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SUBJECT INDEX (A) TIRE
BRAKE

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ABSTRACT

The braking characteristics of tires and their major parameters are studied in detail.

Rubber friction in the tire tread to pavement contact has been recognized as the primary source of tire traction. This process is explained as a viscoelastic phenomenon which is highly dependent upon temperature and sliding speed. Tire mechanics are discussed extensively as another significant factor of tire friction.

Tire tread design and rubber composition, tire load, inflation pressure, temperature, pavement characteristics, and operating conditions are studied as the other major parameters of tire braking performance. ( )

I. SUMMARY

An extensive literature survey has been conducted on all aspects involved in the braking characteristics of a tire. All parameters, known as having an influence upon the braking coefficient of a tire, are discussed and the magnitude of their influence is given whenever possible.

The tire itself is a complicated structure and deformation and stresses in the contact area are not easily analyzed. Rubber friction takes place in the contact area under constantly varying conditions. Rubber friction and tire mechanics are discussed in detail as the major processes involved in tire friction. Adhesion and hysteresis are the two components of rubber friction. Both are viscoelastic phenomena obeying the temperature-rate equivalence principle. Their relative importance, however, depends on the operating conditions.

The mechanical tire properties influence the deformation of the tire, the shape of the contact area and the relative sliding speeds of the tread elements in the footprint.

The friction force developed by a braking tire is influenced by a large number of parameters. Only a few of them, however, have a first order influence. The relative speed between tire tread and pavement has a paramount influence on tire friction. Tire tread design and rubber composition, tire load, inflation pressure, temperature, and pavement properties are other major factors. The presence of contaminants in the contact area has an overriding effect on the tire performance.

II. INTRODUCTION

The trend towards development of modern commercial aircraft with increasing speed and size demands a better understanding of the braking process of an aircraft during landing. It is necessary either to reduce stopping distances or at least keep them in a range which will enable the use of existing airports. In order to accomplish these improvements it is necessary to optimize the braking performance. It is imperative that the brake control utilizes the maximum available ground force at all times. To optimize the latter it is essential to understand more clearly the frictional coupling between the tire and the pavement. The ground friction of the tire is influenced by over thirty factors. In view of the complexity of the problem, the investigators have chiefly used experimental techniques to investigate this problem. In recent years, however, several theoretical studies have been conducted.

Over the years laboratory, road, and runway tests have revealed more and more factors that have a bearing on the magnitude of tire friction. Not all of these factors have the same importance and their significance may vary with the conditions involved.

Every study of tire friction invariably involves a thorough understanding of rubber friction because the tread rubber is the actual partner with the pavement surface. Rubber is a viscoelastic material whose elastic and damping properties are strongly frequency and temperature dependent. This dependence on the rate of deformation and temperature, of the physical properties of viscoelastic materials, causes the frictional performance of those materials to deviate considerably from the simple classic friction concept. Without a thorough understanding of the mechanisms involved the interpretation of experimental data becomes very difficult and may lead to incorrect conclusions.

The tire itself is a complicated structure and deformations and stresses in the footprint area are not easily analyzed or measured. The rubber elements in the contact area undergo multiaxial stress cycles, which are a direct consequence of the rapid variations of the magnitude and direction of load and shear forces acting in the pavement plane. Rubber friction takes place under constantly varying conditions. The mode of tire operation also influences its frictional performance. For example, rolling, slipping, cornering, or skidding produce entirely different friction forces. The frictional force arising in the footprint is credited to two components, namely adhesion and hysteresis forces. The adhesion forces are an interaction between the two surfaces in immediate contact with each other, whereas hysteresis losses account for the deformation energy losses in the rubber bulk of the tire. This concept has thrown a new light on the phenomenon of tire friction and contributed to a better understanding of the empirical data.

At low speeds and dry pavement, the tire friction is dominated by adhesion forces between the tread rubber and the pavement surface as well as deformation losses in the tread rubber. Under wet conditions adhesion is greatly reduced. With increasing sliding speed the liquid entrained acts as a lubricant thereby partially separating the pavement from the tread. As the speed increases the viscous shear losses become predominant until, at a combination of certain speed and depth of liquid, tire tread and pavement are completely separated. This phenomenon is called hydroplaning.

III. FRICTION OF RUBBERLIKE MATERIALS

Much research work has been done in the last decade to explore in depth the viscoelastic properties of materials and their temperature dependence. Some body of information exists where special consideration has been given to the viscoelastic nature of rubberlike materials (7, 56). The establishment of the rate-temperature equivalence principle for viscoelastic properties was a technological breakthrough. This concept has advanced understanding of the mechanics of these materials. Its applicability to rubberlike materials demonstrated clearly their viscoelastic character. An excellent survey of the state of the art on the knowledge of rubber friction has been given by Schallamach (K). This review updates the excellent surveys conducted earlier (15, 57).

A. Viscoelastic Theory

In an ideally elastic material stress is strictly proportional to strain (Hooke's law). In an ideally viscous fluid the shear stresses are strictly proportional to the rate of strain (Newtonian fluid). (B) In a real material the stress is a function of both strain and rate of strain. It may even include time derivatives of higher order. In addition, these proportionality factors (modulus of elasticity and viscosity) are also functions of temperature. For many materials one of these two factors are predominant and the other one may be neglected. For a series of materials, however, both factors influence the stress-strain relationship in the same order of magnitude. These materials are called viscoelastic.

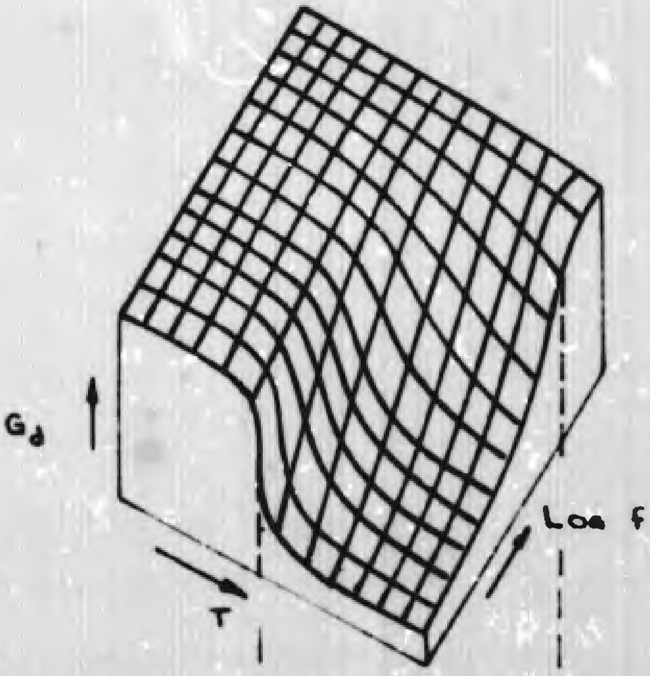

Fig. 1a

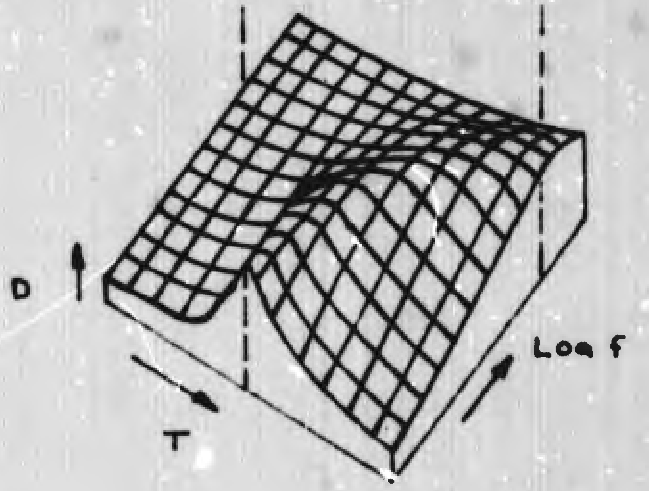

Fig. 1b

Dependence of Dynamic Shear Modulus G_d and Damping Factor D Upon Frequency f and Temperature T

1. The Complex Shear Modulus

It has been shown (60) that the general relationship of stress and strain of viscoelastic materials can be expressed by a linear partial differential equation of arbitrary order. For a sinusoidal variation of stress and strain this concept yields a complex modulus as their relationship. Hooke's law is contained as a special case of this concept (with the imaginary part of the modulus equal to zero and the real part frequency independent).

$$\sigma = (G_d + j \cdot G_l) \cdot \varepsilon$$

$$\sigma = G^* \cdot \varepsilon$$

$$G^* = G_d \cdot (1 + j \cdot D)$$

σ = stress
ε = strain

G^* is called the complex shear modulus, G_d is the dynamic modulus, and D the "loss tangent" or damping factor.

All these factors are frequency and temperature dependent and their relation is indicated in Fig. 1.

2. The Rate-Temperature Equivalence Principle

If a viscoelastic property, e.g., the loss tangent, shall be changed from its existing value D_1 at a certain temperature T_1 and a certain frequency f_1 to another value D_2 this can be accomplished by either one of two ways (Fig. 2): The temperature may be kept constant at T_1 and the frequency increased to f_2 or the frequency may stay constant and the temperature may decrease to T_2. Therefore, decrease in temperature has the same effect on the change of the material property as has an increase in frequency and vice versa. Furthermore, it could be shown

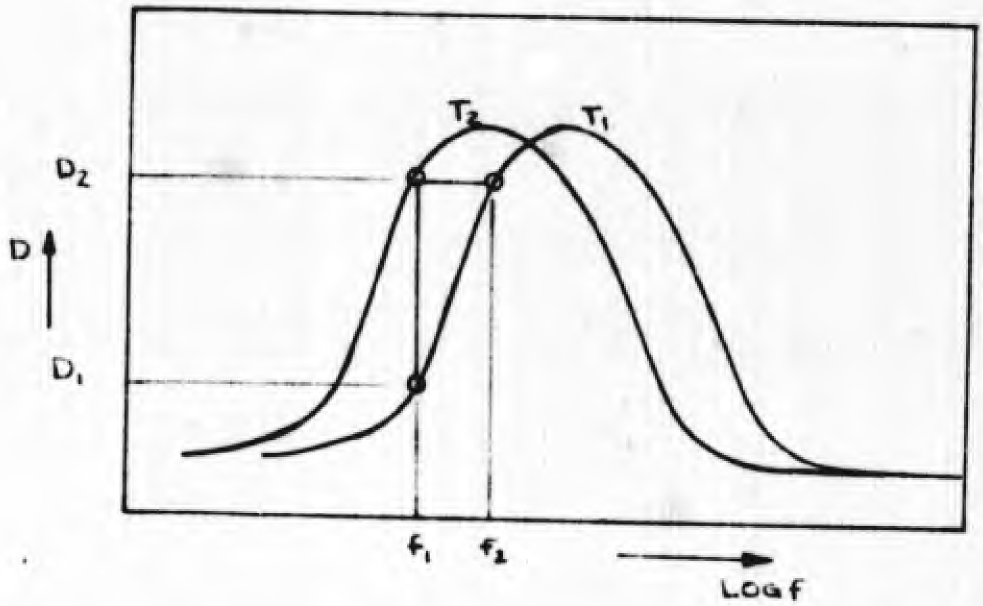

FIGURE 2

Damping Factor D Upon Frequency f for Temperatures T_1 and T_2

(63) that the isotherms of viscoelastic properties when plotted against the logarithm of frequency have the same shape for all temperatures. They can be shifted horizontally to a simple mastercurve by applying a shift function a_T known as the William-Landel-Ferry equation. The shift function a_T is defined as the reciprocal of the frequency scale multiplier necessary to shift horizontally an isothermal from a reference temperature T_o to another temperature T. This shift function depends upon the temperature difference (T_o-T) only.

This principle is not only valid for the moduli aforementioned, but for all properties of a viscoelastic material.

If in addition a reference temperature T_s is chosen with a value of about 50°K above the glass transition temperature* of the particular material, the shift function a_T turns out to be the same for all viscoelastic materials. This may be expressed as follows (63):

$$\log_{10} a_T = - \frac{8.86(T-T_s)}{101.5 + (T-T_s)}$$

This principle allows to interpret data in a wide temperature and frequency range even when the possible experimental range of the rate is limited. This may be seen in Figs. 3 and 4.

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* The glass transition temperature is that temperature below which a viscoelastic material seems to become a rigid "glass-brittle" mass. Exactly, it is the temperature at which a sudden change in the slope of the specific volume versus temperature curve occurs.

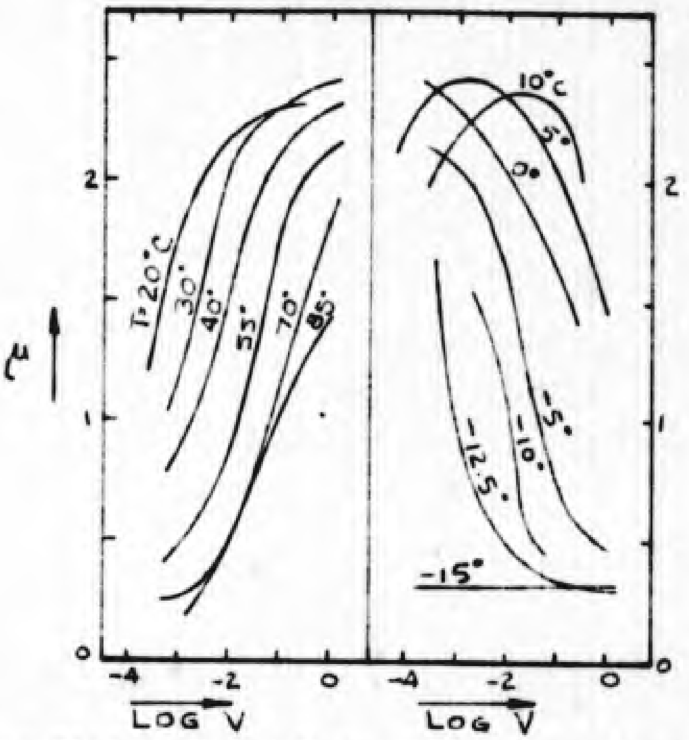

FIGURE 3. μ versus Sliding Speed V for Various Temperatures

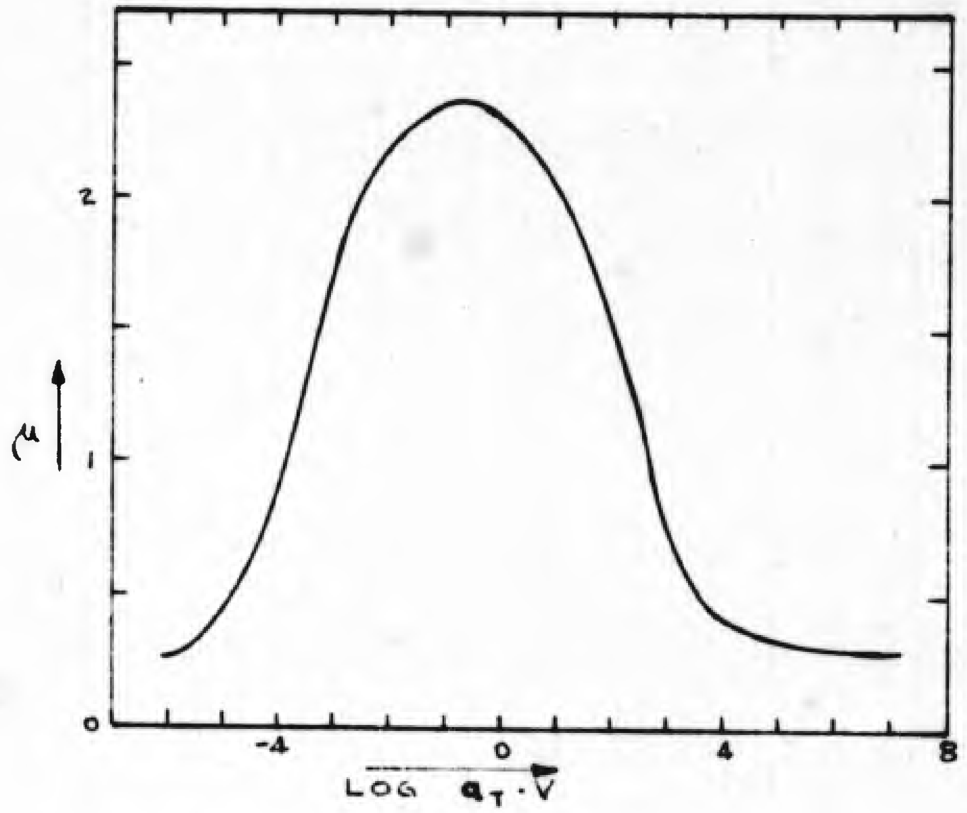

FIGURE 4. Master Curve of μ for T = 20°C, V in cm/sec

B. The Mechanism of Rubber Friction

Research on rubber friction in recent years (8, 41) demonstrated that the frictional forces developed between rubber and some other rigid material may be expressed as the sum of two components:

Friction Forces = Adhesion Term + Deformation Term

The relative importance of these two components is strongly influenced by such factors as the nature of the contacting surfaces, the load, sliding speed, temperature, surface texture, and lubrication.

1. The Adhesive Friction of Rubber

The adhesive friction force of rubber is the force necessary to overcome the bonding forces between rubber molecules and the contacting surface. The rupture of these molecular bonds does not necessarily produce adhesion. There is no evidence for rubber forming irreversible junctions with the track material unless very high temperatures are involved (55). As described in more detail in the appendix, adhesional friction of rubberlike materials is a viscoelastic phenomenon which obeys the rate-temperature equivalence principle. The mastercurve for the friction coefficient of adhesion shows a well-defined peak at a certain sliding speed (see Fig. 4).

a. Load Dependence

Experimental studies (23, 24) have shown that on very smooth, dry surfaces rubber friction is proportional only to the true area of contact. In this case friction is only created through interfacial adhesion. The frictional force is proportional to the load only when the load produces a proportional increase in contact area or an increase in hysteresis losses. Due to the low elastic modulus of most rubbers considerable trapping and hence a large contact area develops even under moderate loads on rough surfaces. A layer of lubricant between the two contacting surfaces suppresses bond buildup considerably and reduces adhesive friction.

b. Velocity

Many experimental results on dry and smooth surfaces (2, 5, 55) are available for the coefficient of friction of rubberlike materials. They all indicate that the coefficient of friction increases with increasing sliding speed up to a maximum value and thereafter decreases again with further increasing speed (see Fig. 4). At room temperature this maximum occurs in the range of 10 to 50 cm/sec for most rubbers. For increased temperatures this maximum shifts to higher sliding speeds without changing its value.

c. Compounds

The addition of carbon black particles to the rubber reduces its value of friction but does not vary its dependence upon speed and temperature (5).

2. The Hysteresis Part of Rubber Friction

When rubber is sliding on a rough surface deformation energy is lost due to a finite hysteresis in the rubber bulk. If the adhesion is reduced through a lubricating film between the two surfaces the deformation losses are predominant (23, 24). Now they account for the main part of the available friction force. These deformation losses are again a viscoelastic phenomenon with a well-defined temperature and speed dependence. It is described in more detail in the appendix.

a. Load Dependence

Hysteresis is dependent on load as long as load increase produces additional deformation.

b. Velocity

As experiments indicate (5) hysteresis losses continue to increase up to a much higher sliding speed as compared to adhesion forces. Even after reaching a maximum value, the friction of rubber does not show a pronounced tendency to decrease with further increasing sliding speed when sliding on a rough surface. On wet surfaces the friction force depends very much on the ability of the two contacting surfaces to eliminate the lubricant at least partially out of the contact area. Increasing speed makes it more and more difficult and supports the buildup of a hydrodynamic film pressure which is able to separate the two surfaces. All experimental data contains, in addition to hysteresis, some adhesion losses. It is not feasible to separate them completely.

c. Composition

The frictional properties of different rubber compositions have been studied under lubricated conditions on a variety of different textured surfaces (51). In these studies their hardness and resilience properties are used as their classification. The addition of carbon black to rubber as a solid filler reduced the hysteresis losses more severely than it did the adhesion losses (F).

IV. TIRE MECHANICS

Even with a well-developed knowledge about the frictional performance of the tread rubber, it has not been possible until now to predict the frictional behavior of a tire. The main reason is the difficulty of predicting the actual sliding speeds of the rubber elements in the tire footprint. The tire carcass is a complicated structure and deformation and stresses in the contact area are not easily analyzed and measured. The rubber elements in the contact area undergo multiaxial stress cycles. These are a direct consequence of rapid variations of the magnitude and direction of load and shear forces acting in the pavement surface plane. The rubber friction in the footprint, therefore, takes place under constantly varying conditions.

A. Empirical Mechanical Tire Properties

The different components of a tire, such as tread, sidewalls, cords, and carcass rubber, influence the drag forces of a tire. For a free-rolling tire these influences have been analyzed (14) and the correlation between the dynamic properties of the materials used in the tire and the drag of the tire, while varying a particular component, demonstrated the relationship between them. This data also shows that the different components do not influence each other and can be considered independently.

The relative importance of the tire components on the drag forces of the free-rolling tire are summarized in Table I.

Tire Component	Proportional to	Contribution to Drag in %
tread compression	G_1/G^{*2}	27
tread bending	G_1	28
carcass rubber	G_1	8
sidewall	G_1	2
cord system	$G_{1,cord}$	35

TABLE I

According to these findings the cord component accounts for the largest contribution to the drag force. The relative importance of tread compression and tread bending depends upon tire size. Even though these empirical results have been obtained at room temperature it can be concluded that these findings are general and apply also to tires running at other equilibrium temperatures. This holds, provided appropriate figures are used for the moduli of the components.

A fairly comprehensive analysis of the experimental data available until 1960, on most mechanical properties of pneumatic aircraft tires, was reported in Ref. L. For the various tire properties, such as vertical force deflection, lateral, fore-and-aft, and torsional stiffness, rolling radius, etc., semiempirical equations were reported. These take into account the major factors pertinent to these properties. Wherever possible the available experimental data was cited to establish the degree of reliability for the equations. The experimental data on which these equations are based were, however, obtained under static or slow speed rolling conditions.

The data available for high speed rolling has not revealed any drastic effect of speed on most tire properties. A need for further studies of the behavior of tires still exists for the complete range of high speed rolling conditions.

The introduction of the braced tread/flexible casing group of tires, usually called belted tires, brought some new aspects to the tire mechanics. This type of tire has basic deflection characteristics which differ considerably from those of the common biased ply tire. Under load the tread in the footprint of a conventional tire is strongly compressed (15) with attendant tread motion. In the belted tire the total tire circumference in the deflected tire is virtually unchanged as compared to the undeflected stage producing very little tread motion. The two tire types show distinct differences in their behavior on wet pavements (48). For example the belted tire under a known side force displays a smaller yaw angle and, therefore, shows improved steering response.

B. Theoretical Mechanical Tire Model

Measured against the state of the knowledge in related fields, the present survey of the literature available shows that tire mechanics still represents a rather poorly developed field of research. The main reason for this lack of knowledge seems to be the rather complicated structure of the tire. It is represented as a cord reinforced, highly elastic, or even viscoelastic, hull stiffened by an interior inflation pressure.

Clark (12) treats the tire as an elastically supported cylindrical shell and uses it as a basis for calculating load carrying and drag properties of a pneumatic tire. This allows the approximation of various tire parameters. Dodge (16) approximates the rolling tire through a rotating cylindrical shell under the action of a stationary point load. Then he proceeded to build a mechanical model which closely resembled his mathematical model for comparative experimental data. Even though a reasonable correlation exists between these two models they are still far from the simulation of a real pneumatic tire. So far work with these models has assumed that the shell (representing the carcass of the tire) was in contact with a frictionless plane. This is equivalent to using a tire without a tread against a pavement surface. The carcass itself bears against the surface. It has not been possible to introduce the tire tread into the mathematical tire model.

For aircraft tires this model has been improved (C) by treating the tire as a pressurized torus of circular cross section without any bending rigidity plus a string on an elastic foundation as "running band" of the tire. Simplified expressions are derived for three of the most commonly used force deflection characteristics (vertical load deflection, side load deflection, and torsional moment twisting) in terms of tire size and inflation pressure. The correlation of theoretical data with actual aircraft tire data is fair. Nevertheless, this model may be quite useful for preliminary design to optimize response under many different input conditions.

The fore-and-aft stiffness of pneumatic tires was modelled by an elastic bar supported by a foundation exhibiting elasticity in shear (17). A series of tires of various sizes and structures were used for testing the validity of this model. Additional structural data, required by the analytical solution of the model, were obtained from the tires. A comparison of calculated and experimental results was reasonably satisfactory, indicating that the proposed model can be used to roughly approximate fore-and-aft stiffness characteristics of a pneumatic tire.

A most comprehensive attempt to describe the mechanical properties of a tire from the point of view of elastic theory is given in Ref. E. In this study research on the stresses and deformations in the casing has been regarded as the primary problem of tire mechanics. Some existing problems were discussed and possible means of solution suggested. It stimulates interest in further developments by presenting methods which can be taken over from other fields. This paper, however, indicates quite clearly that we still lack a full understanding of the mechanical properties of pneumatic tires.

V. THE TIRE CONTACT AREA

The area where the tire touches the pavement is the only possible part for the transmission of forces between the vehicle and the ground. All loads have to be supported by this area. It is also here that all friction forces develop. A thorough understanding of the processes taking place in the footprint would, therefore, be essential for a better understanding of the tire performance. Because of the complex interrelationship of the different processes involved in the force transmission through the contact area, it is very difficult to investigate them as well as to separate their influences from each other.

Due to the fact that these processes are constantly changing, they are also difficult to analyze experimentally.

The ground pressure distribution within the footprint of a tire undergoing translation along the ground can be distorted by different ground-load conditions. This shifts the vertical load center of pressure of the tire either ahead or behind the wheel axle centerline. Tire fore-and-aft elastic effects displace the tire footprint in the direction of the applied ground forces and cause the vertical load center of pressure to move towards the rear of the footprint. Tire hysteresis, inertia, and hydrodynamic effects on the other hand distort the pressure distribution within the footprint in such a way that the vertical resultant of the pressure must move towards the front. For pure tire rolling on a dry pavement tire elastic effects are small whereas hysteresis and inertia effects predominate. This always moves the pressure resultant a small distance ahead of the axle centerline, thereby increasing this forward movement with increasing speed.

On wet pavements hydrodynamic effects tend to dominate more and more with increasing speed and water depth. They will have the same effect on the resultant force arising out of the contact pressure as the rolling resistance. During braking elastic effects predominate and move the pressure resultant force towards the rear of the footprint. These effects are superimposed on the aforementioned rolling effects.

Some light was thrown on the phenomena which take place in the contact area during rolling of two materials with different elastic constants, while transmitting tangential forces by experimental investigation reported in (61). A rubber and a steel cylinder were used for these studies. The results of these investigations indicate the existence of two major zones in the contact area, a locked region and a slip region. The latter region can be subdivided further into a slip development and a constant slip zone. In this respect, the action in the contact area of two rolling bodies with different elastic constants varies from that predicted analytically for two cylinders of the same elastic constant. The radial pressure distribution in the contact area is altered from that predicted by the Hertzian theory. It now depends upon the magnitude of the tangential forces transmitted between the two bodies. The tangential shear stress or traction distribution in the contact area indicates that the bulk of the tangential forces is transmitted through the slip region. Even though a direct comparison of this model with a full scale tire does not seem justified, it indicates qualitatively the processes in the footprint of a tire.

Using the mathematical tire models mentioned before (12, 16) and calculating the dynamic contact area under dynamic rolling conditions of the tire shows that this area is strongly influenced by rolling velocity, structural parameters of the tire and its loss characteristics. The absence of a tread in most analytical models used to approximate pneumatic tires (C, 12, 16, 17) gives no answer about the discontinuity of the shear forces at the forward and trailing edge of the footprint.

To identify these factors and others which make up and influence the total pressure distribution of a pneumatic tire some experiments on a mechanical model were conducted by Clark (13). These closely resembled the two-dimensional mathematical tire model used for calculations. By implication, the same factors which influence the pressure distribution in the fore-and-aft direction also cause variation of the pressure across the width of a real tire.

The inflation pressure is the main source of the pressure in the contact area and has a uniform effect throughout the footprint. The contact pressure is directly proportional to the inflation pressure. Bending of the tire carcass in the tread region introduces a parabolic pressure distribution component. It has its maximum at the center of the contact area and drops to zero at the footprint boundary. Concentrated forces appearing as sharp pressure peaks occur at the forward and aft end of the contact area. They are directly proportional to the bending stiffness of the carcass structure in the tread region and are associated with the so-called shear discontinuities of the carcass. The tread as outer covering of the tire and considerably softer than the carcass structure itself attenuates and diffuses these sharp pressure spikes.

Large tire deflection tends to cause some buckling of the carcass near the center of the contact area. This effect reduces the pressure near the center of the contact area and increases it at the edges. Through superposition of these single influences, the overall pressure distribution may be obtained.

VI. TIRE FRICTION

Although a great deal is known about tire behavior, the conditions in the contact area are so complex that it remains difficult to analytically describe the phenomena that occur when a tire is braking. If the aforementioned theoretical knowledge is applied to the tire only qualitative estimates can be made. It is still impossible to quantitatively predict actual tire braking performance or friction on grounds of the known properties of the tire components.

Although a large number of factors influence the friction coefficient of a tire, only a few have a first order effect on the magnitude of the friction developed (I, 25). These major factors are listed in Table II with the magnitude of their influence (36).

	Factor	Level of Variability Due to Factor Considered Up To
Tire	Tread pattern design	4 : 1
	Tread material	1.5 : 1
	Patterned vs. smooth tire	8 : 1
Pavement	Surface characteristics	5 : 1
	Water film depth 0.05 in. to 0.30 in.	3 : 1
Operating Condition	Speed reduction from 80 mph to 30 mph	10 : 1
	Nonlocking braking system vs. locked wheel condition	3 : 1

TABLE II

Factors Influencing Effective Braking Friction Between Tire and Wet Pavement (100 mph maximum)

When brake torque is applied to a rolling tire of a vehicle, the tire will slow down in its rotational speed while continuing its forward movement. Thereby some sliding speed is introduced to the rubber elements in the footprint. This sliding speed develops adhesional and hysteresis forces obeying the aforementioned laws of rubber friction. The friction forces create additional deformation in the contact area which in turn influences again the actual sliding speed and the magnitude of the developed friction forces. Due to different sliding speeds, local bearing pressures, and temperatures at different points of the contact area, the friction forces developed will vary with the location in the footprint. The friction force developed by the whole tire, therefore, will be the sum of these local forces over the whole contact area. This sliding of the contact area when superimposed upon rolling of a tire is usually expressed as percent slip. The slip describes the nominal sliding speed of the contact area of a tire in percent of the forward velocity. The actual sliding speed of the tread elements in the contact area deviates considerably from this nominal sliding speed due to the deformations involved.

The friction force of a tire and the coefficient of friction will increase with increasing sliding speed, and slip, as long as most of the rubber elements of the footprint are operating on the lower side of their adhesion peak. It will decrease with further increasing slip when this value has been exceeded (Fig. 5). The slip at which this friction maximum occurs is called critical slip and the coefficient of friction at this situation, brake slip coefficient. This relationship between slip and coefficient of friction varies with the combination of tire and pavement, the speed, temperature, the load, and the presence of a lubricant.

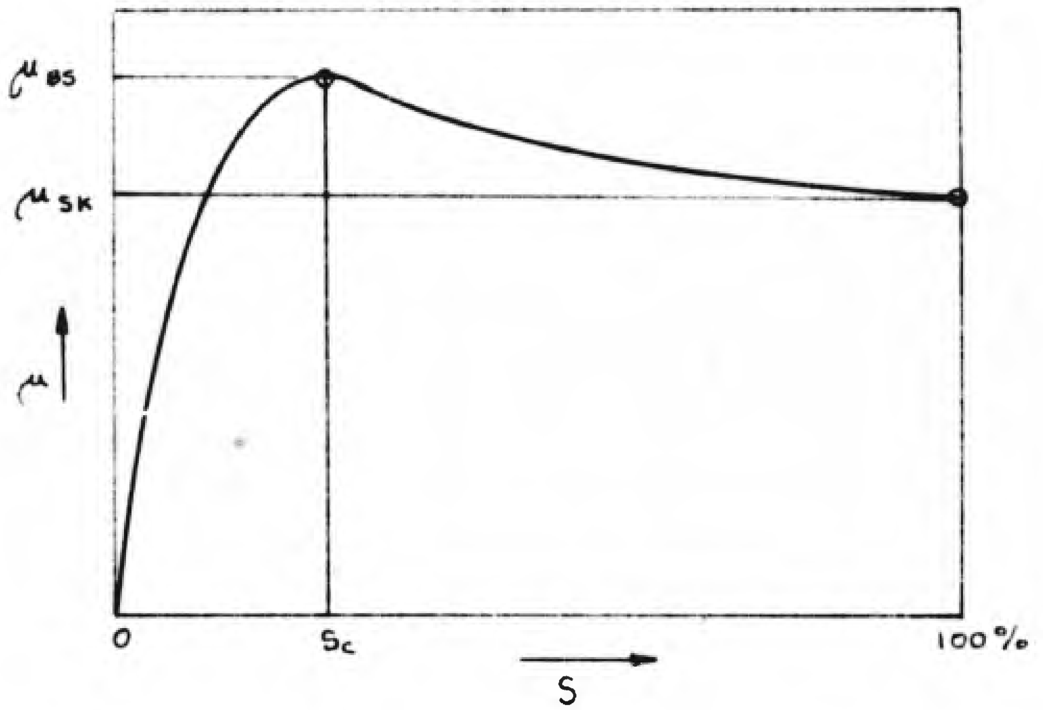

FIGURE 5

Friction Coefficient μ versus Slip S

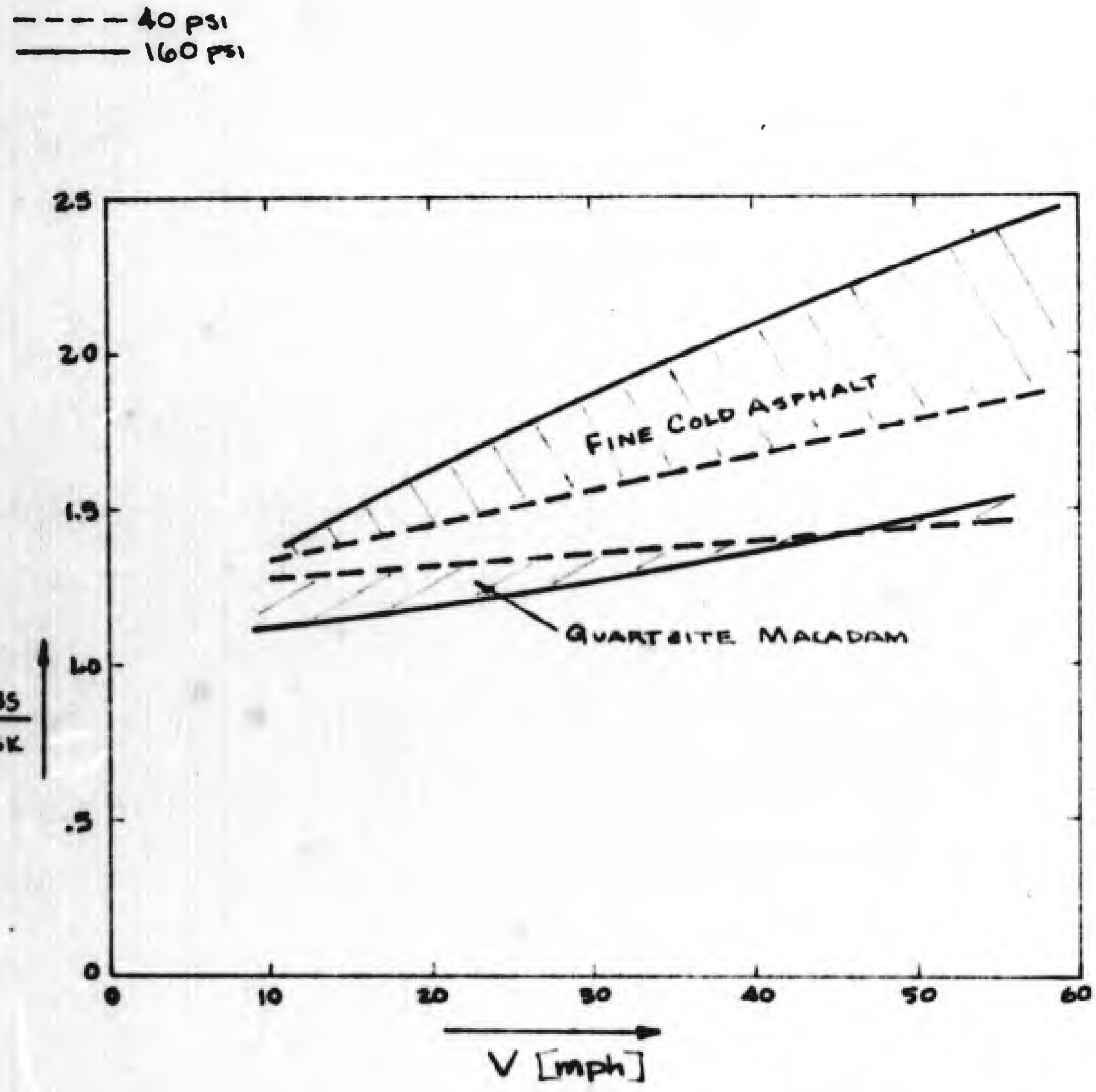

FIGURE 6.

CALC			REVISED	DATE	Ratio of Brake Slip Coefficient to Skidding Coefficient μ_{BS}/μ_{SK} versus Speed V on Two Wet Surfaces with Harsh Micro-texture	
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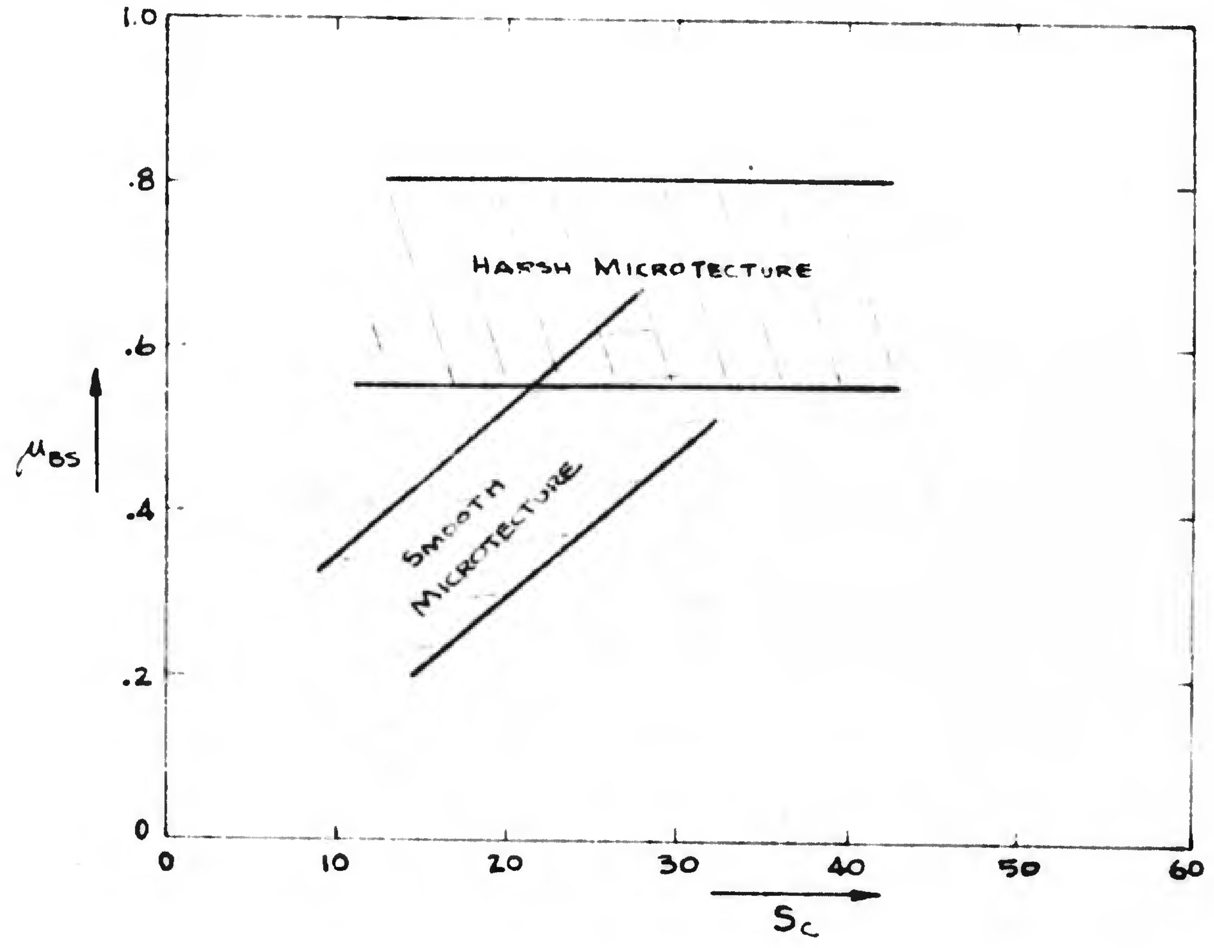

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Range of Brake Slip Coefficient μ_{BS} and Critical Slip S_c for Two Different Types of Pavement

While the brake slip coefficient is dominated by the adhesion between tread rubber and pavement surface, the skidding coefficient is more affected by the hysteresis properties of the rubber (I, 10). It is therefore clear that the ratio between brake slip coefficient and the skidding coefficient will change with operating conditions (Fig. 6). The value of the critical slip is also not fixed, however, insufficient data are available on this subject (Fig. 7). On the other hand, a large number of test data, regarding brake slip coefficient and skidding coefficient, exists for a wide range of tire and pavement combinations under different operating conditions (A, G, N, 47, 48). The general trend of the μ-slip curves with speed on surfaces with different characteristics is indicated in Fig. 13.

A. Tire Tread

The tire tread is the direct contact partner with the pavement. It is therefore understandable that through this tire component the frictional performance of the tire can be influenced.

1. Tread Design

The layout of the tire tread is one of the most effective features of the tire, in influencing its frictional performance on most common pavements under wet conditions (see Table II). The elements to achieve these improvements are the grooves and slots which effectively reduce the lubrication of the water by removing it out of the actual contact area. The effectiveness of a particular tread pattern varies from surface to surface depending upon texture.

On smooth, dry pavements the most effective tire is the one having the largest net contact area with the road, i.e., the completely smooth tire (G).

On pavements with coarse texture which possesses adequate drainage, a patterned tread offers no additional improvement even under wet conditions (20) as long as the pavement is not flooded. Experimental investigations of the pure rolling resistance of a variety of aircraft tires (G) under dry and wet conditions showed that the drag is increasing with increasing velocity under all conditions. The brake slip coefficient was found to decrease with increasing velocity on contaminated runways. Under dry condition its value remained relatively unchanged throughout the whole speed range. The decreasing rate under wet conditions is a function of the pavement texture (46). The circumferential grooves developed the lowest decreasing rate of the brake slip coefficient with speed compared with smooth, dimpled and diamond-shaped tread patterns under wet conditions. Investigations on automotive tires also showed that under wet conditions the tread pattern has a dominant influence on tire performance at high speeds. Even the simplest tread gives considerable improvement at all speeds as compared with a smooth tire. The least reduction of the brake slip coefficient, with increasing speed, can be obtained with a tread pattern having a large number of narrow cuts or slots across its tread surface. Fabric reinforced rubber treads give about the same friction coefficient as the nonreinforced tread (G). At high speeds they tend even to develop slightly higher brake slip coefficients on wet concrete as compared to an all rubber tread.

a. Grooves

The circumferential grooves provide a venting to which the water at the interface of the tire and the pavement can be displaced by the pressure between them. Grooves can improve friction on wet surfaces, e.g., from 20 to 100 percent (64). Increasing the number of grooves by leaving the actual contact area constant also increases the overall friction performance of the tire under wet conditions (A, 45) (Fig. 8). Tread wear and reinforcement for high speed application, however, limit the number of grooves that can be incorporated in the tread. The improvement is less marked when grooves are too narrow (39). The groove depth has little effect on a plain rib design as long as the grooves are deep enough to carry away the water forced into them. Tread grooves are of course, only effective as long as they remain open under the influence of forces acting in the contact area. Blocklike tread elements are relatively free to move under these forces and this can result in a complete closure of the channels. The straight circumferential grooves are therefore best due to their high fore-and-aft stiffness.

b. Slots

Slots across the tire tread provide a wiping action over the wet pavement. On surfaces with extremely low friction this effect can improve the skid resistance up to 100 percent. For most pavements

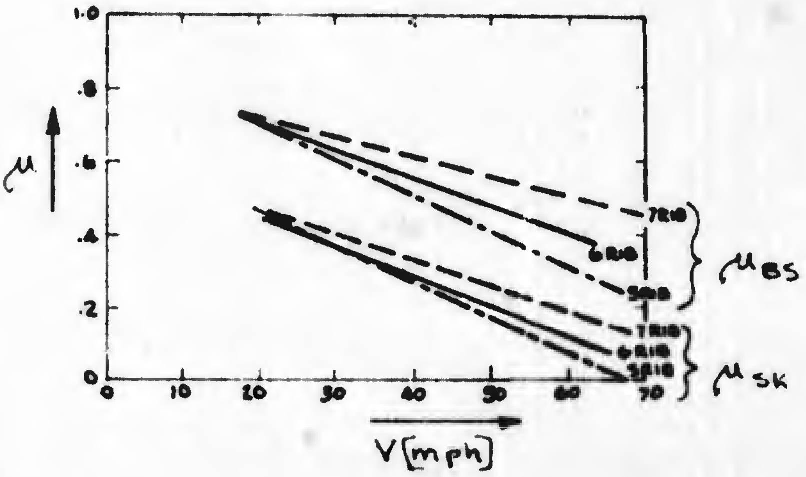

FIGURE 8. Brake Slip Coefficient μ_{BS} and Skidding Coefficient μ_{SK} for a Tire with 5, 6 and 7 Circumferential Ribs on Smooth Asphalt and a Water Depth of 0.05 to 0.10 in.

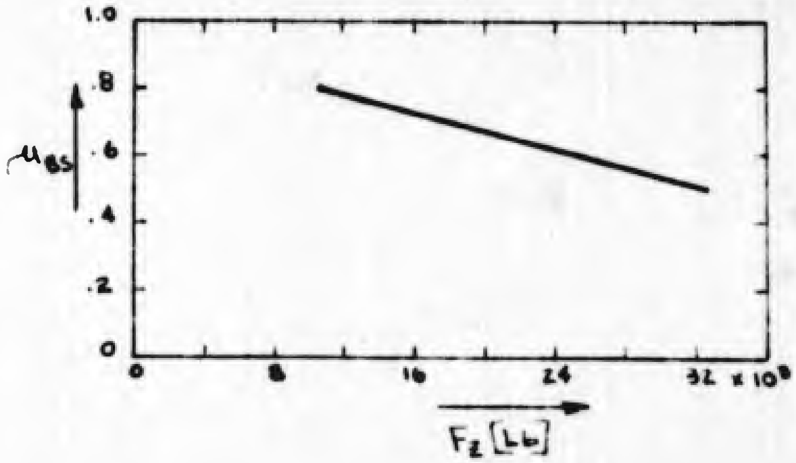

FIGURE 9. Brake Slip Coefficient μ_{BS} versus Vertical Load F_z at Speeds Between 100 and 120 mph

this improvement is 10 to 25 percent (64). Any degree of wear, however, causes a decrease in the effectiveness on wet pavements. This is especially true when the tread elements are worn in the "heel and toe" mode which favors the buildup of a water wedge.

2. Tread Rubber Composition

The basic tread rubber material and the additives, oil and carbon black, are the more important constituents. Their ratio determines the main properties of the rubber compound, dynamic modulus, and damping factor. These are mainly responsible for friction under wet conditions. Finer details in the composition of the tread rubber, like the nature of the carbon black filler, the methods of vulcanization or other compounding parameters have small effects on wet tire friction (10). Tire friction depends much more on a number of other factors, in particular the nature of the opposing surface, the lubricant, and the load, than it does on rubber composition (A) (see Table II). Nevertheless, the frictional performance of a tire can be improved through proper compounding of the tread rubber (9). Some further thought has to be given to the fact that high hysteresis rubber not only improves the skid resistance of a tire but also increases its rolling resistance and the heating of the tire through deformation.

B. Load and Inflation Pressure

Increasing the vertical load on the tire while keeping the inflation pressure constant usually decreases the coefficient of friction. This effect, however, depends to some degree on the tread design (G, 3) (Fig. 9).

Decreasing the inflation pressure under constant load increases the tire contact area and reduces the tire to ground bearing pressure. This results in a higher friction at low speeds and lower friction at high speeds on wet pavements. It indicates that at low speeds the adhesion is increased due to the increased contact area. At high speeds, however, the reduced ground bearing pressure is not able to displace the water out of the contact area and thus reduces the friction at high speeds (G, N). On dry pavement decreasing the ground bearing pressure increases the friction coefficient throughout the whole speed range (Fig. 10) (45).

C. Tire Temperature

Even though the temperature dependence of rubber friction is well understood, there still exists confusion about the influence of temperature on tire friction. This is mostly due to the fact that non-steady-state conditions exist in the footprint of the tire under all operating conditions. The friction force developed between tire and pavement surface is the sum of the friction forces of the single rubber elements of the contact area. These forces are created under varying ground bearing pressure, sliding speed, and temperature depending upon the location of the element in the footprint area. It can be concluded from the independence of the peak value of rubber friction upon temperature that the brake slip coefficient of a tire will also remain fairly temperature independent as long as the decomposition temperature of the tread rubber is not exceeded. But no actual experimental data exists on this problem. Temperature has been neglected in all investigations so far even when

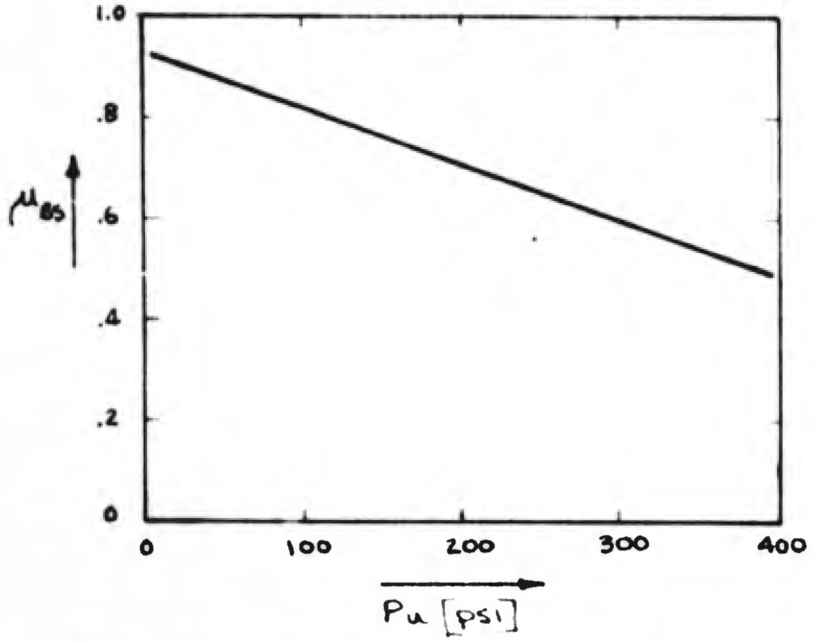

FIGURE 10. Effect of Ground Bearing Pressure P_n on Brake Slip Coefficient μ_{BS} on Dry Pavement

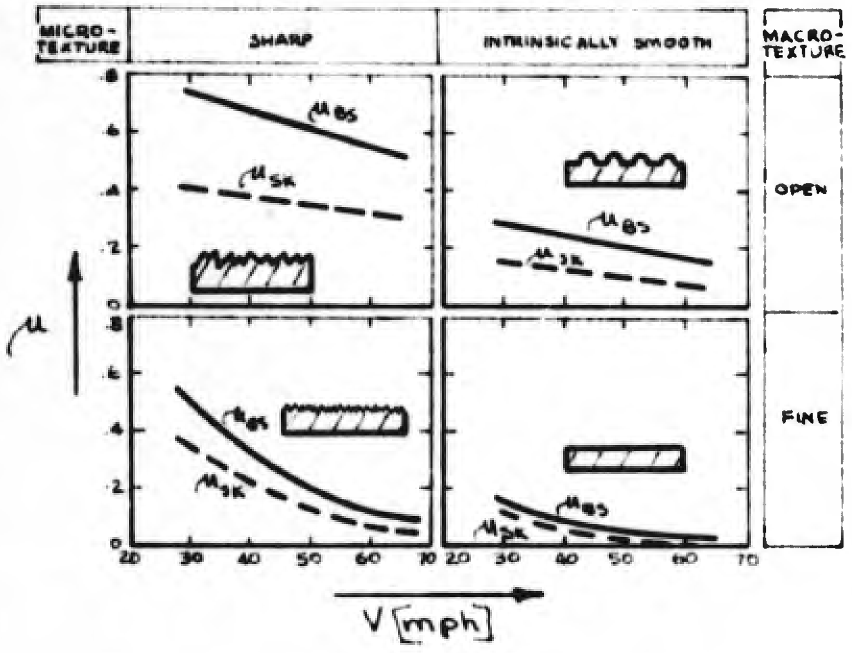

FIGURE 11. Brake Slip Coefficient μ_{BS} and Skidding Coefficient μ_{SK} of a smooth tire on four Characteristic Wet Pavements

people are aware of the large dependence of rubber friction on temperature. This is probably a direct result of the difficulties involved in measuring actual tire temperatures.

Nevertheless, a practical technique for continuously monitoring the internal shoulder temperatures of a tire during operation under speeds up to 80 mph has been developed ([illegible]). A systematic characterization of the effects of load, inflation pressure, speed, and ambient temperature on tire running temperatures for different tread rubber composition has been demonstrated. This investigation showed that the influence of the ambient temperature on the tire temperature is negligible compared with other parameter influences.

Under extreme operating conditions the tire temperature will rise locally up to the decomposition temperature of the tread rubber. This will result in a rapid decrease in the frictional performance of the tire. The temperature of the tire-pavement interface is limited by this decomposition temperature of the tread rubber because the rubber surface is cleaned continuously by the wiping effect of the pavement. On wet pavements, especially during skidding at very high speeds above 80 mph, "reverted rubber skidding" may occur (20). This effect yields a very low skidding coefficient. The rubber immediately below the sliding surface of the tire tread becomes heated above the decomposition temperature. This is probably the result of concentrated hysteresis losses in this zone with simultaneous cooling of the surface layer by the water present in the contact area. It leaves the actual surface layer of the tread rubber unchanged but partially torn away from the underlying rubber.

Tire temperature calculations have been attempted by use of the theory of heat conduction for various operating conditions (M). It was concluded that the tire temperature under normal operating conditions does not reach the decomposition temperature of the tread rubber.

D. Pavement

Any assessment of tire friction performance must be made with the full realization of the nature and magnitude of the pavement influences (Fig. 11). Pavement classifications as proposed in Refs. I and 25 usually distinguish between macrotexture (with asperity distances larger than 1/8") and microtexture (asperity distances smaller than 1/16"). While the macroroughness takes care of the bulk water removal and thus is a measure for the drainage characteristics of the pavement, the microroughness gives the surface a harsh, sandpaperlike feeling and contributes to the thin film penetration in the contact area. The importance of the pavement characteristics for the friction forces developed between tire and pavement, however, is still not fully appreciated today. The surface characteristics determine the coefficient of friction under both, dry and especially under wet, conditions to a much greater extent than any changes in the tire construction or tire tread and tread rubber composition (see Table II).

1. Texture

The texture is again more important for the brake slip coefficient than the material of which the pavement is composed. The texture should be such that it will break up any superimposed film, such as might be caused through the presence of water, oil, dust, detritus, etc., and thereby offer the maximum contact to the tire. A finer texture is more prone to polishing even when it develops a higher friction coefficient, when new, as compared with coarser textures (30). Smooth surfaces are particularly liable to be slippery when wet as their indentations can retain water and thereby assist in the maintenance of a fluid film between tire and pavement. Ultimately the performance of a surface under wet conditions is determined by its microroughness. If this is sharp and harsh a high braking friction will be obtained.

For spherical and conical asperities with various diameters and cone angles sliding on rubber the pressure distribution has been calculated and the developed friction forces measured (50). It was found that for an acceptable coefficient of pavement friction the tip angle of conical asperities should be less than 90 degrees. A small degree of polishing of the tips, however, does not cause appreciable loss of sliding resistance. At the same time these sharp surface asperities will also most likely tear the rubber (24) and increase tire wear.

A considerable part of the effect of pavement texture to increase the tire friction can be attributed to an increase in hysteresis losses (20). The importance of surface texture on actual tire friction may be seen in Fig. 12. Especially the macroroughness contributes to the increase of the hysteresis losses. The microroughness contributes more to the adhesion forces and makes the brake slip coefficient speed dependent

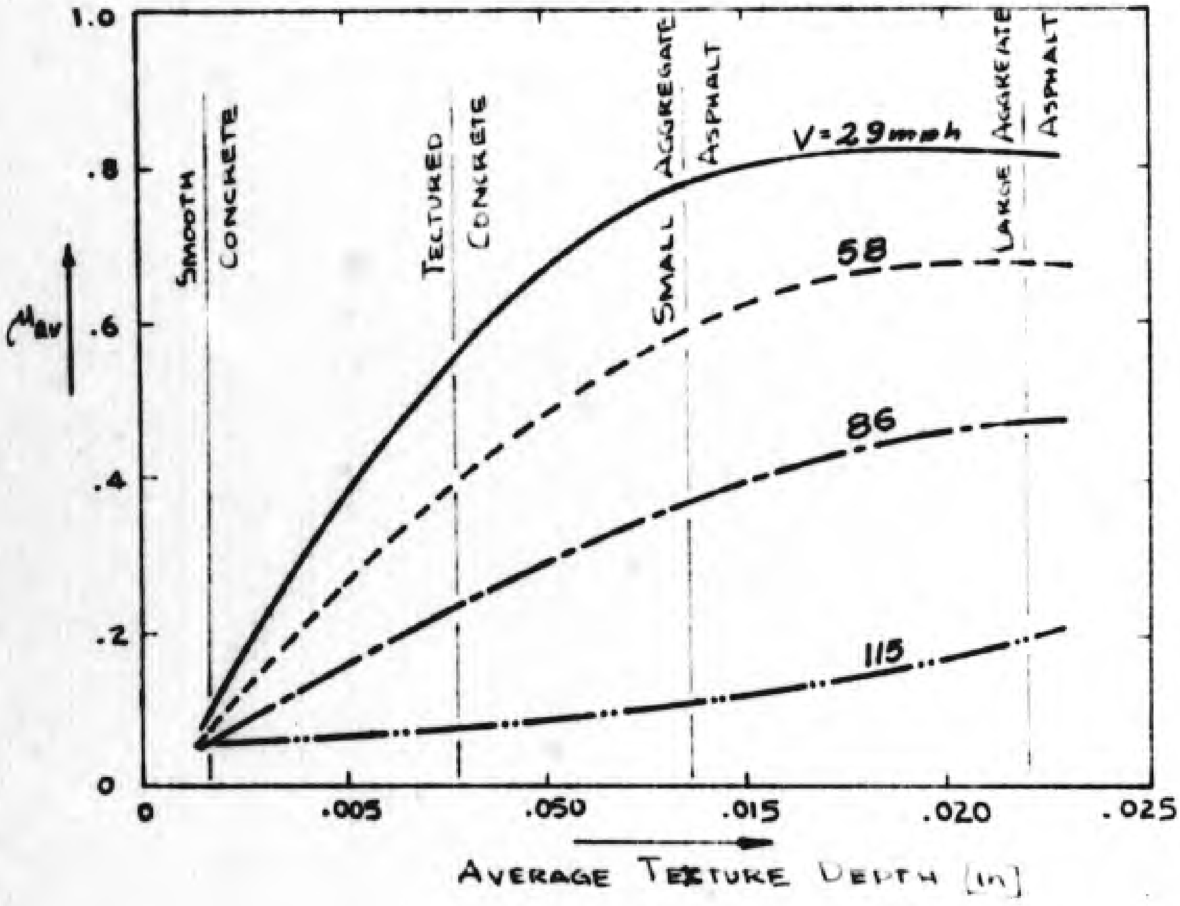

FIGURE 12

CALC			REVISED	DATE	Effect of Surface Texture on the Average Coefficient of Friction μ_{av} for Wet Pavement with 0.1 to 0.2 inches Water Depth	
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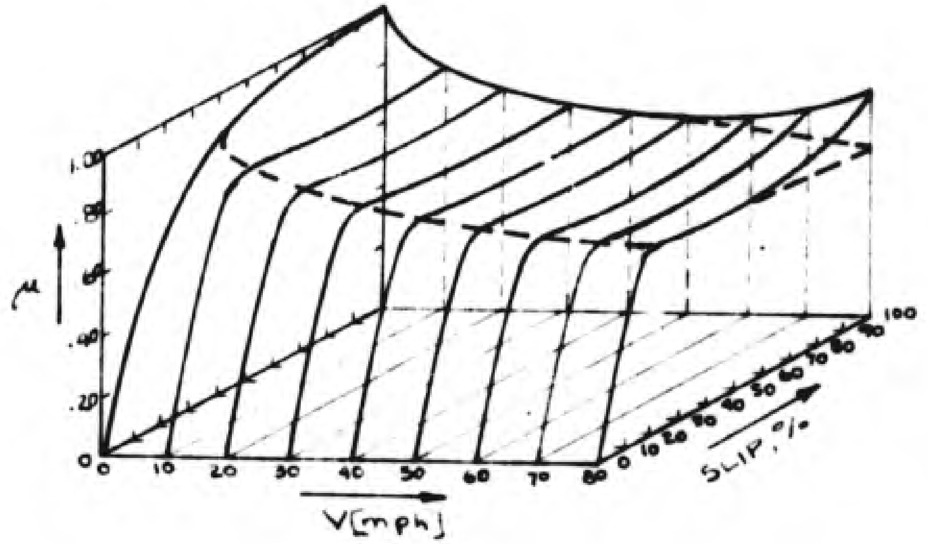
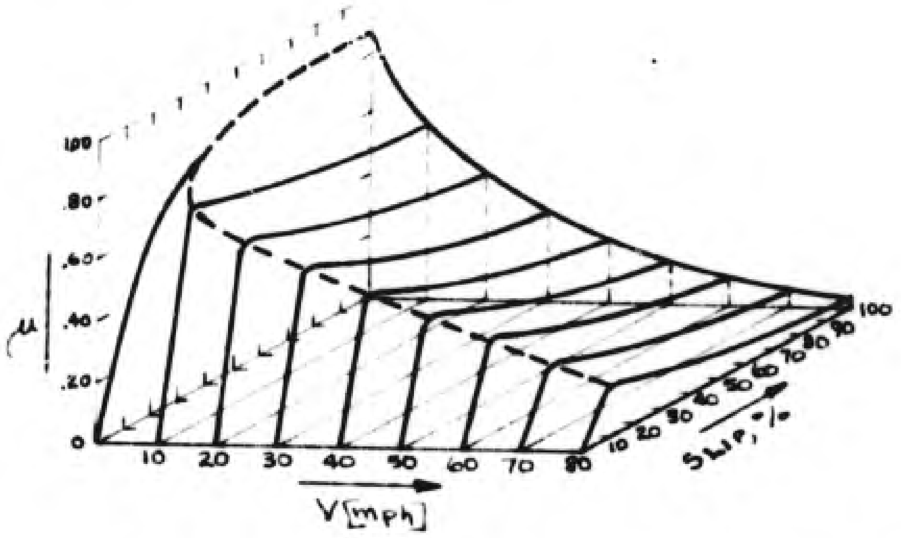


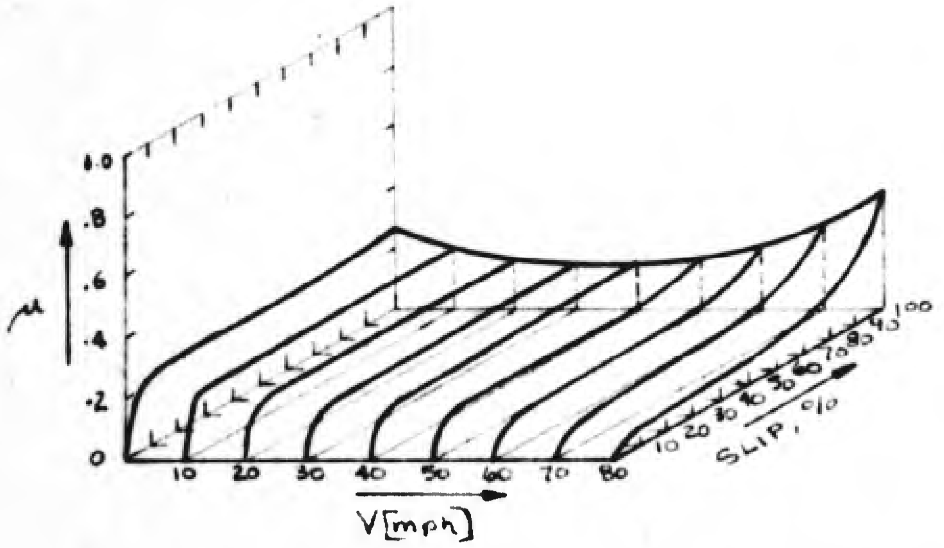
a. On a Dry Pavement



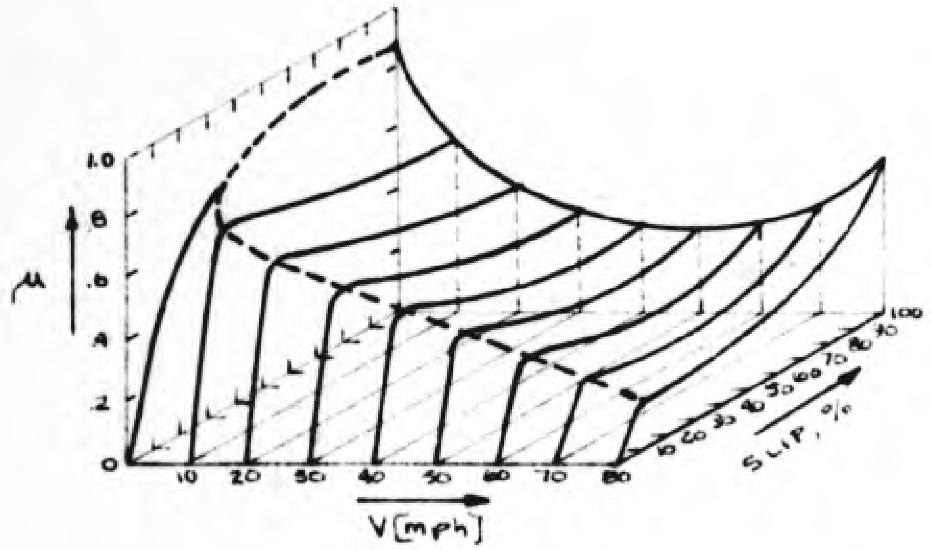
b. On a Wet Pavement of Fine Macrotexture and Sharp Microtexture

FIGURE 13

Tire Friction Coefficient μ
versus Slip S and Speed V



c. On a Wet Pavement with Open But Polishes Macrotexture



d. On a Wet Pavement with Sharp Microtexture and Open Macrotexture

FIGURE 13.

under wet conditions. At high speeds the actual contact area between the tire tread rubber and the pavement is smaller because not enough time is available for the bulk water removal. Therefore, the asperities cannot penetrate the thin water film and contribute to actual contact.

These effects explain the different μ-slip curves obtained under wet conditions on different types of pavements for various speeds (Figs. 13a, b, c, d).

2. Drainage Characteristics

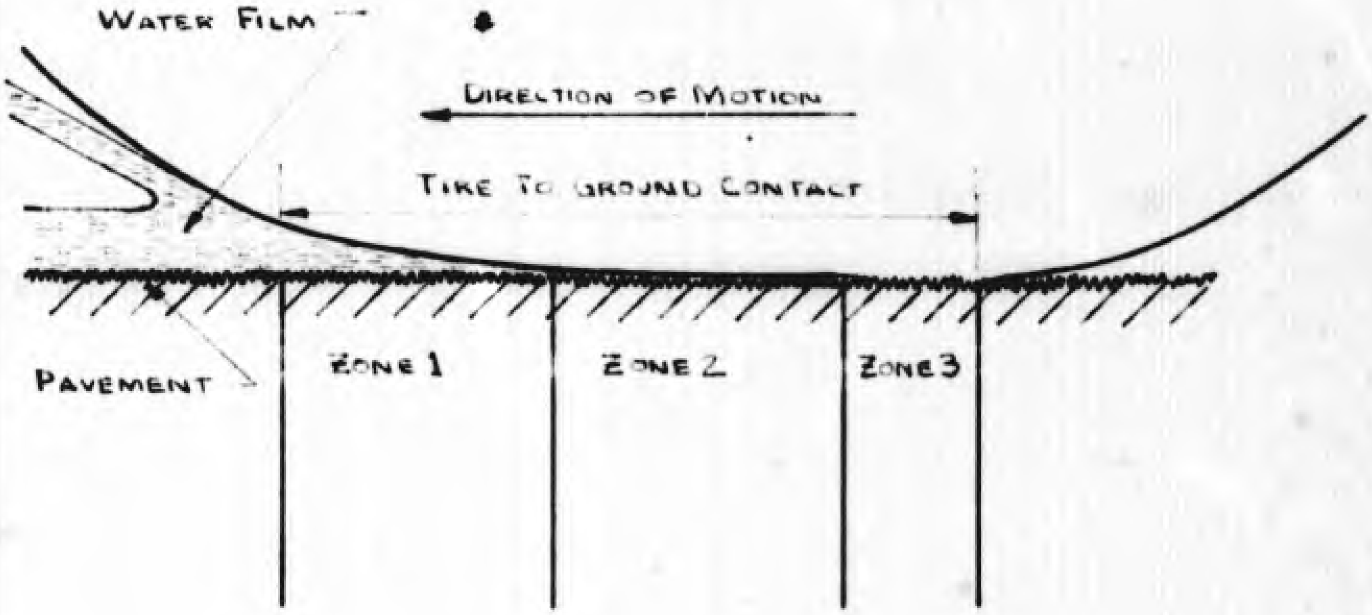
To enable the bulk water removal out of the contact area between the pavement and the tire tread, the pavement should possess enough drainage possibility. This should not only include lateral removal by pavement surface camber or cross cuts, but should also enable vertical escape of the water into the texture. Smooth surfaces which contain pits or shallow grooves are particularly liable to be slippery under wet conditions. The indentations retain the water and thereby assist in the maintenance of a fluid film in the contact area between tire and pavement. To improve the drainage on smooth pavements grooving may be used. In this process grooves of a certain geometry, e.g., 1/8 x 1/8" grooves or larger, one inch apart, are cut crosswise or lengthwise into the pavement. This method has been used sucessfully (31) on landing strips of airfields and on road sections known as slippery when wet. Tests indicate that grooving provides low pressure escape channels for the fluid trapped in the contact area and prevents hydrodynamic pressure buildup in the lubricant. The edges of these grooves tend to puncture the liquid film and improve adhesional contact. At the same time the grooves produce additional hysteresis losses by forcing the tire tread rubber to deflect into them. Measurements, however, indicate (40) higher tire wear on a grooved surface than on an open graded macadam surface of equivalent drainage characteristics.

3. Tire on Soft Soil

Not too much investigation has been conducted up to now about the tire performance on soft soil. Some low speed tests have been conducted by the Land Locomotive Service of the Army (4, 28) for off-road vehicles. No data could be found for high speed applications for landing or takeoff of aircrafts. Theoretical equations have been developed (H) by use of these above-mentioned low speed data for static and dynamic soil forces acting against a pneumatic tire. The results obtained from these equations correspond quite well with data obtained from actual aircraft flight tests.

E. Influence of Lubrication

Since many years it has been recognized that the presence of contaminants in the contact area between tire and pavement, such as water, slush, oil, detritus, ice or snow, deteriorates the frictional performance of the tire considerably. NASA (G, 33, 34, 35, 36) did considerable experimental research work at their Langley Aeronautical Laboratory to investigate the tire performance under adverse runway conditions.



Zone 1: Bulk Water Displacement

Zone 2: Thin Water Film Penetration by Pavement Surface Asperities

Zone 3: "Dry" Tire to Pavement Contact

FIGURE 14

			REVISED	DATE	The Contact Area of a Tire Under Wet Conditions	
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The level of friction between tire and pavement in the presence of a lubricant is primarily related to the ability of the tread design and the pavement texture to remove the lubricant from the gross contact area. In the case of water as a lubricant, the most common case, the contact area can be divided into three effective zones (A). Initially (Fig. 14) the bulk of the water film is displaced leaving a thin residual film to be penetrated at, or absorbed from, the interface before substantially dry contact can be established. The size of the area of dry contact at the rear end of the footprint has an overriding control on the level of the available friction and is dependent upon the time occupied in displacing the water film in the frontal zone. An increase in speed of the tire reduces the time available for water displacement and effectively shortens the area of actual ground contact. In the limiting condition the vertical load on the tire becomes entirely supported by the water film and the condition of hydroplaning occurs.

In this case tire to ground contact is lost completely losing directional stability and braking effectiveness. This effect has been considerably discussed recently (22, 29, 32, 33, 36, 37, 46) but it requires a special combination of circumstances which are not directly related to tire friction and will not be discussed here further. The best way to prevent hydroplaning is to provide sufficient water drainage off the pavement.

Understandably enough, the tread pattern and the surface texture exert a considerable influence upon the rate of water displacement from the contact area and hence upon the relative size of the water supported zone.

The forces developed in the dry zone at the rear of the footprint are dependent upon the frictional properties of the tread and pavement material. It has been demonstrated experimentally (34) that a very significant difference exists in the brake slip coefficients, developed by different tire treads on pavements covered with water and slush, at speeds up to 100 knots, and loads up to 10,000 lbs. Slush has a more severe influence on the tire friction because it can be deposited on a pavement in significant depth, whereas water usually drains off. In general, contamination of the contact area reduces both brake slip coefficient and skidding coefficient of tire friction and makes the first one speed dependent. With increasing speed, both values tend to decrease. The amount of this decrease will be, to a great extent, a question of tread design and pavement texture. It further depends on the amount of the contact area which can be kept active.

VII. CONCLUSIONS

The performance of a braking tire and the processes which take place in the contact area with the pavement surface are difficult to predict quantitatively. In the last years investigators have been able to separate some of the salient parameters involved and theoretically to explain their influences. Big progress has been made in the last decade in the understanding of rubber friction and its viscoelastic nature. Considerable work is necessary, however, before this present knowledge can be applied to predict tire friction based on the properties of the materials from which the tire is built. The main reason for this difficulty is the complexity of the structure of the tire. Until now it is neither possible to analyze the load pressure distribution, actual sliding speeds, and temperatures of the single tread elements during the contact period nor even to measure them with a certain amount of accuracy. Experiments seem still to be the best approach to special tire friction problems. A fundamental theoretical understanding, however, is essential to their useful interpretation. The dependence of the friction coefficient of a tire on the relative sliding speed between tire and pavement has been established by both theory and experiment. The influence of tire tread material, tread design, inflation pressure, load, and pavement characteristics has been investigated thoroughly under dry and wet conditions. The latter condition has become subject of rather extensive studies during the recent years. The tire temperature and its influence on tire friction, however, is still the least understood and major uncertain factor.

VIII. RECOMMENDATIONS

In order to develop a more complete understanding of the braking performance of a tire and to enable its prediction with a higher degree of accuracy additional investigations of certain parameters and their relation to braking performance are necessary:

1. High speed data of the properties of aircraft tires should be collected and cataloged, updating NASA Report R-64. Additional test data will be required to close the gaps between the data already available.

2. All research and development work on tires and their performance which is presently in progress elsewhere should be followed as closely as possible.

3. More accurate information is needed on the relationship between the coefficient of friction and tire slip and its dependence on temperature and other operating conditions.

4. Considerable effort should be spent to develop an analytical tire model which will allow a reliable prediction of the actual sliding speeds and pressure distribution in the footprint.

5. Tire temperature needs special consideration, as it is recognized, as a major factor in tire performance. Temperature measurements in the tire tread under actual operating conditions will be essential.

6. To provide the body of information as outlined above additional instrumentation will be needed on an actual airplane. The measurement of tire temperature, inflation pressure, and actual tire load would be necessary in addition to ground force, tire rotational speed, and forward velocity.

7. The relation between cornering forces and braking performance of an aircraft tire should be investigated further.

8. The development of a model law for aircraft tires would allow to compare data obtained with tires of different sizes and to conduct scaled-down model experiments. This not only would reduce testing expenses but would enable a much closer control of the various parameters. Full scale tests, however, would be necessary to establish the degree of reliability for the model data.

Unless these parameters are better understood, a breakthrough in the area of antiskid control concept would not be possible.

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APPENDIX

THE MECHANISM OF RUBBER FRICTION

The friction forces developed between rubber and a rigid material consist of two components: adhesional friction forces and hysteresis or deformation losses. Their relative importance upon the resulting friction force is strongly influenced by the operating conditions. Both components are not independent from each other and are therefore difficult to separate.

a. Empirical Investigations of Rubber Friction

The most complete investigation of rubber friction in an extended temperature-velocity range has been made by Grosch (F, 27). He employed two kinds of tracks, a gently undulated but optically smooth glass surface and silicon carbide paper of grade 180 under both clean conditions and when dusted with magnesia.

Some of the typical results obtained in this investigation are shown in Fig. 3. They indicate the coefficient of friction as a function of sliding speed for various temperatures on the two surfaces mentioned above (for an unfilled acrylonitrile butadiene rubber sample). If the rate-temperature shift function is applied to these data mastercurves may be obtained (Fig 4). This curve now describes the velocity function of the friction coefficient at a constant temperature over a large range of the velocity. A coherent picture of the functional relations thus emerges. Complete mastercurves could be obtained for most rubber materials except for natural rubber for

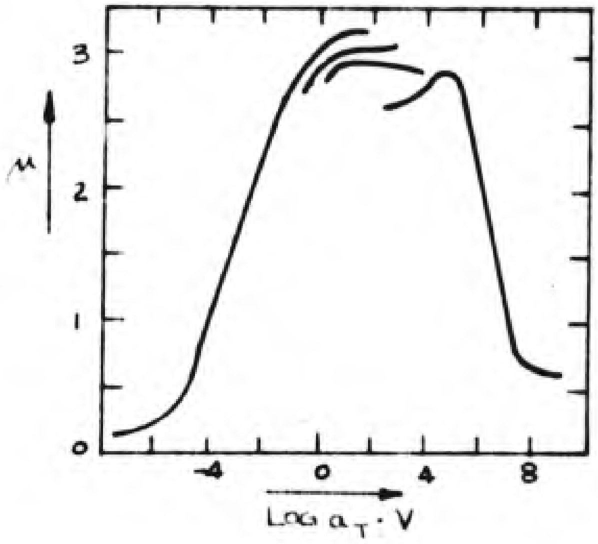

FIGURE A1: Master Curve of the Coefficient of Friction μ of Natural Rubber on Wavy Glass. T_0 = 20°C, V in cm/sec

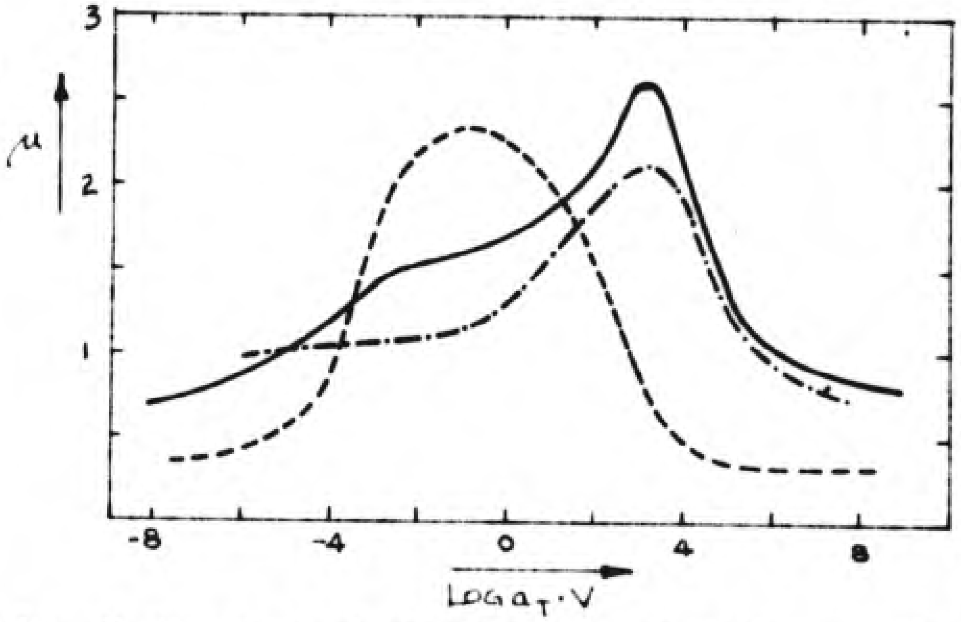

FIGURE A2: Master Curve of Coefficient of Friction μ of Acrylonitrile Butadiene Rubber on - - - Wavy Glass, ——— Clean and -·-·- Lubricated Silicon Carbide Paper. T_0 = 20°C, V in cm/sec which the friction coefficient on smooth surfaces does not yield a homogeneous curve in the velocity range right below the peak (Fig. A1). Some form of crystallization in this range is assumed to be the reason because deformation losses are not affected.

The possibility to transform the measured friction data for all materials investigated into one mastercurve is the strongest possible evidence that rubber friction is a viscoelastic phenomenon. If a mastercurve is plotted for each of the data obtained on glass and silicon carbide paper the peak value for the silicon carbide data occurs at a higher speed (Fig. A2). At the same time the mastercurve for the rough surface is of an asymmetrical shape with an additional hump at a speed which coincides with the friction maximum of the mastercurve for the smooth surface. This hump vanishes if the rough track is dusted with magnesia.

These results have been explained by the existence of two friction mechanisms. One is the molecular adhesion which is the only type of friction acting on smooth surfaces. The second one is the mechanical energy loss due to gross deformation of the rubber surface by the track asperities. This is the main source of friction on a coarse textured, well-lubricated surface. Both forms of friction however are not independent of each other and therefore very difficult to separate. If the frequencies at which the loss modulus and the loss tangent have their respective maxima, at the same reference temperature, are correlated with the speeds at which the friction coefficients have their maxima, it can be found that the

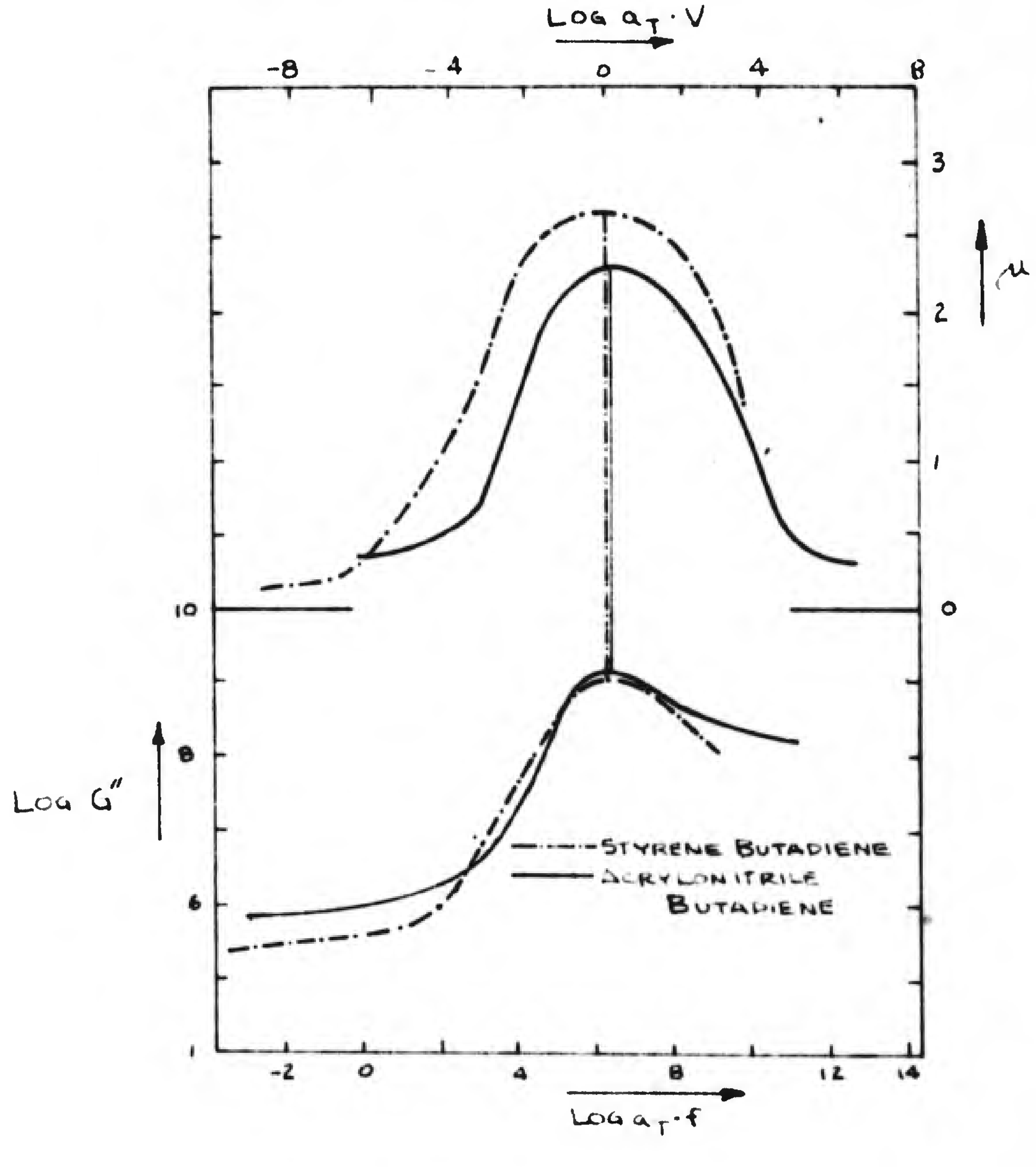

FIGURE A3

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Master Curves of Friction Coefficient
μ versus Sliding Speed V and Loss
Modulus G″ versus Frequency f for the
Respective Reference Temperture T_s

THE BOEING COMPANY
RENTON, WASHINGTON

velocities of maximum friction on smooth surfaces agree well with the frequency of the loss modulus maximum when a wavelength of $\lambda = 6 \times 10^{-7}$ cm is assumed. The frictional sliding may be conceived as a molecular activation process (1, 55, 58) which releases adhesional bonds between rubber and track surface, with an average frequency f_1 and jumping a certain distance λ. The experimental evidence indicates that the values of λ have molecular dimensions which agree with this interpretation (Fig. A3). On rough well-lubricated surfaces the speed at which a friction maximum is reached correlates with the frequency at which the dynamic loss tangent has its maximum. The proportionality factor λ assumes different values for different surfaces. For example the experimental data on silicon carbide paper dusted with magnesia show that $\lambda = 1.5 \times 10^{-2}$ cm. This factor is clearly related to the geometry of the used surface. A 180 mesh abrasive paper has an average asperity spacing of 1.4×10^{-2} cm. Additional investigations (T) extended the data range obtained by Grosch (F) to very low sliding speeds and a wider temperature range. It not only showed a close agreement with Grosch's data but also manifested again the close relationship between friction at various sliding speeds, temperatures, and the viscoelastic properties of the rubber.

b. Rubber Friction Theories

Based on aforementioned findings, several theories of rubber friction have been developed. They all agree to the point that there are two components of the friction forces developed between rubber and a rigid surface - namely adhesion forces and deformation or hysteresis losses. They only differ from each other in the way they explain the adhesion term.

(1) Theory of Adhesion

The adhesion or external friction term includes those frictional forces which result from the work necessary to separate adhered portions of contacting surfaces. For rubberlike materials these forces are associated with the formation of molecular secondary bonds (6). The rupture of these bonds does not necessarily produce abrasion. In the theory adhesion of rubber is regarded as a molecular-kinetic process (1, 55, 57, 58) caused by thermal motion of the molecular chains against a contacting surface. Schallamach (K, 58) considers making and breaking of these bonds as separately activated processes. A newly formed bond does not have to sustain a force which develops only as the bond and the surrounding rubber are deformed by relative motion of the rubbing members. The bond breaks after a certain average lifetime and the same site on the rubber surface forms a new bond after some average time lag τ.

The frictional force is directly proportional to the number of bonds with the solid surface. This theory however, fails qualitatively by predicting vanishing friction at very low and very high sliding speeds.

Bartenev (1) regards the adhesion forces between rubber and a hard substance to be of the Van der Waal* type. In this theory a molecular-kinetic activation process which is governed by the structure of the rubber is considered compatible with the observation that low velocity creep occurs before the peak frictional force is developed (21). This theory holds that a molecular chain is in contact with the opposing surface for a limited time, then moves to a new contact point or into the body of the rubber with a different chain making contact. Under the action of the tangential forces the movement is disturbed from that of equal probability in any direction. The mean speed of the displacement of the chains is taken as the sliding speed. A layer of lubricant between the two sliding surfaces suppresses bond building and reduces the adhesional friction force considerably. Savkoor (53) does not consider thermal activation responsible for breaking of bonds between the two surfaces but applies a

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* Van der Waal forces are interatomic or intermolecular forces of attraction due to the interaction between fluctuating dipole moments. These dipoles result from momentary dissymmetry in the positive and negative charges of the molecule and a neighboring molecule. These dipoles tend to align in antiparallel direction and thus result in a net attractive force. This force varies inversely as the seventh power of the distance between ions.

macroscopic energy model. The total friction force is equally borne by identical asperities on the rubber surface. Each asperity when becoming bonded to the track takes up its full share of normal load and friction force. Furthermore, each asperity creeps both in compression and shear. The stored energy of the asperities increases with time and the bond breaks when the stored energy equals the adhesion energy of the bond. The adhesion energy originates from the Van der Waal forces. After the asperity has broken loose from the track it immediately forms a new bond.

In Rieger's theory (49) the track carries on its surface a sinusoidally distributed force field attracting cross links of the rubber which are connected to the bulk by springs. Depending on their position in this field they are deflected as a whole segment backward or forward. As the rubber segment moves forward an unstable state is reached. The segment jumps forward instantaneously by a finite amount. If the spring is considered viscoelastic with a force constant depending on sliding speed then transition between two stable positions of the segment is retarded by the viscous component.

Kummer (I, 44) explains frictional adhesion as electrostatic attraction between rubber and track. The track is assumed to carry regularly spaced surface charges which interact with similar charges in the rubber surface. This theory treats both forms of rubber friction in a unified manner by expressing the strength of the adhesional bonds in terms of an "electric roughness" and by relating the dissipated energies of the hysteresis term to the elastic and loss modulus of the rubber. The pronounced dependence of both forms of friction on sliding speed and temperature can be explained by a likewise pronounced frequency and temperature dependence of the two moduli. This unified theory of rubber friction suggests that in principle, adhesion and hysteresis mechanisms are very much alike.

(2) Theory of Hysteresis

The friction forces of rubber which are based on the deformation of the rubber bulk may be divided into three categories:

1. Elastic hysteresis in deformed rubber
2. Energy of tearing or cutting of rubber by track asperities
3. Energy of nonrecoverable deformations

When rubber slides or rolls on a hard, textured surface a certain amount of energy is necessary to deform the rubber approaching the front of an asperity and elastic work is recovered from the rubber leaving the rear of the asperity. Since rubber shows a finite hysteresis some energy is lost. In rolling this is the primary source of frictional work (18, 62). In sliding it is in addition to any shearing work involved (23, 24).

The hysteresis loss is caused by the periodic agitation of the rubber chains (I, 43) by the geometric roughness of the rigid track. Therefore, the corresponding energy is dissipated in the bulk of the rubber when the rubber is "flowing" over and around the asperities. The damping possessed by the rubber opposes the displacement of the rubber as well as its recovery. It is, however, difficult if not impossible, to separate hysteresis completely from adhesion. This is because adhesion will always produce additional deformation. Addition of a lubricating film between rubber and an opposing surface reduces adhesion considerably and makes the deformation losses predominant (23, 24).

REVISIONS

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