The Logical Design of Optimum Skid-Resistant Surfaces

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A logical sequence is suggested for the design of optimum skid-resistant pavements. The mean wavelength and slope of the texture may be determined from drainage requirements at the average maximum speed for the section of pavement under consideration, and the values may be checked by the demands of the hysteresis contribution to friction in the skidding mode. For surfaces where the asperities are rounded by wear and the demands of traffic, it is necessary to provide a micro-roughness at asperity peaks to establish adhesion between tire and road in wet rolling. The amplitude of the micro-roughness must be greater than the elastohydrodynamic water-film thickness which would otherwise exist at asperity tips due to relative slip between tread and road in driving or braked rolling, whereas the adequacy of its sharpness is indicated qualitatively by "feel." It is estimated that for practical road surfaces the wavelength lies in the range 3 to 20 mm, and the micro-roughness has an order to magnitude of at least 10 to 100 microns.

•IT IS a well-known fact that the coefficient of sliding friction on a wet road surface decreases with increase of speed (1), and that the rate of decay is a function primarily of drainage ability. Thus, coarser surfaces having inherently greater void volume between individual asperities (and hence greater drainage capacity) exhibit a lesser rate of decay than finer surfaces. The fallacy of attempting to characterize the skid resistance of a particular pavement by establishing one friction value at the speed of testing is at once obvious. Two pavements (one fine and one coarse) may have the same coefficient of sliding friction at a particular sliding speed, but since the slopes of the coefficient of friction vs velocity curves are entirely different, the finer texture is superior at speeds below the test speed and the coarser texture is superior at speeds exceeding the latter.

The situation is not serious if the test speed corresponds either to the speed limit of the particular pavement section, or to the average maximum speed (in cases where no speed limits are posted), since the pavement is then rated at its worst friction value. However, if the test speed is considerably less than the speed limit (or average maximum speed) as shown in Figure 1, it is clear that the measurement of friction values at one speed is not sufficient. Either one or more additional speeds (clearly different from the original test speed) must be selected at which to measure skid resistance, or otherwise the gradient of the friction vs velocity curve for that pavement must be established from drainage considerations. The latter information combined with the measurement of skid resistance at one sliding speed is sufficient to determine frictional performance over a range of speeds.

OPTIMUM SURFACE TEXTURE

The mean wavelength and slope of the individual asperities of the road profile can be shown to give a maximum hysteresis contribution to friction at a particular sliding speed (2). For typical road surfaces and rubber materials, this speed normally ex-

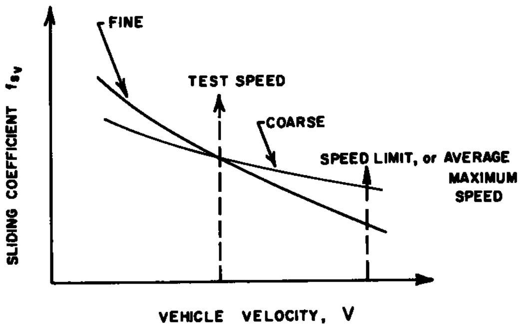

Figure 1. Friction/velocity curves on fine and coarse surfaces.

ceeds the average maximum speed (even in Europe). It is also necessary that the mean wavelength provides asperities which are sufficiently large to insure adequate drainage of water into the neighboring voids (3) at some typical maximum speed. In practice, the mean wavelength selected may be a compromise between drainage considerations (which suggest a lower size limit) and hysteresis requirements (which indicate an upper limit) at the speed limit or average maximum speed for the pavement under consideration. However, since the hysteresis requirement pertains to the sliding mode alone and drainage considerations apply to both rolling and sliding, it is certain that the drainage criterion predominates in the final selection of wavelength.

The adhesion contribution to friction can be maximized by providing in addition a sufficiently sharp texture. Figure 2a shows one form of an idealized random road surface, where the individual asperities are pointed to provide sufficiently high localized pressures between tread and surface, which will break through water films entrained by elastohydrodynamic action (4) as the wetted rubber slips over the road asperities. Sandpaper surfaces largely exhibit this profile, although the scale of the wavelength is much too small to match the hysteresis/drainage requirements of road surfaces.

Actual road surfaces have profiles more in accordance with that shown in Figure 2b. Here again, the hysteresis and drainage conditions may be satisfied by choosing the wavelength in accordance with a maximum design skid-speed, but it is clear that since the asperity tips are predominantly rounded rather than pointed, it will be necessary to carefully select an adequate micro-roughness at asperity peaks to eliminate skidding according to a method previously outlined (5).

The selection of optimum surface texture follows a rational procedure which is depicted in Figure 3. The mean wavelength and slope are dictated by hysteresis/drainage factors, whereas the micro-roughness is selected to insure the existence of an adhesional mechanism at asperity peaks in defiance of water-film entrainment. The various factors involved are grouped for convenience in the following categories:

1. Driving conditions (forward speed, rolling/sliding, nominal slip and wet/dry);
2. Tire properties (viscoelasticity, tread design);
3. Interaction events (hysteresis, drainage, elastohydrodynamic factors, hydroplaning); and
4. Pavement geometry (wavelength/mean slope, micro-roughness).

ELASTOHYDRODYNAMIC CONSIDERATIONS

Perhaps the most significant interaction event occurring when a pneumatic tire rolls with brake or drive slip on a wet road surface, is the generation of hydrodynamic

(a) ONE FORM OF IDEALIZED RANDOM ROAD SURFACE (SANDPAPER)

(b) TYPICAL ROAD SURFACE PROFILE WITH MICRO-ROUGHNESS

Figure 2. Idealized and typical road surfaces.

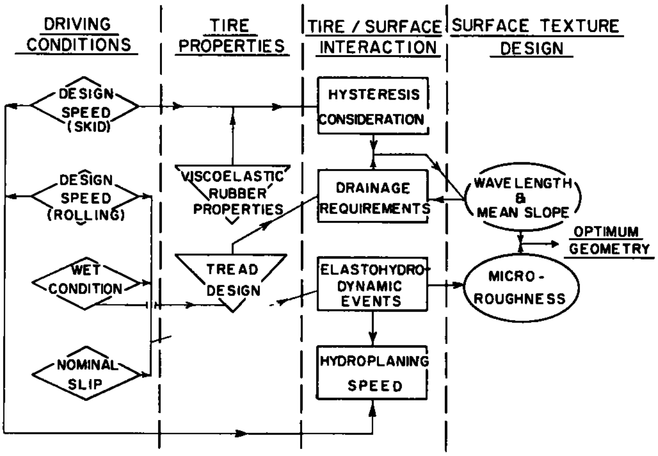

Figure 3. Sequence of events in selecting optimum surface geometry.

pressure wedges on the leading edges of road asperities, as a result of relative slip between tire and road in the contact patch. The degree to which the rubber is deformed outward from the road profile by such pressure generation is determined by tread viscoelasticity and inflation pressure (4, 5), and there must be a compatibility between the hydrodynamic and viscoelastic pressure distributions (Fig. 4). The resulting elastohydrodynamic or viscoelastohydrodynamic pressure acting at asperity tips in the road profile can then be used to determine the minimum film thickness from lubrication theory, and the amplitude of the minimum micro-roughness ϵ_{MR} required at asperity tips to eliminate or counteract this effect is thereby prescribed. Figure 5 shows part of the rear of the contact area in wet rolling at any instant, where the generation of hydrodynamic pressures on individual asperities of the road surface attempts to entrain water over the tips of the latter and thereby to separate tread and road locally.

In theory, however, not all road surfaces require the existence of a micro-roughness (Fig. 6). Let it be assumed that the wavelength λ has been selected previously by hysteresis/drainage requirements, but that the mean slope is variable within prescribed limits. It is also stipulated that increasing slope and sharpness are related in some manner. The peak pressure on any asperity increases rapidly and nonlinearly with mean slope to a critical value at the point C, but the elastohydrodynamic pressure distribution can be sustained only in the region A to C. As the sharpness increases be-

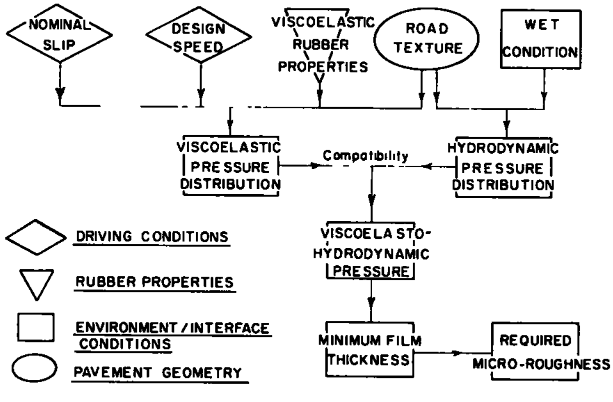

Figure 4. Selection of an optimum micro-roughness for a given pavement.

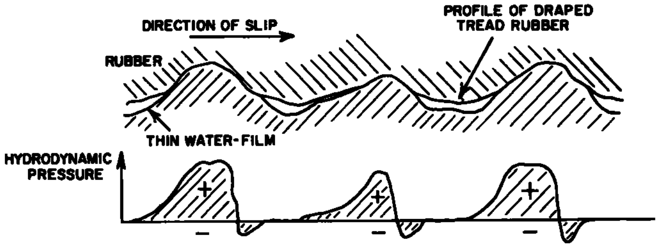

Figure 5. Generation of hydrodynamic pressures on individual asperities of wet road.

yond the value at C, the corresponding elastic pressure is too great to permit the existence of a water film at asperity tips, and thus the hydrodynamic pressure component has zero value along DE. The elastic or viscoelastic pressure distribution continues to increase indefinitely along CB.

It is apparent that in the region C to B no micro-roughness is required to counteract water-film entrainment, since none exists in this range. This type of surface is similar to the sandpaper profile depicted in Figure 2a, although the wavelength would, of course, be greater. For very small slopes, there will be inadequate drainage in the range A to F. The design limits for the selection of micro-roughness are therefore clearly specified by C and F (F^1) as indicated in Figure 6. The extent of the range CF^1 remains to be determined from further research, but it is certain (4, 5) that λ has an order of magnitude of 3 to 10 mm and ϵ_{MR} ranges from 10 to 100 μ.

FLOODED AND DAMP CONDITIONS

In flooded conditions, the tread grooving of the tire and the mean void width of the pavement must be capable of discharging an adequate amount of water from the contact patch at the average maximum speed for that particular road section. Other investigators (2) have shown that when a rolling tire is braked on a flooded road surface, the available coefficient of friction falls off much more rapidly with increase of speed beyond the design limit for that pavement (Fig. 6). Furthermore, as the design limit is increased (by appropriately increasing the wavelength and drainage capacity of pavements), there is a loss of braking capacity at speeds below the average maximum speed or design limit. Thus, it is clear (Fig. 6) that pavement B is designed for a higher speed range than A, but the performance of B is inferior to that of A below the

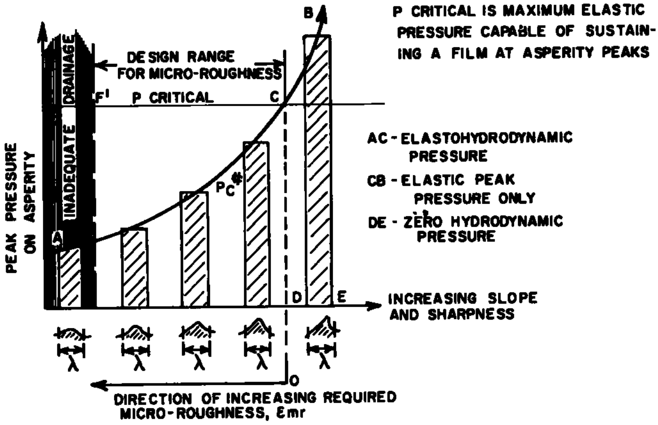

Figure 6. Micro-roughness requirements for different asperity shapes.

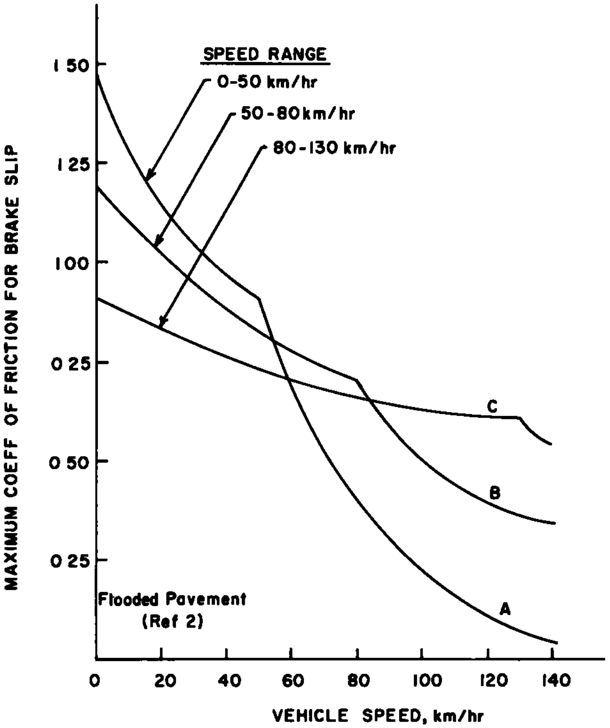

Figure 7. Optimum surface roughness for flooded pavements (2).

design speed limit of the former. A similar argument applies to surface C, when compared with either A or B. In practice, it is desirable to have as constant a friction coefficient as possible over the design range of speeds for any pavement. Thus, the size of wavelength which has already been tentatively selected as a compromise between hysteresis and drainage considerations must lie between a minimum value (determined from the requirement that the transition point, which is apparent in Figure 7, lies outside the speed range) and a maximum suggested by the sacrifice in braking ability at lower speeds within that range.

An interesting application of these principles is the optimum design of runway surface texture. If it be assumed that aircraft may land in either direction on a particular runway, then it is clear that maximum rolling velocities (equivalent to touchdown speed) occur at either end of the landing strip. Now the deformation frequency upon which the hysteresis contribution to friction depends is given by the ratio of forward speed to pavement wavelength. It is therefore apparent that the wavelength selected to maximize skidding friction is greatest at touchdown (or take-off) speeds, which corresponds to the ends of the runway. This criterion also satisfies drainage requirements. As the aircraft speed is reduced after initial touchdown, the wavelength of the texture will decrease gradually towards the center of the runway length. The optimum surface texture will therefore exhibit a decreasing wavelength as the center of the runway is approached from either end. The question arises: Why not preserve the same texture which is presumed adequate for touchdown speeds, since drainage requirements are more than satisfied at all lesser speeds? However, Figure 7 shows that unless the wavelength matches speeds at all sections, there may be a loss in braking effectiveness on flooded landing strips. This, of course, would increase the length of runway required for safe braking under wet conditions.

With damp pavements, the phenomenon of viscous hydroplaning (4) may occur. This is due to the entrainment of a very thin water film over asperity tips in the road texture, as a result of localized slip between tread rubber and road surface in rolling. Whereas the mean wavelength and slope of texture is designed for the flooded condition from hysteresis/drainage requirements, the criterion for the selection of an adequate micro-roughness at asperity peaks is the effective counteraction of elastohydrodynamic film entrainment under damp or thin film conditions. The micro-roughness permits effective adhesion to take place between rubber and surface even in the presence of thin films.

Although the flooded condition is relatively rare on roads and runways, the damp or thin-film situation occurs whenever there is any precipitation whatsoever or even a high humidity. Furthermore, the viscous hydroplaning phenomenon occurs at the rear of the contact patch in wet rolling, when the front part experiences dynamic hydroplaning under flooded conditions. The adhesion-generating mechanism is therefore the principal contributor (4) to braking effectiveness in wet rolling, irrespective of the degree of precipitation or film-thickness.

The gross relative slipping velocity between tire and surface in the rear of the contact patch for wet rolling necessitates the existence of micro-roughness at asperity peaks to maintain effective adhesion and oppose the lubricating effect. At the same time, the rubber elements in the front of the contact patch (for thin-film conditions) have virtually no longitudinal motion relative to the road surface. Here, the sharpness of the micro-roughness itself must be capable of discharging minute droplets of the film into neighboring voids. It should be noted that the distance moved by these droplets is infinitesimal, since this is consistent with the observation that very thin films when impacted by tread rubber in high-speed rolling must behave like solids (6, 7) in transmitting high shear forces with no finite displacement. The effectiveness of the micro-roughness in permitting this phenomenon to take place is still best described by Giles qualitative test (8)—the "feel" of the surface texture. Surfaces which are sufficiently harsh to the touch may therefore be deemed to have an adequate sharpness of micro-roughness; at the same time, the minimum permissible amplitude of micro-roughness is determined by elastohydrodynamic considerations in the rear of the contact patch as described earlier.

CONCLUSIONS

A logical design sequence for the selection of an optimum surface texture in roads and runways has been proposed on the basis of research performed by the author and other investigators. It is concluded that the mean wavelength and slope of texture is chosen from drainage requirements (with consideration of the contribution of hysteresis to skidding friction) at the average maximum speed or design speed limit for the particular pavement under consideration. For surfaces which are sufficiently pointed and sharp (Figs. 2a and 6), there is no need for a micro-roughness at asperity tips, since the elastic pressure peak is sufficiently great to preclude the existence of a continuous water film. Most road surfaces have rounded asperities, however, and it is necessary to design a micro-roughness to oppose the lubricant effect at asperity peaks due to fluid entrainment. The amplitude of the micro-roughness should exceed the elastohydrodynamic film thickness which would otherwise exist at asperity peaks, and its sharpness should permit the displacement of fluid droplets through an infinitesimal distance to establish adhesion between tire and surface. It has been shown (4) that adhesion contributes substantially to the coefficient of friction in wet rolling.

It is certain that the wavelength for road surfaces lies in the range 3 to 30 mm (depending on average maximum speed), whereas the micro-roughness may be of the order 10 to 100 μ. The sharpness of micro-roughness is qualitatively measured by its feel, but no mechanical measure of this parameter has yet been proposed. Considerable work has been done on the drainage of road surfaces and in the prediction of skid-resistance gradient (3, 8, 9) and in the general evaluation of surface texture as related to its friction-generating potential (10, 11). Yet there is need for further refinements in establishing the exact geometry of the optimum surface texture for a given set of environmental conditions.

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