CONTACT AND SLIP BETWEEN TYRE AND ROADWAY

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RINGKASAN

Friksi dan gaya normal yang diperlukan untuk mendukung, mengarahkan dan menampung pergerakan kendaraan, ada pada daerah kontak ban. Ini adalah daerah pada permukaan jalan yang menerima beban dari ban, sehingga membangkitkan tahanan terhadap pergerakan ban. Slip akan muncul pada daerah ini, misalnya saat pengereman atau percepatan, jika kecepatan sudut rodanya berbeda dengan pada waktu berjalan biasa. Karakteristik dari pergerakan ban , daerah kontaknya, dan distribusi tegangan akan diuraikan pada makalah ini.

SUMMARY

The friction and normal forces needed for vehicle support, guidance and maneuvers arise in the tyre contact area. This is the area of road surface receiving pressure from the tyre, and thus generates resistance to the tyre movements. The slip will occur in this area, such as during braking or accelerating, if its angular wheel velocity differs with the rolling angular wheel velocity. The characteristics of tyre motions, their contact area, and the stress distribution will be described in this paper.

I. INTRODUCTION

For a wheel to produce friction forces in the contact area, either braking or sideway, there must be some reduction in wheel speed. A wheel is said to be slipping if it circumferential velocity is different from its travelling velocity. The normal pressure in the contact area does not suddenly rise at the edge of the contact area from zero to a finite value, but rather increases, gradually or suddenly at a finite rate. The low normal pressure at the edge of contact patch (hence small adhesion limits) perhaps leads to a conclusion derived by Novopol'skii and Tret'yakov [1963], that even when the tyre is rolling, there are slip areas where contact begins and ends.

II. CLASSIFICATIONS OF TYRE MOTIONS

According to Pacejka [1966] the motions of a tyre can be distinguished into two main groups, steady-state (stationary) and non steady-state motions. The first is associated with constant slip velocity in the rolling direction and perpendicular to it. For example:

a. Tyre rolling with constant braking slip or at constant slip angle.

The second have a character varying with time for lateral slip and angular motions. For example [Hegmon (1982)] :

b1. Tyre rolling with fast sweep of slip angle (~10°/second) at constant braking slip.

b2. Fast braking to wheel lock (~ 0.5 second) at constant slip angle.

Another classification is representing a small time interval of the steady-state behaviour [Uffelmann (1983)], so called quasi steady-state motions. For example [Hegmon (1982)]:

c1. Tyre rolling with slow sweep of slip angle (~3°/second) at constant braking slip.

c2. Slow braking to wheel lock (~ 5 second) at constant slip angle.

Most operating conditions can be regarded as the steady-state and quasi steady-state motions when the automobile is cruising in a normal manner. Under emergency or panic stops, the non steady-state motion often occurs.

III. TYPES OF SLIP

Slip has been defined as the ratio of the difference between the angular wheel velocity when the tyre is rolling or slipping to the angular wheel velocity when the tyre is rolling [Kummer and Meyer (1967)]. Slip is commonly expressed as a percentage by multiplying by 100. It is convenient to define slip as a vectorial quantity S thus:

$$\overline{S} = \left(\frac{\vec{v} - \vec{V}}{v}\right) \times 100$$

where $\vec{v}$ is the travelling velocity, $\vec{V}$ is the circumferential velocity, and v is the magnitude of $\vec{v}$.

For a pure circumferential slip, the slip in percentage is given by:

$$S = \left(\frac{v - V}{v}\right) \times 100$$

When braking (v > V), S is positive with the maximum value of 100% for a locked wheel (V= 0). The maximum braking force is obtained at a slip between 7%-30% [Giles (1964), Holmes and Stone (1969), Schallamach and Grosch (1982)]. During acceleration (v < V) is negative and becomes negative infinity when the stationary wheel spins [Schallamach and Grosch (1982)].

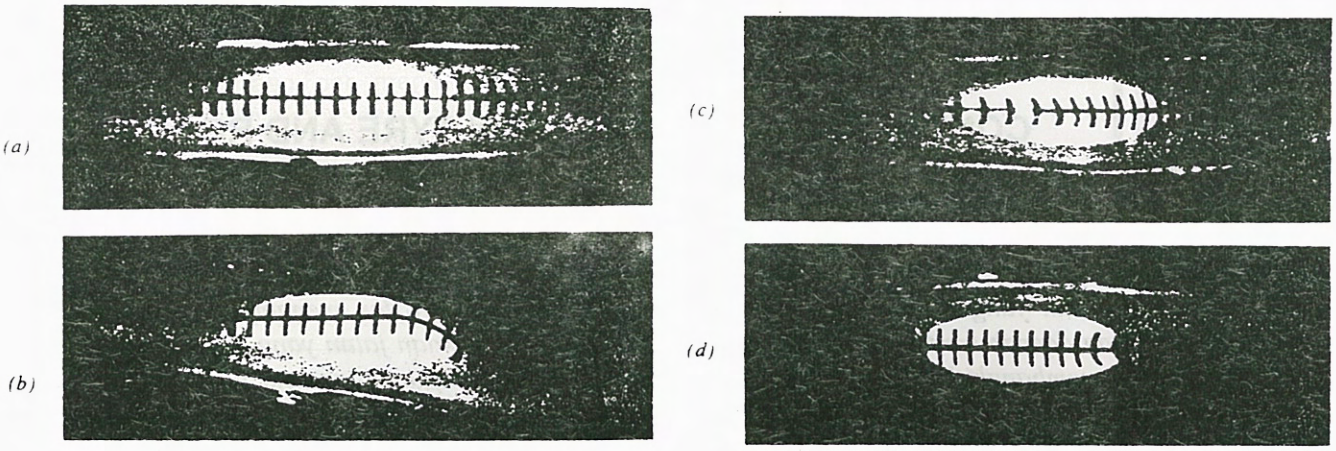

Fig.1. Model Experiments for : (a) Free Rolling, (b) Side Slip, (c) Braking, (d) Driving. Travelling Direction From Right to Left. [Schallamach and Grosch (1982)].

When the wheel rolls in a direction making the slip angle α with its plane, the situation is one of pure side slip :

$$S = \sin\alpha \times 100$$

There is a critical value of α where the sideway force developed is a maximum, and beyond this the force begins to decrease. This value is around 5^{o} - 20^{o} [Bradley and Allen (1930), Holmes and Stone (1969), Veith (1971), Shah and Henry (1978)].

The mechanism of slip produced by braking/driving and cornering was illustrated by model experiments by Schallamach and Turner [1960], and Schallamach and Grosch [1982]. A wheel of 2.5 inch diameter and 0.5 inch thick was made to travel over a Perspex track under different conditions of slip. The wheel surface was marked with lateral equidistant markings, the orientation of these markings on the slipping tyre indicated the tangential stress distribution in the contact area.

The strains set up in the contact area of a slipping wheel are showed in Figure 1. All cases have in common that a circumferential element of the wheel on entering the contact area adheres to the track at first. As the element moves further into the contact area, the imposed slip produces a deflection which increases linearly with increasing distance from the front edge. This is clearly seen in Figure 1b, where the deflection is at right angles to the wheel plane. The corresponding surface stress increases in the same sense until a limiting frictional stress is reached and the element begins to slide back towards its undeformed position.

A braking force (Figure 1c), lengthens an element in the circumferential direction before entering the contact area, and the element adheres at first to the track in this state of strain. The deflection of the wheel increases linearly with increasing distance from the front edge, until sliding commences towards the front of the contact when the tangential stress exceeds the limiting frictional stress. Under a driving torque, contraction of an element takes place before entering the contact region (Figure 1d).

IV. SLIDING AND SKIDDING

According to Kamm [1938], there is appreciable sliding at the rear of the contact surface even in straight unbraked rolling, at high speeds. In the general case, the contact surface can thus be divided into adhesion and sliding regions, an adhesion region being defined as one in which there is no relative motion between coincident points of the tyre and ground surfaces.

In extreme cases of course the relative motion is one of pure sliding, for which the term "skidding" may be reserved. In vehicle scale, skidding as defined by Stonex [1959] is the motion of a vehicle under partial or complete loss of control caused by (pure) sliding of one or more wheels. Transition between partial sliding and skidding of a tyre is of particular importance since it corresponds to total loss of tyre directional stability. Schuster and Weichsler [1935] point out that as long as there is even partial adhesion, the tyre may be said to have a "virtual guiding rail" as a result of frictional forces (this "rail" is an elastic one).

The sliding or skidding potential of a road surface is commonly measured by locked wheel or side slip modes of operation of skid testing machines. The locked wheel test simulates the longitudinal sliding conditions of a braked vehicle, whereas the sideway test simulates sliding condition when a vehicle is cornering.

Fig.2. Typical Contact Area For an Automobile Tyre. [Browne et.al (1982)]

V. CONTACT AREA

The shape of the contact area between tyre and roadway depends on the tyre cross section shape and structure. For example, the contact area between an aircraft tyre and a flat surface usually appears to be nearly elliptical in shape. For an automotive tyre a somewhat different set of relationships exists due to the fact that the usual construction involves the use of a relatively heavy tread, particularly in the shoulder region. A typical contact area is shown in Figure 2.

Experimental evidence indicates that tyre deflection is the most important variable governing the area of contact. Results from Hadekel [1952] show that the relationship between tyre deflection and gross contact area is nearly linear. If inflation pressure and load are simultaneously varied so as to maintain constant tyre deflection, the tyre contact area will remain effectively constant [Browne et.al (1982)]. Using a single truck tyre, an experiment by the U.S. Army Engineers Waterway Experiment Station [1964] showed that in general the contact area of a slowly rolling tyre is slightly lower than of a standing tyre.

When fluid contaminants such as water, oil, slush, or mud are present on the pavement surface, (dry) contact area between tyre and pavement is reduced due to the persistence of a fluid film in portions of the formerly dry contact area [Horne and Dreher (1963), Yeager (1974)]. Just how much the dry contact area will remain depends on tyre, pavement, fluid, and vehicle factors. According to Browne et.al [1982], the fractional dry contact area is reduced, with increasing of: speed, fluid (viscosity, density, depth), size of tread elements; and with decreasing of: inflation pressure, carcass rigidity, width of grooves (number held constant), number of grooves (width held constant), and groove depth (width held constant).

VI. STRESS DISTRIBUTION

At the interface between the tyre and the roadway an element of tyre surface area is acted upon by a force vector which can be expressed as two components, one perpendicular to the contact surface, called the normal component, and one tangential to the contact surface. This latter component may be further decomposed into two components, each lying in the contact plane, but one parallel to the central plane of the tyre and the other perpendicular to it. These components in the contact plane are commonly called the shear components.

6.1. Normal Contact Stresses

Contact pressures between tyre and ground are not necessarily uniform, mainly because of tyre detail design and partly because of road surface irregularities. Measurements of contact pressure confirm that since the contact pressure are about 50% greater than the inflation pressure, the casing stiffness plays a part in the load-carrying, otherwise an infinitely flexible casing would result in contact pressures equal to inflation pressure [Gough (1958-59)].

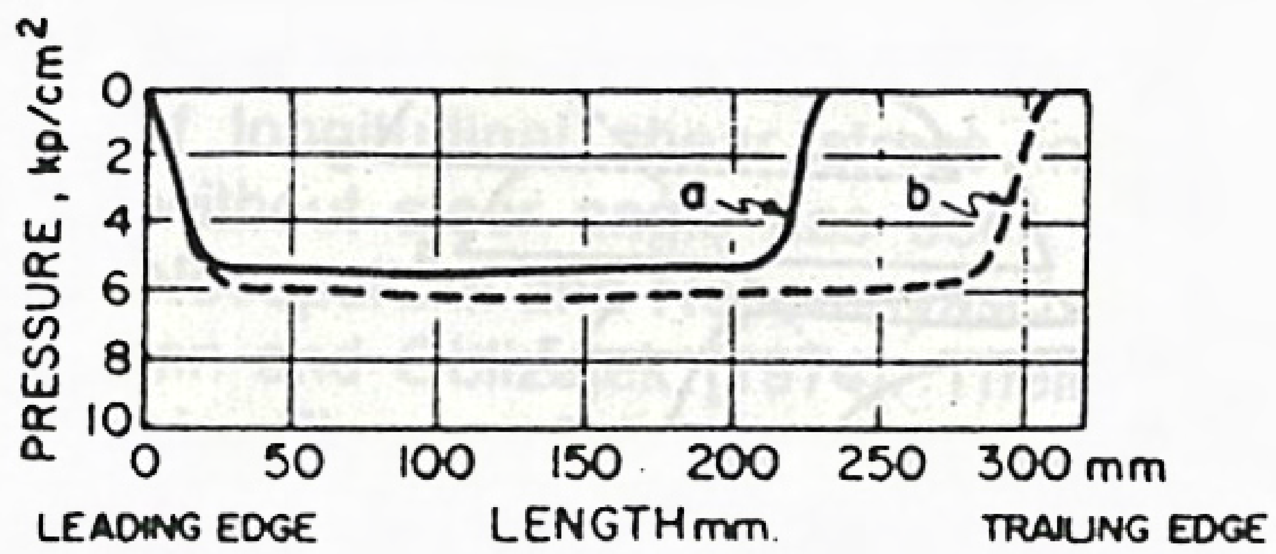

Fig. 3 Pressure Distribution Down The Length of a Tyre With no Tread Pattern, at Constant Speed 15 kph, Inflantion 6.5 atm, Load (a) 1680 kp, (b) 3740 kp.[Bode (1962)]

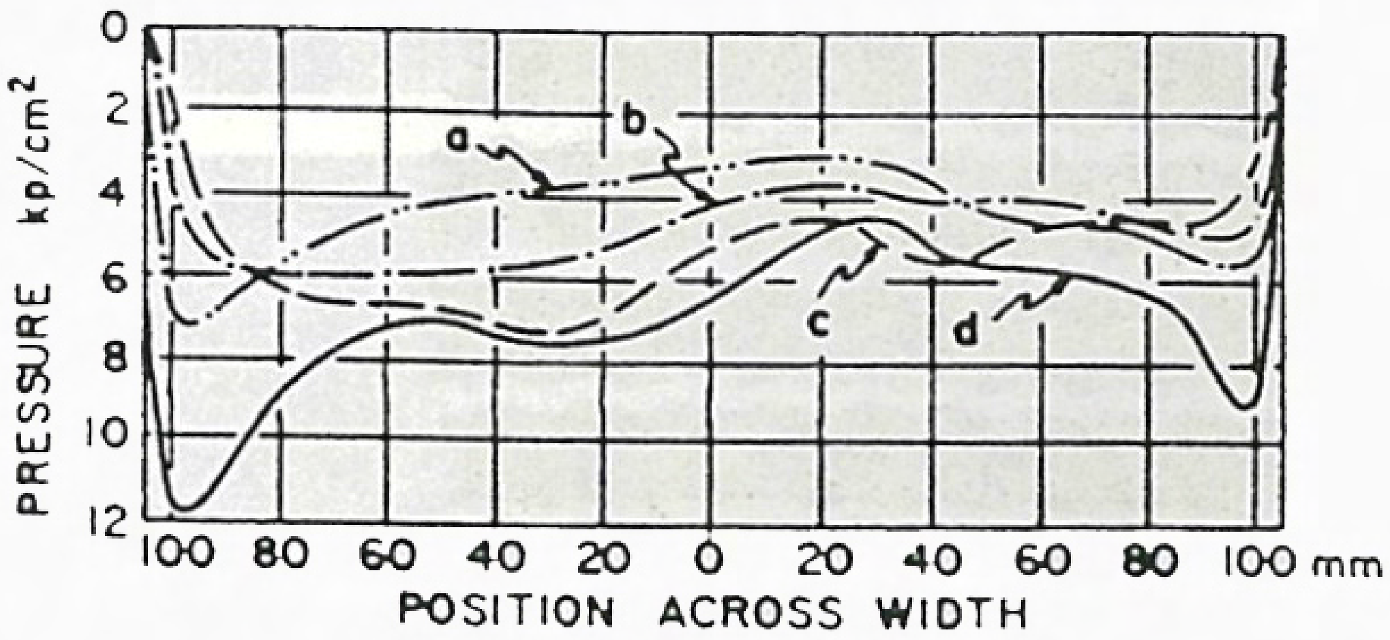

Fig.4. Pressure Distribution Across the Widh of a Tyre With no Tread Pattern, Costant Speed 15 kph, Load : (a, b, c) 1680 kp, (d) 3740 kp; Inflation : (a) 3.5 atm, (b) 5 atm, (c,d) 6.5 atm. [Bode (1962)]

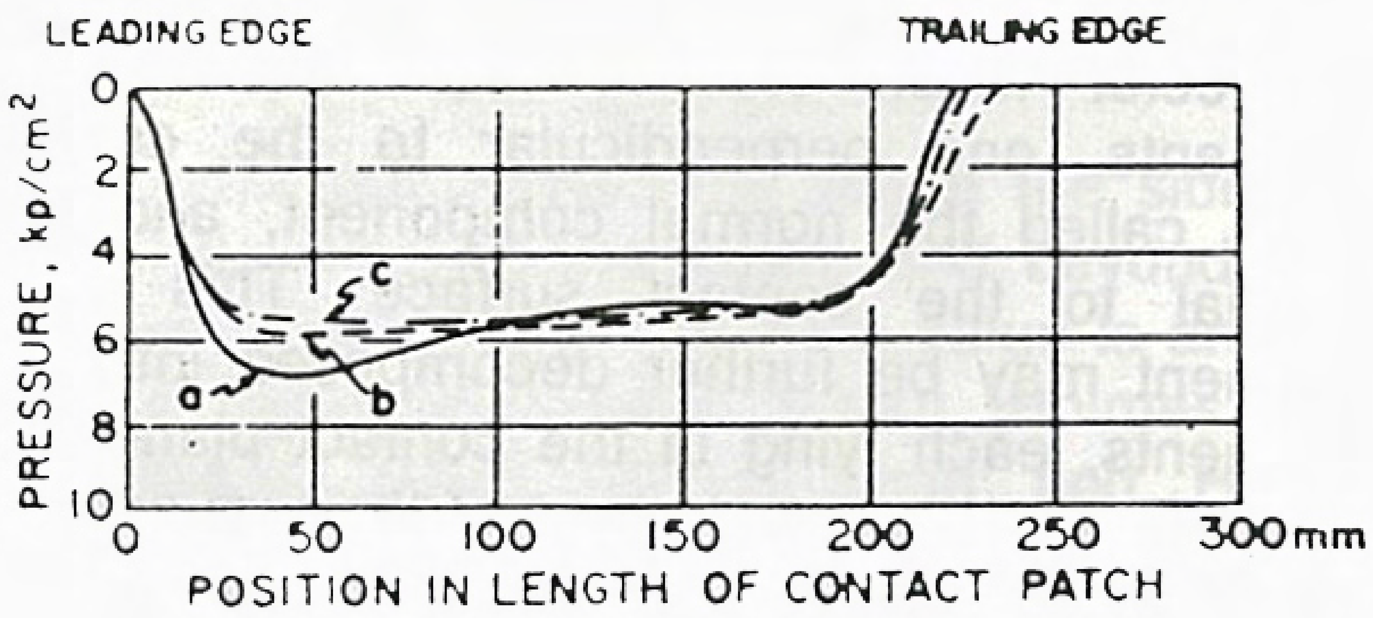

Fig.6. Pressure Distribution Down the Length of a Smooth Tyre, Load 1680 kp, Inflation 6.5 atm, Speed : (a) 10 kph, (b) 35.7 kph, (c) 14.5 kph; Deceleration : (a) 4.1 m/s2, (b) 2.7 m/s2, (c) 2 m/s2. [Bode (1962)]

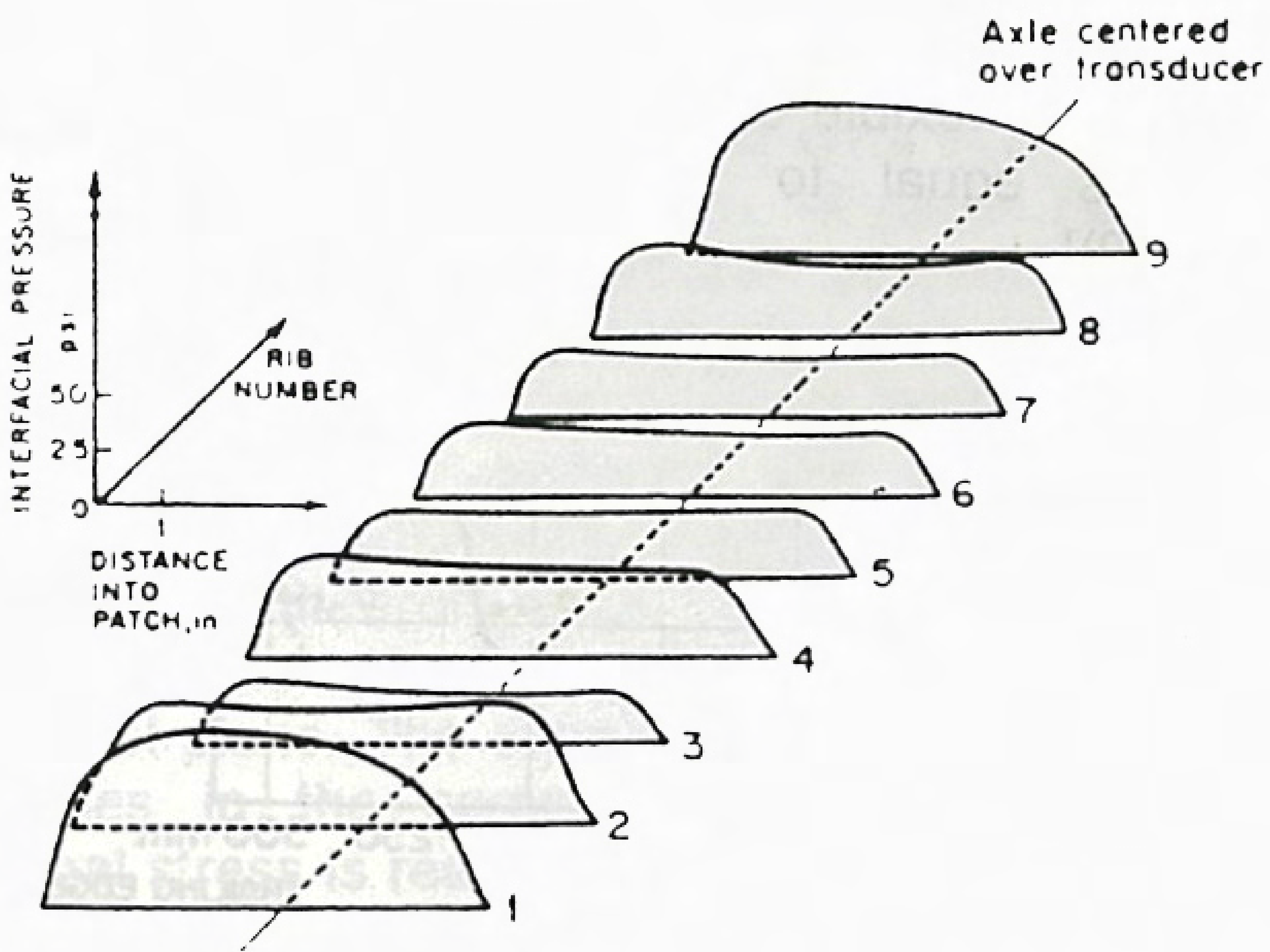

Fig.7.Pressure Distribution of Bias-Belted H size tyre, 26 psi, 0° Slip Angle, 100% T and R Load = 1580 lb. [Lippmann and Oblizajek (1974)]

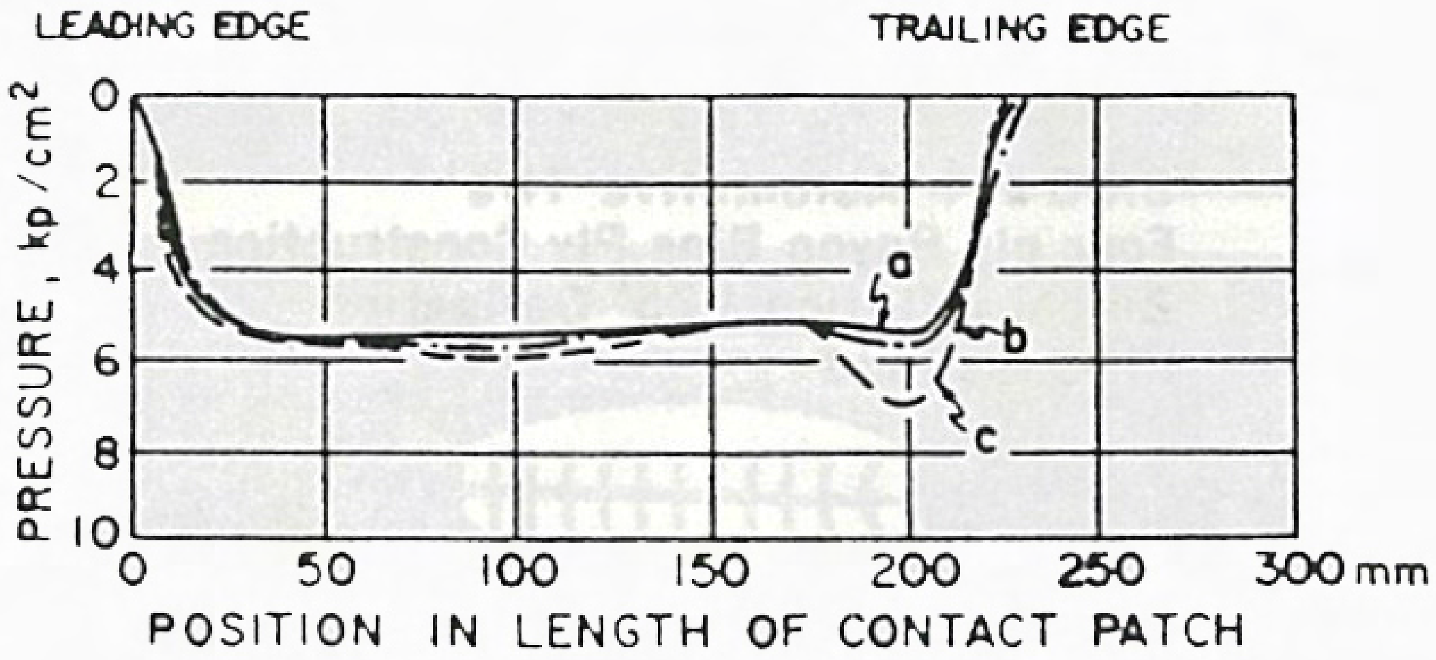

Fig.5. Pressure Distribution down the Length of a Smooth Tyre, Load 1680 kp, Inflation 6.5 atm, Speed : (a) 10.2 kph, (b) 8.4 kph, (c) 8.9 kph Acceleration : (a) 0.6 m/s^2, (b) 1.6 m/s^2, (c) 4.1 m/s^2, [Bode (1962)]

Modern instrumentation techniques have allowed measurement of normal pressures under a variety of conditions. Some of this data has been reviewed briefly by Hadekel, with particular emphasis on the early work by Martin [1936] and Markwick and Starks [1941] for road vehicle tyres, and by Teller and Buchanan [1937] and Kraft [1941] for aircraft tyres. The following facts emerge from the above data [Hadekel (1952)].

a. There is (as might be expected) a tendency for the pressure to rise from the centre outwards, up to some point at some distance from the edges, but more particularly so in transverse direction, the zones of highest pressure being near the sides of the contact surface. According to Martin, near the centre the stress may be actually less than the tyre air pressure.
b. There is a fairly gradual drop to zero at the edges.

Detailed measurement on truck tyres have been reported by Bode [1962], such as shown in Figures 3-6. Additional data has been reported by Lippmann and Oblizajek [1974] on car tyres. One set of pressure distribution from their work is illustrated in Figure 7. They found (as expected from Figure 1b) that by introducing steering, on one side of the tyre the length increases, and decreases by a similar amount on the other side of the tyre.

A number of investigations have examined the role of velocity in modifying the distributions, including the work of Bode as well as the work of Zakaharov and Novopol'skii [1957]. In general, the results seem to show that increasing speed causes an increasing vertical contact pressure at the forward end of the patch and a decreasing value at the rear portion of the contact patch.

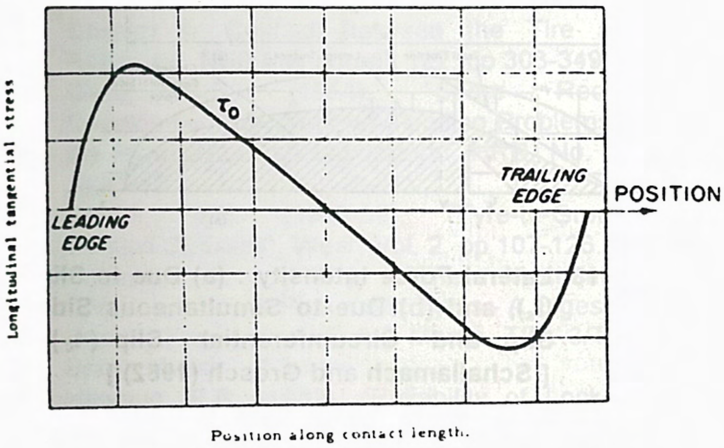

Fig.8. **Longitudinal Shear Stress Distribution in the Runing Direction of a Tyre Under Free Rolling [Novopol'skii and Nepomnya shchii (1967)]**

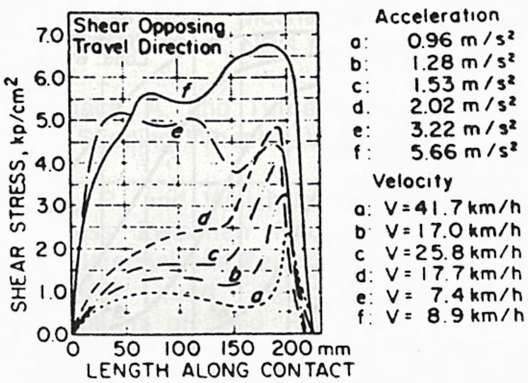

Fig.10. Longitudinal Shear Stress Distribution in the Running Direction of a Smooth Tyre Under Traction, Load 1590 kp, Inflation 6.5 atm. [Bode (1962)]

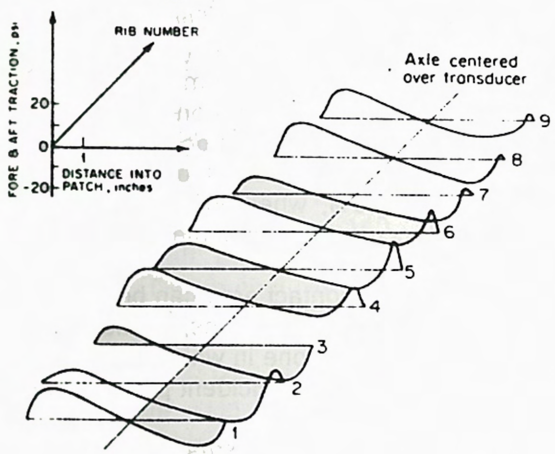

Fig.9. Longitudinal Shear Stress Distribution in the Running Direction of a Bias-belted H size Tyre Under Traction, 26 psi, 0° slip Angle, 100% T and R Load = 1580 lb. [Lippmann and Oblizajek (1974)]

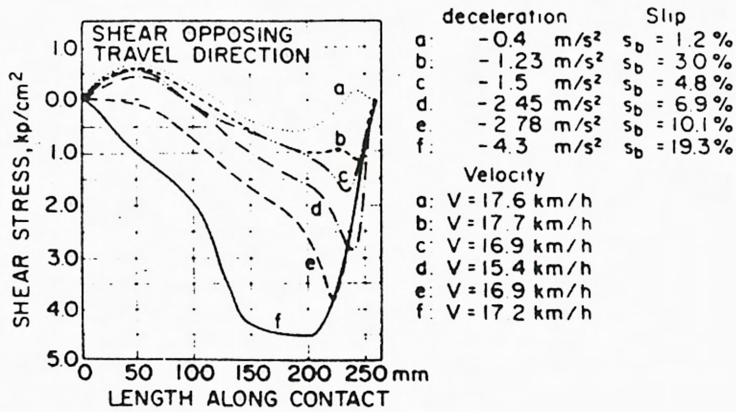

Fig.11. Longitudinal Shear Stress Distribution in the Running Direction of a Smooth Tyre Under Braking Force, Load 2610 kp, Inflation 6.5 atm. [Bode (1962)]

6.2. Tangential Stresses

According to Browne et.al [1982], the direction and magnitude of the longitudinal tangential stresses of a driving or braked wheel are determined by the sum of the stresses created in the rolling of a free wheel and the additional stresses created by the application of a torque. In driving, immediately before the contact the tread elements are contracted, and they are stretched at the point at which contact is released, as a result the shear is opposing travel direction. In braking, the situation is reserved, and the shear is in the direction of travel.

The form of longitudinal shear stress in a free rolling tyre without steer angle has been studied, such as by Novopol'skii and Nepomnyaschii [1967] and Lippmann and Oblizajek [1974]. Their results are shown in Figures 8-9. Similar results are obtained by Markwick and Starks [1941], who state that the distribution on a longitudinal section is somewhat similar for a standing tyre, as it is caused by the bending of tyre (carcass) with consequent symmetric strain distribution.

Extensive experimental work on the longitudinal component of shear stress has been published by Bode [1962], such as shown in Figures 10-11. It can be seen that the influence of braking or tractive forces is to throw the major part of this longitudinal component to the rear of the contact patch. Even moderate values of such forces are sufficient to completely change the stress distribution.

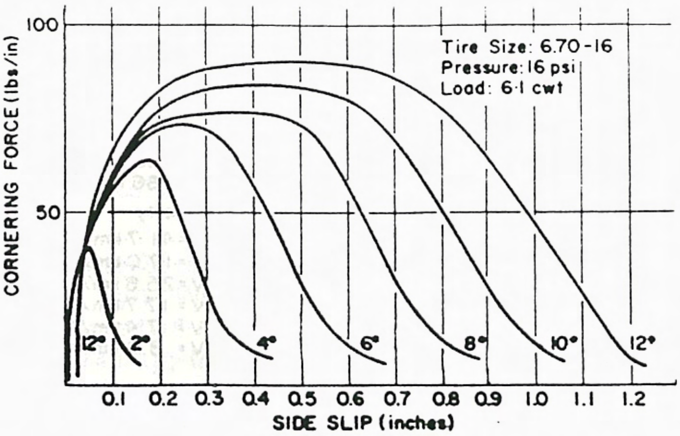

Fig.12. Lateral Force Intensity Along the Contact Spot, at Slip Angles up to 12°
[Browne et.al. (1982)]

If a tyre is caused to move at a slip angle, it will develop a ground frictional force resisting that slip. A pneumatic tyre adheres to the road in the front part of the contact, where it accommodates the slip angle by lateral deflection. Sliding is confined to the rear part of the contact, where the elastic forces overcome friction. For this reason, the contact area can then be separated into two regions. As stated by Browne et.al [1982], the first region is one of essentially static contact between tyre and the road surface, but nevertheless a region in which secondary slip may exist; whereas the second region, adjoining the first, is the region of primary slip where the tangential surface stresses exceed the local frictional stresses available.

In the first (adhesion) region, since the stresses in the contact are simply related to the deflection, it is expected that the lateral stress is gradually increased until it meets the second (sliding) region, where after that the lateral stress is decreased following the decrease in the available friction stresses. A typical of lateral (cornering) force intensity is given in Figure 12.

Tyres are often required to transmit lateral and longitudinal forces to the ground at the same time, a common instance being driving wheels in a curve. Simultaneous lateral and longitudinal slips alter the relation of the lateral and longitudinal forces with their own slip. This mutual interference is pronounced at large slips when a substantial part of the contact is sliding because the total available force p must be shared by the two forces.

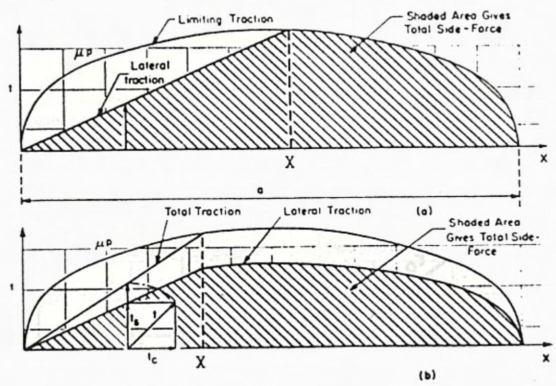

Fig.13. Lateral Force Intensity : (a) Due to Slip (t_s), and (b) Due to Simultaneous Side Slip and Circumferential Slip (t_c). [Schallamach and Grosch (1982)]

A simplified example of stress distribution due to simultaneous slips is shown in Figure 13 [Schallamach and Grosch (1982)].

VII. CONCLUSIONS

1. If the automobile is cruising in a normal manner, most operating conditions can be regarded as the steady-state (constant slip velocity) and quasi steady-state motions. Under emergency or panic stops, the non steady-state motion (varying with time) often occurs.
2. The maximum braking force is obtained at a slip between 7%-30%, whereas the maximum sideway force occurs at a slip angle between 5°-20°.
3. In general case, the contact area can be divided into adhesion and sliding regions, an adhesion region being defined as one in which there is no relative motion between coincident points of the tyre and ground surfaces.
4. If appreciable (or even quite small) sideway or braking forces are applied, sliding begins at the rear of the contact surface in which the available friction is exceeded. In extreme case the relative motion is one of pure sliding, for which the term "skidding" may be reserved.
5. The shape of the contact area depends on the tyre cross section shape and structure. The normal pressures, on the other hand, are not uniform but drop gradually to zero at the ends of contact. Normally, only the pressure distribution across the width of the tyre can be treated as uniform.

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