FACTORS AFFECTING TYRE-ROAD FRICTION ON WET ROAD

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RINGKASAN

Jika air atau setiap pelumas yang berfungsi sebagai perantara dengan ketahanan geser rendah, membasahi permukaan jalan, maka friksi yang tersedia akan berkurang secara drastis. Tingkat pengurangan friksi tersebut akan tergantung dari bermacam faktor, seperti ketebalan film air, temperatur, jenis ban, dan faktor operasi. Makalah ini menguraikan faktor-faktor tersebut yang mungkin bisa mempengaruhi besarnya friksi ban pada jalan yang basah.

SUMMARY

If the water or any lubricants, which act as medium of low tangential shear, wetted the road surface, the friction available is drastically reduced. The reduction in friction levels depends on many factors, such as water film thickness, temperature, tyre type, and operational factors. This paper describes those factors which may significantly affect the magnitude of tyre friction on wet roads.

I. INTRODUCTION

Holmes et.al (I972) have listed 47 factors associated with the friction between tyre and a road surface, but some of these factors have been to have insignificant effect on the skid resistance. Moyer (1959) identified 15 variables as the major factors contributing to the large variation in the friction coefficient measured on various road surfaces. In general, the variation in skid resistance can be attributed to the following groups: pavement/lubricant conditions, tyre, and operating conditions.

II. PAVEMENT/LUBRICANT CONDITIONS

2.1. Road Surface Texture

Road surface texture refers to the distribution and the geometrical configuration of the individual aggregates on the road surface. The texture is generally divided into two components, namely: (a) the macro-texture, to refer to the large scale texture of the pavement which represent the easily visible asperities, and (b) the micro-texture, to refer to the fine scale texture on the surface of individual pieces of aggregate. In quantitative study, however, it had been shown that road surface texture can be divided into more than two scales [Yandell and Gopalan (1976)]. The function of the texture is to provide a close contact with the tyre surface, to secure sufficient deformation of the tread rubber, and to facilitate the removal of surface water especially when the tyre surface is smooth.

The role of macro-texture in removing bulk water was demonstrated by Wallace and Trollope (1969). They found that as the texture depth increased the normal water force underneath the tyre decreased resulting in the increase of tyre friction. An experiment on wet surfaces by Schlosser (1977)showed that the influence of macro-texture is mostly prominent at high speeds. His results showed, even with worn tread, that the locked wheel and sideway force coefficients remained almost constant up to speed of 100 km/h on the coarse macro-texture surfaces. It is well known that at high speed, shorter time will be available for the water to drain away, thus the remaining water film would be thicker if adequate drainage is not provided as with the cases of smooth macro-texture surfaces.

The effect of micro-texture in reducing the thin water film (hence establishing dry contact with the tyre surface) was quatitatively studied by Rohde (1976). He found that the time of descent of a tread element under constant load decreased significantly when the micro roughness amplitude was increased. The shape of the micro-texture also influenced the sinkage time, with the triangular texture pattern taking shorter time than the square pattern to reach a given minimum film thickness. The increases in the level of harshness of micro-texture, on the hand, can cause an increased tyre wear without a proportional increase in the tyre friction [Yandell and Gopalan (1976), Lees et.al (1977)].

2.2. Aggregate Characteristics

The characteristics of aggregate which influence the skid resistance are the shape, grading, type, state of wear or polishing. The pressure distribution of the surface of asperities pressed into tread rubber depends on the shape of asperities rather than their size, provided that the macro-texture is coarse enough to drain off the surface water [Tabor (1959)], its spacing is such that there is no texture saturation by the rubber [Yandell(1970,1971)] and visco elastic frequency effects do not intrude.

Laboratory study by Stephens and Goetz[1960] found that the mixture made from finer gradation gave higher values of skid resistance. It is generally agreed that all types of limestones are highly polishable and result in extremely slippery roads under wet condition although they give high skid resistance when newly laid [Finney and Brown (1959), Gray and Renninger (1965)]. Sandstone and quartzite aggregates were found to posses the highest permanent skid resistance properties [Havens (1959)]. According to Lees [1984-85], aggregates which have a distinct difference in hardness between primary minerals (such as quarts, augite, hornblende) and weathered secondary minerals (such as kaolinite,chlorite, terpentine, sericite) will also produce high skid resistance.

With all types of aggregates and methods of construction of roads it is possible to get high skid resistance when the road surface is new. However, with age, the aggregates under the action of heavy traffic tend to polish, resulting in lower skid resistance. The polishing of the road stones is principally due to the continual attrition of fine abrasive mineral particles found on the road surface caused by the traffic movements, and it is seen that the finer the detritus, the greater will be the degree of polishing [Maclean and Shergold (1960)]. Stiffler [1969] concluded that the abrasives of size less than 10 micron diameter will cause polishing.

2.3. Seasonal Effects on Surface Texture

Giles and Sabey [1959] reported a marked difference in test results on wet surfaces for winter and summer. The coefficient of friction is higher in winter than summer. The above report reveals that the road surface was found to be covered with fine dust during summer. The dust polished the roadstone thus resulting in a lower friction coefficient. In winter (when the road was wet for 60% of the time), the dust particles were quickly washed off the tyre and the abrasion patterns tended to disappear. The polished stones got roughened by weathering in the presence of water.

2.4. Amount of Water

The effect of water film on friction has been found to be the predominant factor compared to the speed and temperature dependent viscoelastic effect [Clamroth and Heidemann (1968), Lupton and Williams (1972)]. Giles (1959) and Besse [1972] found that the friction continue to decrease as the water film increase, until the film thickness of about 0.02 in (0.508 mm) where the friction tends to level off.

2.5. Temperature

It is well known that with increasing temperature (air, surface, tyre tread), the skid resistance tends to decrease [Giles and Sabey (1959), Grosh and Maycock (1968), Meyer and Kummer (1969), Meyer et.al (1974)]. Both Giles et.al and Grosh et.al measured an increase in rubber resilience with increased temperature of rubber which indicates a decrease in hysteresis losses of rubber.

The effect of water temperature was studied by Meyer et.al [1974].

They measured skid resistance on several pavement with water temperatures of 140° F (60° C) and 60° F (15.5° C) and found that the difference was about 1 skid number (0.01 locked wheel braking force coefficient), the higher temperature gave the lower values. Hence, it is seen that the temperature dependence of friction is through its effect on rubber properties rather than the rate of change of water removal caused by viscosity of the water (in which case the friction would increase and not decrease at higher temperature).

It is found that the temperature dependence of wet friction is dependent on the texture of the road surface. On wet coarse texture road surfaces the decrease in friction is more than that on wet fine textured road surfaces [Giles and Sabey (1959), Maclean and Shergold (1960)]. The possible explanation is that on the coarse texture, the temperature will be higher than for the smooth surface due to the greater contact stresses (as caused by lesser actual contact area), and due to the break down of the carbon filler [Yandell et.al (1983)].

III. TYRE FACTOR

The choice of tyre type (cross ply, radial) for use in a vehicle can have a large influence on skidding characteristics. The variability in wet skid friction has been investigated by Allbert and Walker [1965-66], for example up to 4:1 for tread pattern design, and up to 1.8:1 for changes in tyre compound. To fulfil its function the tyre (tread) compound, as being reflected by its physical properties (such as: resilience, hardness, elasticity, and damping), must meet a number of different tyre requirements. A compromise in many properties sometimes must be sought, so that a tyre with high skid resistance as well as high abrasive resistance, can be obtain simultaneously [Peterson et.al (1974)]. In the following, those most important factors: tyre type, tread pattern, damping property, and hardness, will be described in details.

3.1. Tyre Type

The three basic types of tyres in use nowday are the bias-ply(sometimes called the cross-ply or conventional), the radial-ply (belted) tyre, and the bias-belted tyre. These three types are shown in Figure 1. Within each of the three basic tyre types, many variations are possible such as: low or high aspect ratio (i.e. ratio of the section high to the section width), and tube or tubeless type.

Radial-belted tyres although have lateral spring rates considerably lower than bias-ply tyres, but usually have higher cornering stiffness properties [Davisson (1969)]. In other words, for a given slip angle, the lateral force developed in radial-belted is greater than bias-ply. According to Davisson (1969), belted tyres have less tread movement in the contact area, and exhibit a slower rate of wear than bias tyres.

Results from DeVinney [1967] on hydroplaning tests show that radial-belted tyre have greater coefficient of friction. He explain that the "belt" gives a rigidness to the tread which serves to keep the grooves open as the tyre rolls through the contact patch, providing greater water "drainage".

Test on cornering coefficient by Sakai et.al [1978] found that when the water film is thin (1 mm) radial-ply tyres are considerably superior to cross-ply tyres. In contrast, when the water film becomes thick (5 mm) the radial-ply tyres are superior in the low speed region but inferior in the high speed region.

3.2. Tread Pattern

From the point of view of removal of water from the ground tyre contact, the tread pattern and the road surface macro-texture function in a somewhat similar manner. The tread pattern provides outlet channels for the surface water to escape from the contact area, under the squeezing action of the tyre. By this reasoning, the tread pattern should have a greater effect on smooth textured surfaces where drainage is generally poor. Conversely, tread patterns are least effective on rough open textured surface. There is also a contrast under dry and wet conditions, where best dry skid resistance is obtained when a tyre has no tread design at all. However, tread design plays a vital role in wet friction where accidents due to friction mostly occur on wet surface instead of on dry surface.

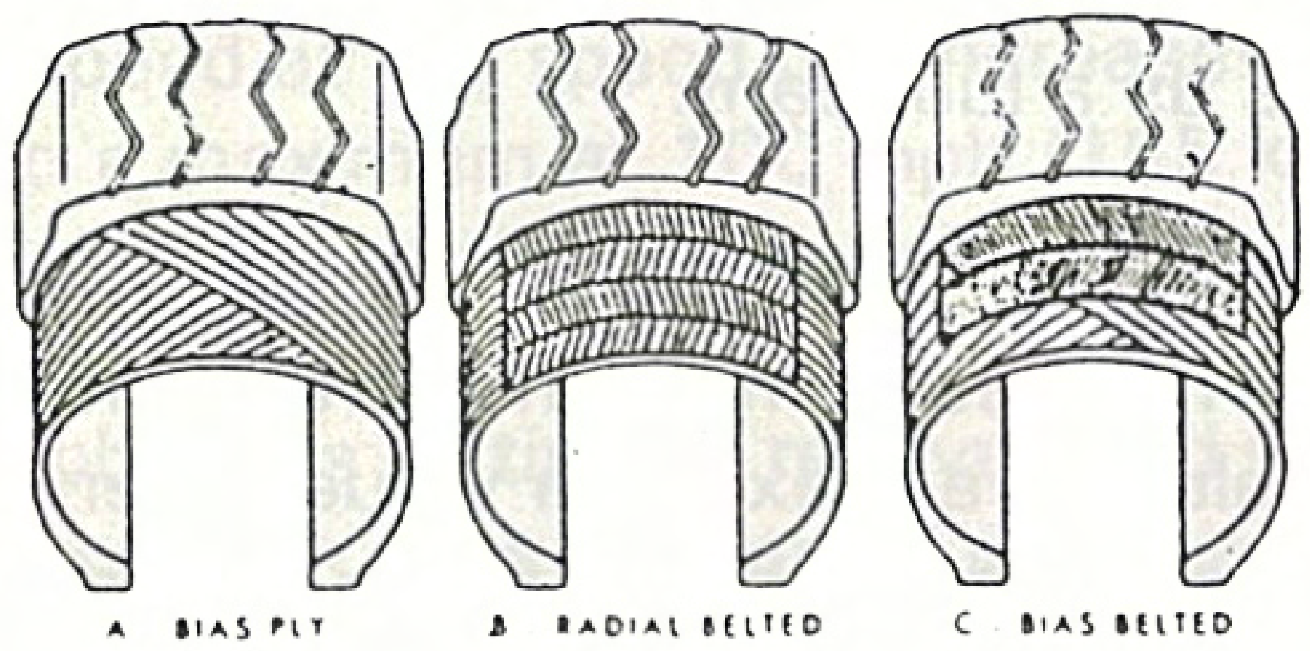

Fig.1. Basic tyre structures. [Davisson (1969)].

The simplest and the most common tread pattern is the provision of longitudinal grooves on the tread surface which, has shown to increase the friction on wet surfaces by 20 to 100 percent depending upon the initial value of the friction [Marick (I959)]. The skid resistance was also found to increase with the number of grooves and groove widths [Allbert and Walker(1965-66), Maycock (1965-66)]. This was attributed to the greater groove volume in relation to the total drainage area, to the slightly higher pressure acting in the contact zone as the groove area increases and probably to the shorter travel paths of water to reach the drainage channels [Maycock (1965-66)].

On the other hand, Kienle [1974) found that the effectiveness of widening grooves is asymptotic, and there is an optimum tread width for a given number of ribs. A similar result is obtained by Veith [1977], using the "fractional groove volume"ϕ which he defined as the ratio of groove volume to the total tread volume, as a measure of a tread pattern effect. He found an exponential relation between the locked wheel coefficient of friction and ϕ, where the tread pattern effect is seen to reach a limit at ϕ of about 0,4 (beyond which the coefficient remain unchanged with increased ϕ).

In addition to longitudinal grooves, the lateral edges on the tread surface have been found to provide wiping action over the wet surface. On some rough surfaces, it was seen that a suction of 10 psi (7 g/mm2) developed behind the transverse grooves [Wallace and Trollope (1969)]. This agreed with Gough's observation that sharp transverse edges of the tyre tread increase the skid friction by wiping water from the road surface [Gough (1954-55)]. Slits in the tyre function as pockets to absorb local lubricant pressure and promote dry contact [Allbert and Walker (1965-66)].

Since the fall of friction coefficient with speed is associated with the greater difficulty the tyre has in displacing the water beneath it , it is evident that tread pattern proves more effective at high speeds. Maycock [1968) found that the tread pattern, even of the simplest design such as straight ribs, gave on the smooth surface a large improvement in both peak and locked wheel braking force coefficients with the speed range of 30 mph to 60 mph. At low speeds the effects of tread pattern are not significant especially on coarse texture road surfaces.

3.3. Damping Property

The damping factor is usually measured by allowing a weighted pendulum to strike a rubber sample from a given height. The elasticity is the percentage of potential energy regained at the first rebound. Therefore a rebound to the original height would indicate 100 percent elasticity, that is no damping loss. The energy lost in the process is called damping energy and is dissipated in the rubber as heat. Yandell [1970] defined the damping factor as the energy lost divided by the energy applied during one complete loading-unloading cycle. Rubber with high damping losses (low resilience) will give high values of friction coefficient [Sabey et.al (1970)].

As rubber is partly viscoelastic material, its damping losses are influenced by temperature and frequency of loading. The damping decreases as temperature increases, and increases with increasing frequency. With increasing temperature, peak damping for a given rubber compound decreases and shifts towards higher frequencies [Kummer and Meyer (1962)]. Furthermore, they found that the damping for synthetic rubber is always considerably greater than for natural rubber. The superiority of natural rubber, however, is for the low heat buildup characteristic [Davisson (1969)].

3.4. Hardness

The hardness is usually measured by Shore Durometer [Bashore (1937)]. Rubber hardness has been less definitely correlated with friction. There are reports in the literature that increasing rubber hardness increases friction [Marwick and Starks (1941), Grime and Giles (1954-55), Giles et.al (1962), Goodwin and Whitehurst (1962, Sarbach et.al (1965)], or has no effect [Sabey and Lupton (1964), Bassi (1965)]. The general explanation for the increased friction is that the harder rubber gives a smaller contact area, resulting in higher contact pressure, better drainage and hence increased friction [Csathy et.al (1968)].

Carr [1967] reported that the relative influence of rubber hardness depends on the texture on which it slides. Report from Percarpio and Bevilacqua [1968] found that on slippery road surfaces, the increased hardness conversely leads to decreasing friction. Their report then suggest that friction increases with hardness only on highly abrasive surfaces.

IV. OPERATING CONDITIONS

4.1. Speed

Numerous tests have been carried out to study the effect of speed on friction [Hofelt (1959), Sabey (1966), Kern (l967), Allbert and Walker (1965-66), Maycock (1968), Sabey et.al (1970)]. Some of these tests were conducted in a laboratory, however, all the results generally indicated a decrease in friction with increasing speed. An exception to this trend was reported by Sabey et.al [1970] which indicated a significant interaction effect between speed and road texture (see Figure 2). The usual explanation given for the decrease in friction on dry surfaces with increasing speed is that the high temperature generated within the contact patch causes the rubber to melt, the melted rubber then serves as a lubricant.

Foster [1961) confirmed that the coefficient of adhesive friction incrases from a low value to a maximum value when sliding takes place, then drops as the velocity further increases. Papenhuyzen [1938] found that the increase in the adhesive friction is less pronounced on rough tracks, and the velocity-friction curve begins to take a negative slope at a higher sliding velocity than on a smooth surface. Savkoor [1965] demonstrated that the adhesive friction of rubber on glass is viscoelastic, and he concluded that the adhesive friction develops a peak at a velocity which moves towards a higher velocity when the temperature is increased.

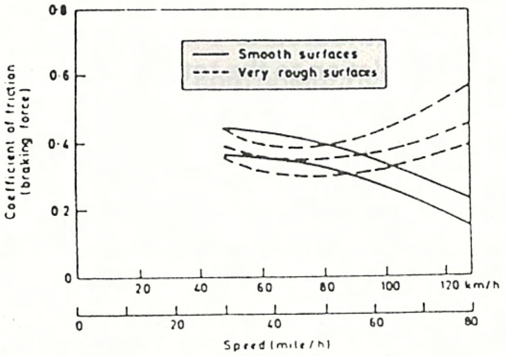

Fig. 2. Effect of speed and road texture to skid resistance. [Sabey et.al (1970)].

A Theory for speed dependence of adhesive friction has been developed by Kummer and Meyer [1966], in which the exposed atoms of the rubber chains are bilieved to form junctions with the regular array of stone surface atoms. The junctions, according to their theory, break off after the bulk of rubber moves forward. The rubber molecules in the process recoil and form another junction. The formation and breaking of junction dissipates adhesive energy which is a maximum at a particular velocity and temperature.

The behaviour of the lubricated friction under different sliding speeds up to 60 mph (100 kph) was studied by Hegmon [1965, 1968], and found that eventually the lubricated friction reaches a second peak. Kummer and Meyer [1966] proposed that the hysteresis friction does not vary greatly with speed at low speed but increases rapidly to a maximum at 100 mph (165 kph). They attributed the increase in friction at high speeds to the fact that at high speeds the rubber has no time to recover and separate from the downstream surface of the asperity and the resultant of the remaining reactions opposes the sliding (see Figure 3).

Meyer and Kummer [1969] superimposed their theories of viscoelastic adhesion and viscoelastic hysteresis to form a unified theory of friction, according to which the low speed friction peak is due to adhesion, and high speed friction peak is due to hysteresis. While they assumed that hysteresis occurs at a particular scale of texture, Yandell [1970] on the other hand maintains that since a road surface consists of numerous superimposed scales of texture, the resultant hysteresis friction is made up from a large number of friction-speed curves with each having a peak at a different speed.

The reduction of friction under wet conditions with increasing speed can be attributed to the following reasons.

a. Difficulty in squeezing water films from between the tyre road contact within the available time, which decreases as the speed increases.
b. The higher frequency of loading (due to the higher speed) beyond the rubber's characteristic peak leads to a lower coefficient of friction [Carrol (1965)].
c. The possible temperature rise in tread rubber (lost energy converted into heat), when the remaining water is thin, causing a reduction in damping factor of rubber, hence results in a decrease in hysteresis friction.
d. Lack of interasperity drainage at high speeds which results in lower effective load carried by the asperity [Wallace and Trollope (1969)]. This effect is more severe in fine textured road surfaces causing steeper friction-speed curves.

4.2. Wheel Load

In general, the change in wheel load appears to have a small effect on skid resistance, and can be regarded as insignificant [Staughton and Williams (1970), Schlosser (1977)]. However, if the friction is separated into adhesion and hysteresis components, there is a tendency that the increasing loads leads to a decrease in adhesive friction [Schallamach (1958), Tabor (1959)], and an increase in hysteresis friction [Tabor (1952), Greenwood and Tabor (1958), Sabey (1958)].

The influence of load on the adhesive friction is dependent on the range of contact pressure considered [Thirion (1946), Archard (1953, 1957-58), Denny (1953), Tabor (1959)]. When pressure is small, the area of actual contact has been found to be proportional to the load, in which case the friction coefficient is independent of the loads. For high pressures, however, the adhesive friction is load dependent because the actual area of contact cannot be made to increase indefinitely with the load. Schallamach [1958] believed that the adhesion increased with the area of contact and decreased with the load.

The coefficient of water lubricated friction increased with the load in some tests, the increase was more rapid on coarse textured

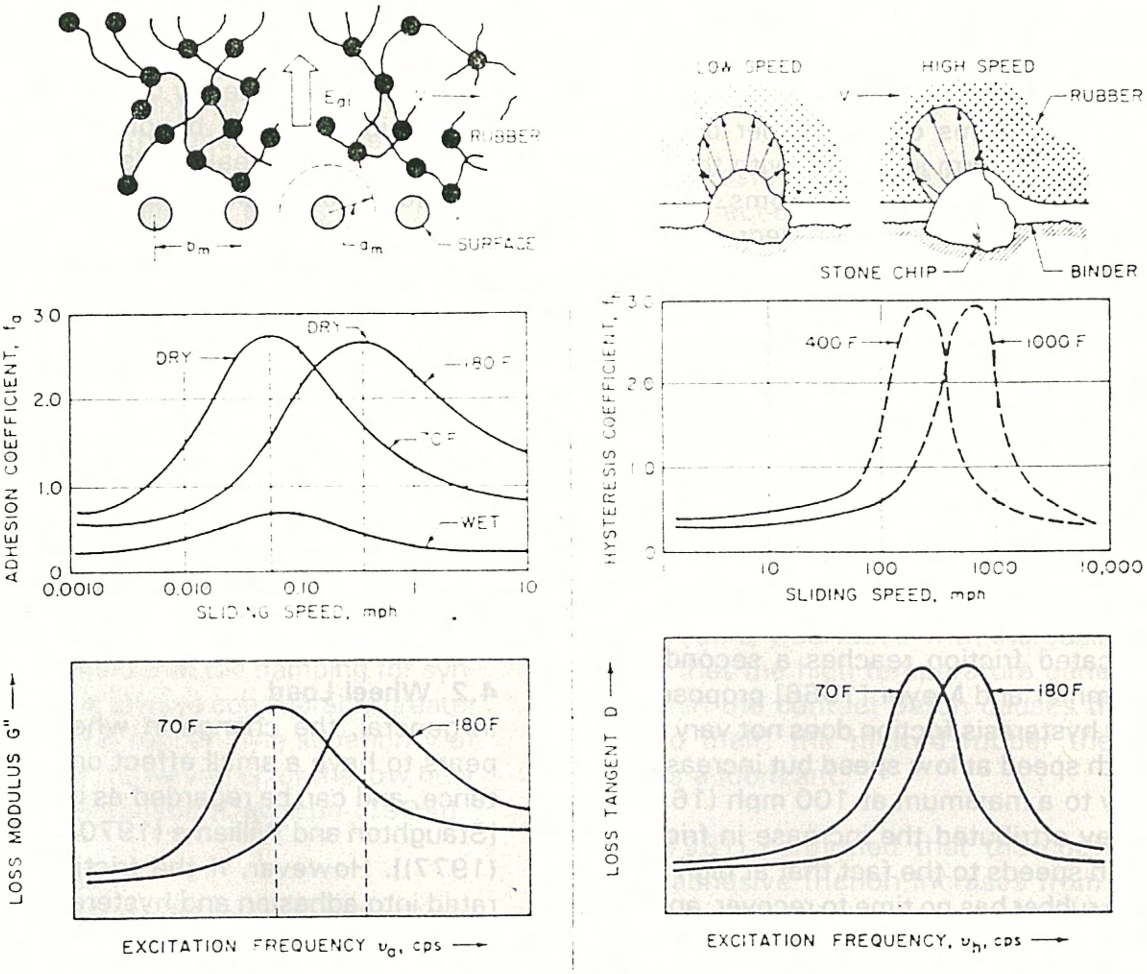

Fig.3. Friction mechanism due to adhesion and hysteresis . [kummer and Meyer (1966)]

road surfaces [Stutzenberger and Havens (1958), Stephen and Goetz (1961)]. According to Yandell [1974], the increase in hysteresis friction with increased load is caused by partially unmasking the particular scale due to the decreased film thickness, and by increasing average absolute slope for cylindrical asperities. On the other hand, he found that it is also possible that the hysteresis friction decreased with increased load, in which this is caused by preventing the stress flux in the rubber from increasing as rapidly as the normal load (so he called "the stress saturation of rubber by the texture").

4.3. Inflation Pressure

Similar to wheel load, the effect of tyre inflation pressure on the friction coefficient is marginal [Hofelt (1959), Kummer and Meyer (1967)], however there is a general trend that as inflation pressure increases this coefficient decreases on wet pavements [Moyer (1934), Orchard (1947), Pike (1949), Goodwin and Whitehurst (1962)]. On dry pavements, there is a little evidence that the friction coefficient increases with increased inflation pressure [Pike (1949)]. The change in inflation pressure may due to the change in the temperature of the tyre rubber, where the hotter the tyre the higher the inflation pressure.

The increase in the inflation pressure has been found to increase the pressure under the central ribs of a pneumatic tyre without appreciably changing the pressure under the shoulder ribs [Hofelt (1959)] and to decrease the contact area of the tyre with the road surface. Although the increase in the pressure under the central ribs is good from the point of view of water removal which may result in better skid resistance, but the decrease in the contact area may have an opposite effect due to decrease in contact area per unit load [Moyer (1934)].

Lander and Williams [1968] found that the change in friction coefficient due to inflation pressure is also influenced by the type of surface texture. Using the sliding speed of 60 mph they observed a 0.1 reduction of the braking force coefficient on the fine textured surface by increasing inflation pressure from 40 psi to 260 psi, but little change on the coarse textured surface. (This may be due to stress saturation of the rubber on the fine texture [Yandell (1974)].

4.4. Mode of Operation

The vehicle maneuvers basically can be grouped into four categories: rolling, cornering , decelerating/accelerating (or braking/driving), and combined cornering with decelareting/accelerating (such as braking-in-a-turn, or turning-in-driving). It is quite common to treat skid resistance as a pavement property since road surface properties influence more than either tyres or the automobile. However, in the following it will be described that the magnitude of the friction coefficient is also controlled by the elastic tyre properties and degrees of slip.

In rolling motions, the dissipation of energy due to bending of the tread as it rolls through the contact patch, causes higher normal pressures in the leading half of the contact. Hence, the moment of the normal pressures with respect to the axis of rotation is not zero. In the free-rolling tyre, the applied wheel torque is zero, therefore frictional forces must exist to maintain equilibrium. The resultant frictional force (called "rolling resistance force") is a result of the normal pressures and zero applied wheel torque [Nordeen and Cortese (1963)]. However, the magnitude of rolling resistance coefficient is very small, being in the order of 0.01-1.015 [Hadekel (1952)]. This coefficient increases with increasing speed and load, and with decreasing inflation pressure [Fuller et.al (1984)].

In cornering motions, the skid resistance characteristics are described by the relationship between lateral (sideway) force coefficient and slip angle, as typically shown in Figure 4 [Bergman (1977)]. The lateral coefficient increase teeply in the range of slip angle between 0^0 and about 8^0 . Within this range, the curves for wet and dry surfaces were indentical. this indicated that, within this region, road friction has practically no effect on the relationship between lateral coefficient and slip angle. Instead, it is controlled primarily by elastic tyre properties [Bergman and Clemett (1975)]. The effect of road friction first begin to appear near the crictical angle value wich is reached at about 12^0 on wet surface and at about 30^0 on dry surface. The curves then show gradual decline with further increase of slip angle.

Skid resistance characteristics in braking are describe by the relationship between longitudinal (braking) force coefficient and wheel slip, as typically shown in Figure 5 [Bergman (1977)]. These curves show a general similarity to the cornering coefficient curves for the same tyre in Figure 4. The braking force coefficient increases up to its peak value reached at a critical value of wheel slip and then shows a gradual decline with further increase of wheel slip. In the region below the critical slip, the relationship between braking coefficient and wheel slip is also diminated by the type properties [Gough (1974)].

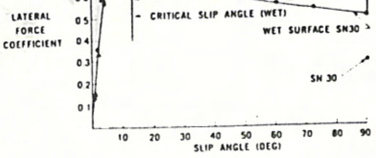

Fig. 4. Lateral force coefficient vs slip angle of J78-15 tyre. [Bergman (1977)].

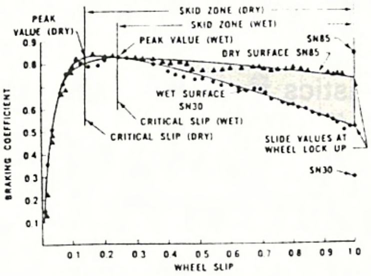

Fig. 5. Braking force coeffcient vs wheel slip of J78 - tyre. [Bergman(1977)].

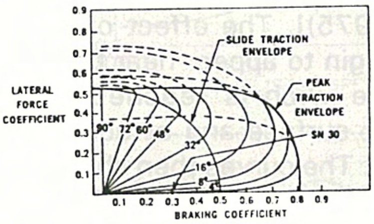

Fig.6. Peak and slide traction envelopes of J78-15 tyre in braking-in-a-turn. [Bergman(1977)].

In braking-in-a-turn, skid resistance characteristics are determined primarily by the peak and slide envelopes of the resultant braking-cornering coefficient, as typically shown in Figure 6 [Bergman (1977)]. The lateral coefficient versus braking coefficient curves plotted for individual slip angles describe skid resistance characteristics as well as elastic properties of braking-in-a-turn tyres. The skid resistance characteristics at transition from peak-to-slide are described by the solid portion of these curves located between the peak and slide traction envelope.

V. CONCLUSIONS

Several factors which significantly affect the tyre friction on wet roads, and their role, have been described in details. Since the skid resistance force results from the interaction between tyre and road, the friction coefficients are not solely the indicator of pavement properties. In addition to pavement/lubricant conditions and the tyre itself, the way of operating the vehicle are also involved in determining the magnitude of tyre-road friction. Including in the pavement/lubricant conditions are: road surface texture (macro and micro textures), aggregate characteristics (shape, grading, type, state of wear or polishing), seasonal effects, amount of water, and temperature (air, surface,tyre tread). Factors associated with the tyre are: tyre type (cross ply, radial), tread pattern, damping property, and hardness. The operating conditions cover the factors of: speed, wheel load, inflation pressure, and mode of operation (rolling, cornering, decelerating/accelerating).

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