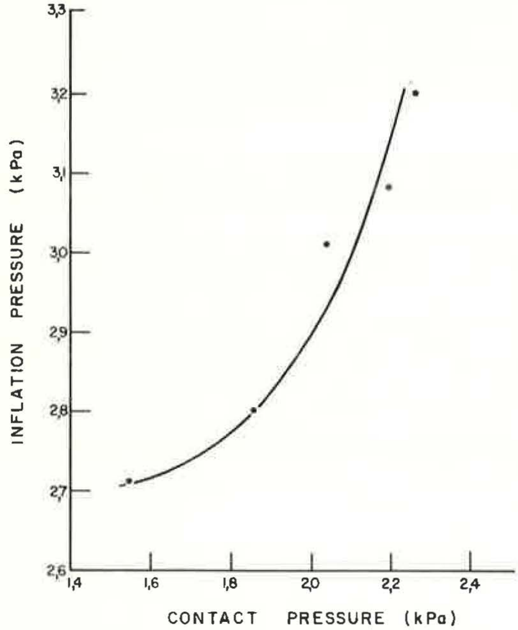
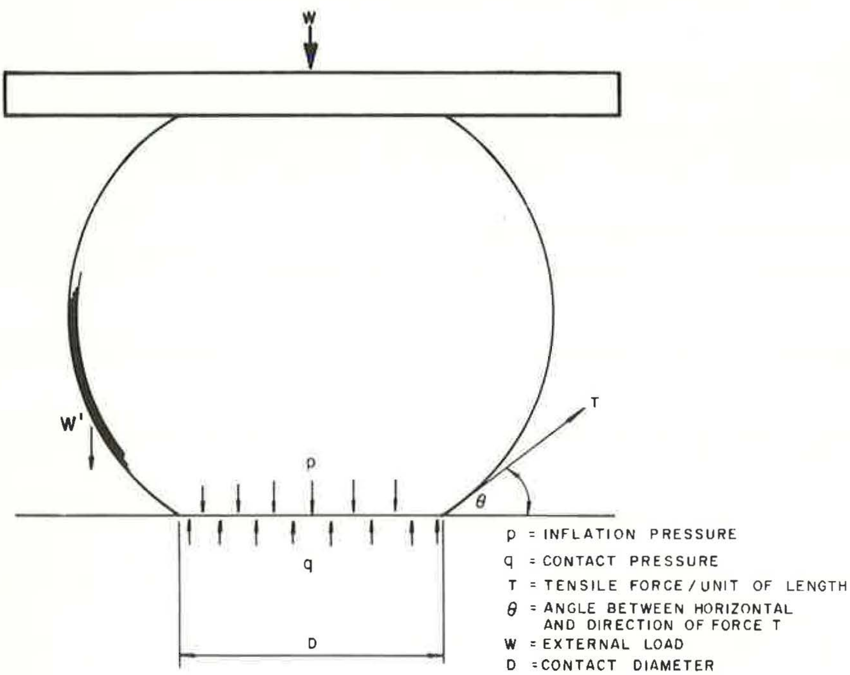


Figure 2. Forces acting on a balloon in contact with a smooth horizontal plane.



Assuming a circular area of contact

$$l = \pi D$$

and

$$A = \frac{\pi}{4} D^2$$

Eq. 1 reduces to

$$q = p - \frac{4T}{D} \sin \theta \qquad (2)$$

Therefore, q must be smaller than p as long as T, D, and θ are positive.

Contact Pressure of a Ball With Some Wall Stiffness

When a stiffer balloon is loaded, a certain portion of the load is carried to the pavement by the stiff walls (W′ in Fig. 2). This stiffness contribution can be determined by loading the ball at zero internal pressure and measuring the load to deform the ball to the same contact area as when it is inflated. If this load is W′, Eq. 2 becomes

$$q = p - \frac{4T}{D} \sin \theta + \frac{W'}{A} \qquad (3)$$

As T is a function of p and W, q is a function of both p and W. That is,

$$q = f_1(p) + f_2(W, p) \qquad (4)$$

where

$f_1(p)$ = function of inflation pressure, and
$f_2(W, p)$ = combined function of inflation pressure and load.

Average Contact Pressure of a Vehicle Tire

The relationship between inflation pressure and average contact pressure is considerably more complex when a vehicle tire is analyzed (Fig. 3) because the problem is bisymmetrical and, as a result of the physical thickness of the rubber, there is p distribution from inside to outside making a, the imaginary internal contact area, and A very different. The exact distribution also is not known and the relationship cannot be calculated. Figure 3 shows the forces acting on the tire and the contact between the tire and the ground.

Equilibrium of forces requires that, for the tire,

$$Q = qA \qquad (5)$$

and, at the contact between tire and smooth pavement,

$$q f_1(B, L) + 2T_1 \sin \theta_1 f_2(\ell) + 2T_2 \sin \theta_2 f_3(b) = p f_4(b, \ell) + C \qquad (6)$$

where

$f_1(B, L)$ = A, which is a function of B and L;
B = contact width;
L = contact length;
T_1 = tensile stress per unit length in the tire wall;
θ_1 = angle between the horizontal and the force direction of T_1;
$f_2(\ell)$ = projected length over which T is active;

Figure 3. Forces acting on a vehicle tire in contact with a smooth horizontal plane.

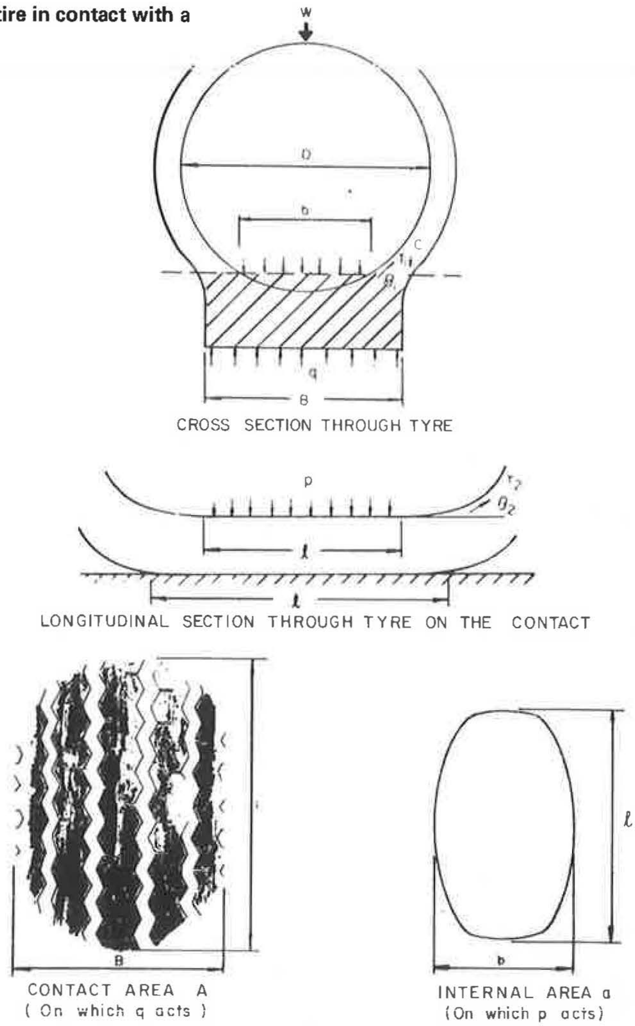
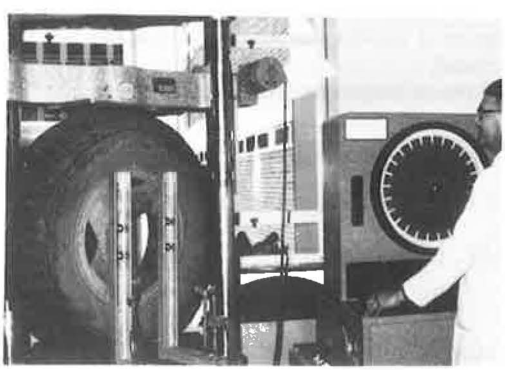


Figure 4. Test tire in Baldwin press.



ℓ = imaginary length inside the tire over which p acts;
T_2 = tensile stress per unit length in the tire base;
θ_2 = angle between the horizontal and the force direction of T_2;
$f_3(b)$ = projected length over which T_2 is active;
b = imaginary pressure width;
$f_4(b, \ell)$ = a, imaginary contact area inside the tire, which is a function of b and ℓ; and
C = component of load that is transmitted through the tire wall.

So, the formula is again a complex form:

$$q = f_1(p) + f_2(p, W) + C' \quad (7)$$

C′ will depend on factors such as tire dimensions, ply rating, rubber thickness and hardness, and tread pattern.

PRACTICAL MEASUREMENT

Experimental Work

The relationship between tire inflation pressure and tire contact pressure was determined empirically for 6 highway tires ranging in size from 7.50-15 × 10 to 11.00-22 × 14. This represents the bulk of tires used on heavy commercial vehicles in South Africa. The method was as follows. A truck tire was mounted in a Baldwin press (Fig. 4) and left for 24 hours to attain equilibrium at a given temperature. The tire was then loaded to the desired load and a print of the contact area was obtained on a smooth surface. The printing medium was ordinary black shoe polish. Two areas could then be measured—the apparent contact area and the actual contact area. The former is the total area included in the envelope of the contact print including points of no contact; the latter is areas of contact only (Fig. 5). Although calculations that use the actual contact area will give the actual contact pressure on the pavement surface, this is of interest only for the uppermost portion of the surface, and the stress concentrations disappear at a shallow depth.

Combinations of load and inflation pressure ranging between 9.0 and 17.0 kN and 300 and 500 kPa respectively were used, and the corresponding contact areas were determined.

Figure 6 shows typical load versus contact area curves at various inflation pressures for an 8.25-20 × 10-ply tire. (This tire will be used as an example throughout this paper.) The test was performed at 43 C. Similar curves also were obtained at 25 C. In Figure 7, these results are replotted as inflation pressure versus contact pressure curves for various loads. Taking the average of results obtained at 25 C and 43 C (the difference between these curves is about ±3 percent), we obtain a formula that gives the relationship among q, p, and W for this tire:

$$q = (0.013p + 10.5)\,W + 0.119p + 125.9 \quad (8)$$

The conclusion that contact pressure depends on wheel load, inflation pressure, and, to a large degree, the constant C′ can be drawn from this relationship. Within the range of testing, this formula is valid for any combination of wheel load and tire inflation pressure. The tire manufacturers, however, recommend a certain relationship between inflation pressure and tire load as shown in Figure 8 (9). Truck operators tend to follow these recommendations because they ensure the longest tire life. This relationship is given by the formula

$$W = 0.228p + 4.98 \quad (9)$$

Inserting Eq. 9 into Eq. 8 gives

$$q = 0.0003p^2 + 0.417p + 175.7 \quad (10)$$

Figure 5. Differentiation between apparent and actual contact areas.

APPARENT CONTACT AREA IS THE TOTAL AREA WITHIN THE ENVELOPING LINE ACTUAL CONTACT AREA IS THE SUMMATION OF THE DARK AREAS

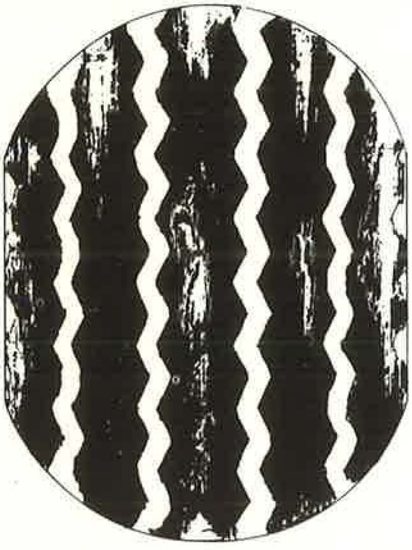


Figure 6. Relationship between contact area and load for an 8.25-20 x 10-ply tire at 43 C.

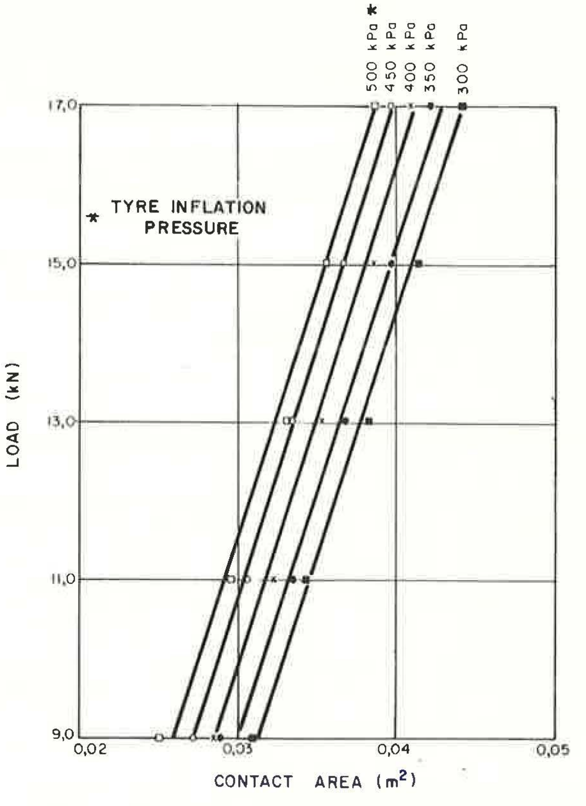
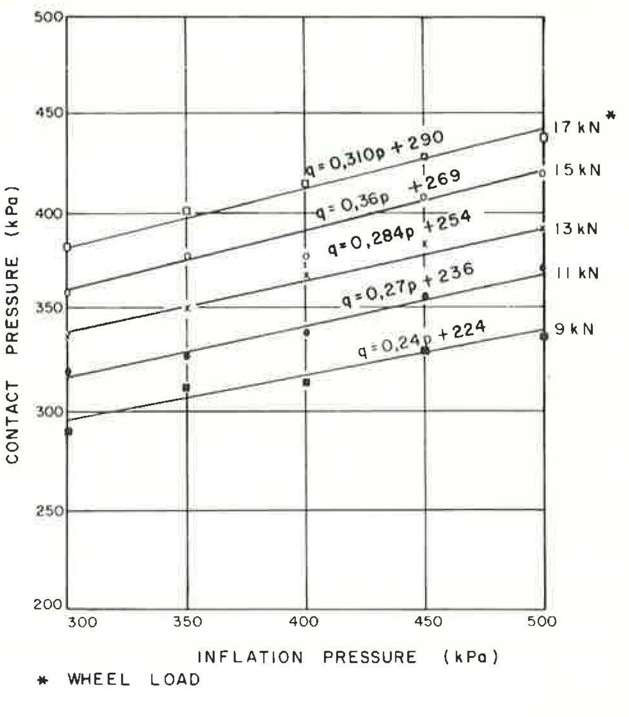


Figure 7. Relationship between tire inflation pressure and contact pressure for an 8.25-20 x10-ply tire at 43 C.



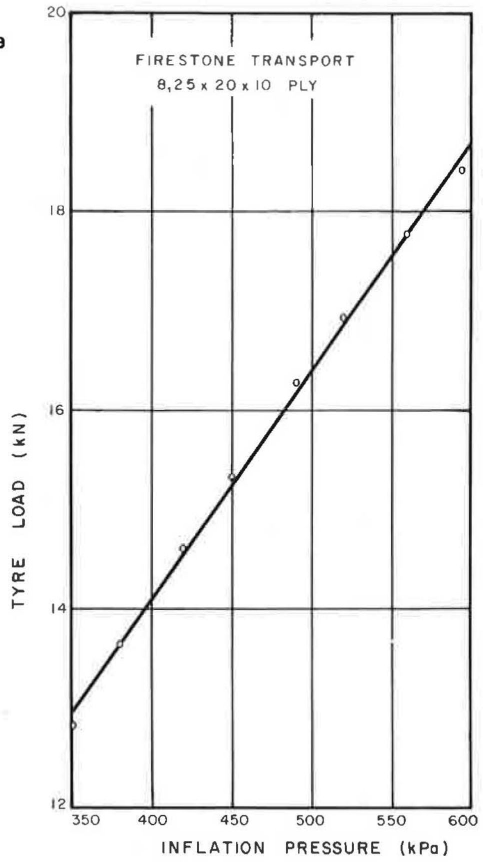


Figure 8. Relationship between recommended load and inflation pressure for an 8.25-20 x 10-ply tire.

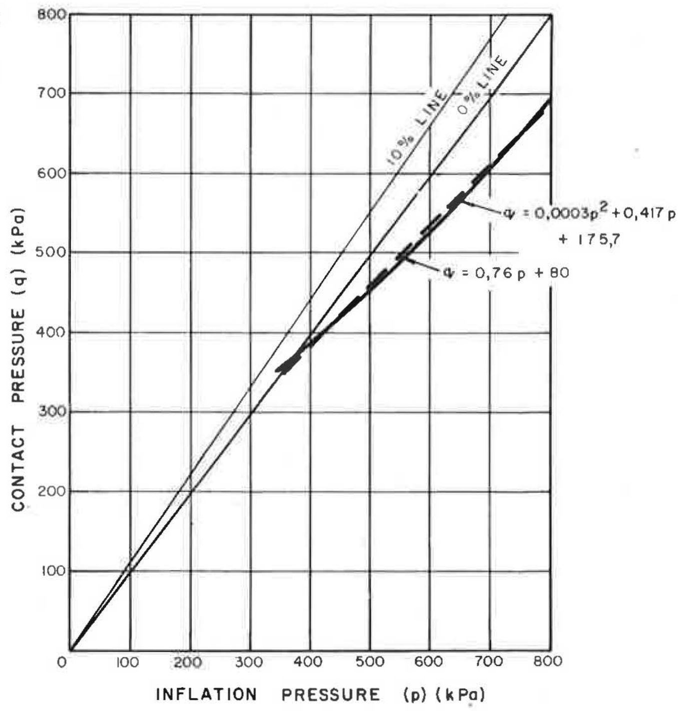


Figure 9. Relationship between inflation pressure and contact pressure for an 8.25-20 x 10-ply tire (for recommended combinations of load and inflation pressure).

This equation, which represents the relationship between contact pressure and inflation pressure, is shown in Figure 9. The 10 percent and 0 percent assumption lines are also shown. From this figure the transition point can be clearly discerned; at low inflation pressures, where the stiffness of the tire wall is predominant, the contact pressure is higher than the inflation pressure, but above about 350 kPa the contact pressure is lower because, after this point, the tire walls go completely into tension and their stiffness is no longer important.

The test range equation, Eq. 10, can be approximated by the much simpler straight-line equation

$$q = 0.76p + 80 \tag{11}$$

This is most important because the contact pressure will be a constant 76 percent of the inflation pressure for the entire practical range of wheel load and inflation pressure.

Effect of Changes in Wheel Load and Inflation Pressure on Contact Pressure

This effect can be studied by using Eq. 8. Figure 10 shows the effect on contact pressure of changes in inflation pressure for values W of 12.6 kN and 18.0 kN, which are the minimum and maximum values given by Tredco (9). It is obvious that a change in inflation pressure will result in a change in the contact pressure of approximately a third. Higher inflation pressures thus may not have the deleterious effect on pavements as was commonly believed. Operators who formerly enjoyed special axle-load exemptions because they operated at very low inflation pressure may now have to forfeit this privilege because very low inflation pressure is not associated with an equally low contact pressure.

Figure 11 shows the effect on contact pressure of changes in wheel load at constant inflation pressure. This figure, more than any other, contradicts the belief that a direct and general relationship between contact pressure and inflation pressure exists, that the contact pressure is directly proportional to the wheel load. Van Vuuren (10) has indicated that most damage to road surfaces is done by light wheel loads operating at high inflation pressures. Although this is correct, Figure 11 indicates that the effect will, in practice, be less than anticipated previously. For example, when a truck operates fully loaded in 1 direction, it will have a certain contact pressure associated with its inflation pressure. When it returns empty with a lower wheel load but the same inflation pressure (pressure inside a tire does not change significantly with a change in wheel load), it will operate with a greatly decreased contact pressure, and the resultant damage to the surfacing will be much less than anticipated.

All of this, including Eqs. 8, 10, and 11, applies only to the 8.25-20 × 10-ply tire tested. Similar equations for all the tires tested are given in Tables 1, 2, and 3. Figure 12 shows a combination of relationships between contact pressure and inflation pressure for all the tires tested for combinations of load and inflation pressure as directed by Tredco (9). It is interesting to find them all clustered together within a narrow envelope. Figure 13 shows the average line through all these curves, and I recommend that this line be used as the general relationship between tire contact pressure and tire inflation pressure for tires used on road vehicles.

CONCLUSIONS

Under normal combinations of wheel load and inflation pressure, the average contact pressure between the tire and the road will be less than the tire inflation pressure.

At constant inflation pressure, the contact pressure varies with load. A 100 percent increase in load normally is associated with a 30 to 40 percent increase in contact pressure.

At constant load, a 100 percent increase in inflation pressure will be associated with an average increase of 30 percent in contact pressure.

If both wheel load and tire inflation pressure change in accordance with the tire manufacturer's recommendations, a change in inflation pressure will be associated with a 60 percent change in the contact pressure.

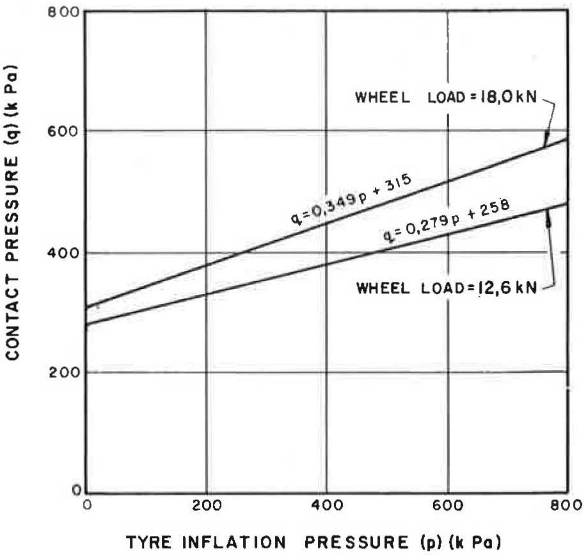


Figure 10. Relationship between tire inflation pressure and contact pressure for constant values of wheel load.

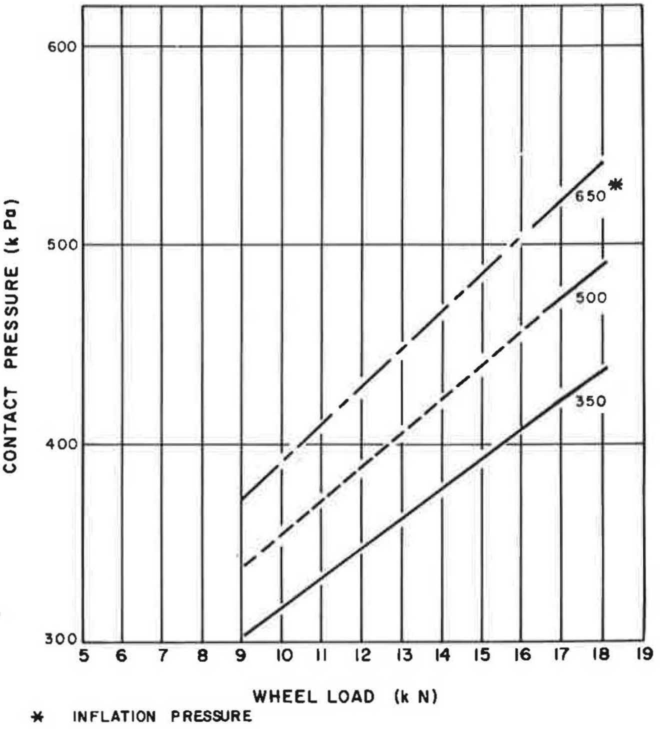


Figure 11. Relationship between contact pressure and wheel load for constant values of inflation pressure (8.25-20 x 10-ply tire).

Table 1. Relationship of contact pressure, inflation pressure, and wheel load for Eq. 8.

Tire	Relationship
7.50-15 Michelin Radial	$q = (-0.0029p + 13)\,W + 0.52p + 52$
8.25-20 × 10 Firestone Transport	$q = (0.013p + 10.5)\,W + 0.119p + 125.9$
9.00-20 × 10 Firestone	$q = (0.024p - 0.9)\,W - 0.001p + 259.6$
10.00-20 × 14 Papleguas Goodyear Brazil	$q = (0.002p + 6.8)\,W + 0.33p + 110.0$
11.00-20 × 14 General SDT	$q = (0.008p + 2.3)\,W + 0.04p + 313.0$
11.00-22 × 14 General Jet Cargo	$q = (0.009p + 2.6)\,W + 0.098p + 211.0$

Table 2. Relationship between contact pressure and inflation pressure for Eq. 10.

Tire	Relationship
7.50-15 Michelin Radial	$q = 0.00005p^2 + 0.71p + 134$
8.25-20 × 10 Firestone Transport	$q = 0.0003p^2 + 0.417p + 176$
9.00-20 × 10 Firestone	$q = 0.0006p^2 + 0.109p + 256$
10.00-20 × 14 Papleguas Goodyear Brazil	$q = 0.00005p^2 + 0.530p + 161$
11.00-20 × 14 General SDT	$q = 0.0002p^2 + 0.170p + 331$
11.00-22 × 14 General Jet Cargo	$q = 0.0003p^2 + 0.258p + 219$

Table 3. Approximate linear relationship between contact pressure and inflation pressure for Eq. 11.

Tire	Relationship
7.50-15 Michelin Radial	$q = 0.66p + 145$
8.25-20 × 10 Firestone Transport	$q = 0.76p + 80$
9.00-20 × 10 Firestone	$q = 0.66p + 134$
10.00-20 × 14 Papleguas Goodyear Brazil	$q = 0.38p + 194$
11.00-20 × 14 General SDT	$q = 0.27p + 380$
11.00-22 × 14 General Jet Cargo	$q = 0.37p + 292$

Figure 12. Relationship between contact pressure and inflation pressure for various tires (recommended combinations of wheel load and inflation pressure).

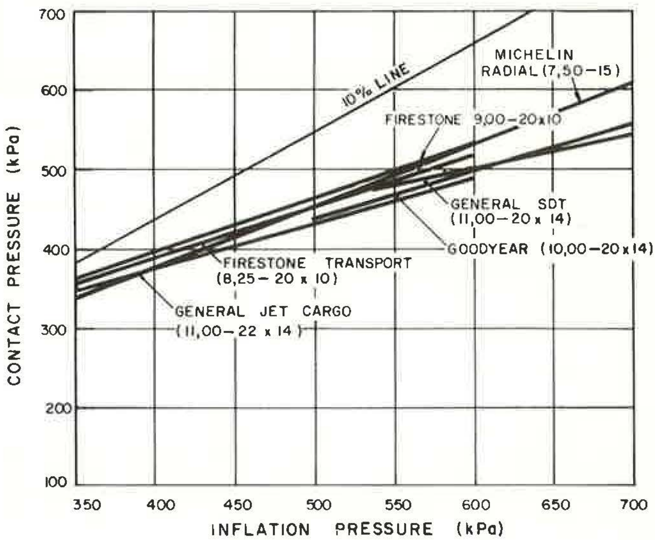
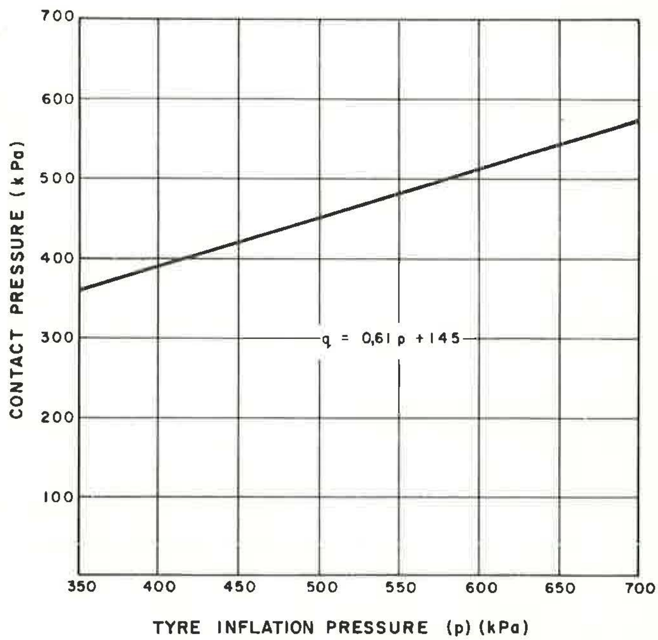


Figure 13. Average straight-line relationship between contact pressure and inflation pressure (for recommended combinations of wheel load and inflation pressure).



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