A purely theoretical means for predicting tire-road friction has been the subject of research for the past two decades. It is based on a faithful simulation of a pneumatic tire sliding over the wet texture of the road surface. This involved the stress-gross strain analysis of the tread rubber, the effect of shear rate, heat, and lubrication. A device called the Yandell-Mee texture friction meter is described and is the end product of this research. When placed on a road surface, it samples a total texture profile 60 cm long to an accuracy of 0.05 mm and predicts side force and locked-wheel wet friction for three speeds in seconds. Because the result varies only with texture changes, this is an excellent control tool for pavement engineers.

A study has been under way since 1968 of the part played by surface texture on tire-road friction (1-12). Much of the work was influenced by that of Tabor (13) and Kummer and Meyer (14). It was assumed that tire-road friction was caused by hysteretic energy loss in the tread rubber as it flowed over the road surface texture and that intermolecular adhesion would not occur on wet roads. Yandell (3) summarized some of the basic elements involved in hysteretic sliding friction and the change in microtopology of road surfaces in service. In that paper (3) the principles of the mechano-lattice stress-strain analysis for gross deformations used in the prediction of hysteretic friction from one texture parameter—the average absolute slope—were shown. It was also shown how the friction of small stone surfaces lubricated with liquids of various viscosities sliding on tread rubber could be predicted in the laboratory.

Before the mechano-lattice stress-strain analysis can be used, the damping and resilient properties of the tread rubber as they vary with strain, rate of strain, and temperature must be known. This work was performed by Zankin and Yandell (11) using a temperature-controlled apparatus capable of measuring damping in rubber sliding at up to 80 km/hr. Taneerananon and Yandell (10) modified Reynold’s equations for sliding and sinkage to use with the mechano-lattice stress-strain analysis so that masking water film thicknesses could be determined.

The authors’ friction prediction was based on the concept that a profile of the road surface texture could be broken up into a number of components ranging from coarse to fine. Although large volumes of rubber were expending energy as they flowed over the coarsest scales, smaller shallower volumes of rubber simultaneously expended energy as they flowed over the finer scales of texture. The total hysteretic friction was the sum of frictions generated on each scale of texture. The friction on a scale was a function of the effective damping factor of the rubber and the average absolute slope of that scale. The damping factor is the energy lost divided by the energy applied in deforming rubber in a load-unload operation (3). The average absolute slope is a function of texture roughness.

The next stage in the development of a system for predicting wet friction from road surface texture involved measuring the texture of a number of roads of diverse surface texture with either bituminous or concrete surfacing (12). The coarse texture was measured with a profile former (row of needles), the fine texture by a Zeiss light section microscope. The total texture was divided into four scales. The dry hysteretic friction was determined from the average absolute slope of that scale of texture and the damping factor of the tread rubber using the mechano-lattice analysis (12). The coefficients of wet sideways force and locked-wheel braking friction for speeds of 16, 48, and 80 km/hr were computed and compared with predicted values measured by a multimode friction measuring truck. An example of a correlation for locked-wheel braking is shown in Figure 1. The R-squared value was 0.7. This process, although reasonably accurate, was clumsy and time consuming. Accordingly a portable device that would do the same job in seconds was devised. It was called the Yandell-Mee (Y-M) texture friction meter. Mee designed the circuit boards and wrote the Pascal programs that controlled the original meter’s operation. The meter simulates the behavior of a smooth pneumatic passenger car tire traveling on a wet pavement. A later version (Mark 2) of the Y-M texture friction meter was developed with the assistance of S. Sawyer and will now be described.

Y-M TEXTURE FRICTION METER MARK 2

The first portable Y-M texture friction meter was built under the sponsorship of Pavement Management Services, Ltd., in Sydney. This company incorporated it in their Australian Road Evaluation Vehicle with which friction measurements were made simultaneously with other pavement characteristics in Australia and Indonesia. The Y-M texture friction meter Mark 2 was developed from the Mark 1 model at the University of New South Wales (NSW) with the NSW State Road Authority’s financial support. Mark 2 is superior to Mark 1 in that it is operator independent, has a texture profile sample 60 cm long, is surface brightness independent, and is faster.

General Description

The portable instrument has two main components: the compact surface texture measuring unit and the personal computer (PC) with screen that controls the entire operation. Figure 2 is a summarized flowchart showing the operation of the device. The following parts of the flowchart are described.

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FIGURE 1  Braking force numbers at 48 km/hr versus those predicted from texture measured by light section microscope and profile former in 1982. \( R^2 = 0.67 \).

A. Read texture condition and analyse into 4 bands with 5th order Bessel Filter.

B. Looking at coarsest component of texture: is texture rough?

Yes  

C. Compute number of large asperities in contact patch, drainage lengths and those parts of texture that are in contact with the tyre.

No  

D. Drainage length equals radius of contact patch.

E. Compute average absolute slope of each scale of texture.

F. EFFECT OF WATER FILM  
Compute film thickness and \( a/d \) on the second finest scale for each of the three speeds - 18, 48 and 80 km/hr and for SFC and LWBFC.

G. EFFECT OF DAMPING FACTOR OF RUBBER  
Compute damping factor of tread for each speed and for SFC and LWBFC.

H. Calculate coeff of hysteretic friction \( C_i \) for each scale of texture.

I. Coeff of Wet Friction  
\[ C = \frac{a}{d} C_1 + \left( \frac{a}{d} \right)^2 C_2 + \left( \frac{a}{d} \right)^3 C_3 \]

FIGURE 2  Simplified flow chart showing operation of the Y-M texture friction meter.

A. The profile 60 cm long is read with an accuracy of 0.05 mm by means of a black-and-white video camera viewing the image of a laser line projected at an angle onto the surface (Figure 3). Any gaps in the profile are filled in. This profile, recorded digitally as 12,000 ordinates, is divided into four bands with a fifth-order Bessel filter.

B. If the average absolute slope of the coarsest component is greater than an arbitrary 0.1, the surface is regarded as "rough" and the program goes to C for drainage path length computation. If the surface is "smooth," the program goes to D where a longer drainage path is computed.

C. The number of large asperities in the hypothetical contact patch of the tire on the rough surface—that part of the texture in contact with the tire and the drainage path lengths—is computed. Then move to E and F.

D. The drainage path length on the smooth surface is assumed equal to the radius of the contact patch. Then move to E and F.

E. The average absolute slope of the texture is computed of that part of each scale that is in contact with the tire. (The average absolute slope of the two sides of an equilateral triangle, for example, is \( \sqrt{3} \)).
The average water film thickness and the ratio of \( a/d \) is computed: \( a \) is the asperity height and \( d \) is the average depth of the coarsest component of microtexture. This is done for each of the speeds (18, 48, and 80 km/hr) and for the sideways force coefficient and the locked-wheel braking force coefficient. Then move to I.

G. The damping factor of the rubber is determined for each of the three speeds of sliding and for sideways and for locked-wheel friction. The effect of temperature rise during locked-wheel braking is accounted for. Zankin and Yandell (11) provided this information.

H. The coefficient of dry hysteretic friction \( C_i \) is calculated for each scale of texture using the damping factor of the rubber and the average absolute slope of that scale of texture to give \( C_0 \), \( C_1 \), \( C_2 \), and \( C_3 \).

I. The coefficient of wet (not flooded) hysteretic friction is equal to the sum of the coefficients of dry hysteretic friction, each modified by the effect of surface water film, thus

\[
\text{Coefficient of wet friction} = C_0 + \frac{a}{d} C_1 + \left( \frac{a}{d} \right)^2 C_2 + \left( \frac{a}{d} \right)^3 C_3
\]

where

- \( a/d \) = film thickness ratio from F;
- \( a \) = height of the coarsest component of "microtexture" not masked by the water film;
- \( C_i \) = coefficients of hysteretic friction computed from average absolute slope and tread damping factor using the mechano-lattice analysis (10).

The expression is Taneerananon's hypothesis.

Texture Measuring Device

The texture measuring device is housed in a lightweight case measuring 40 \( \times \) 50 \( \times \) 40 cm. A slot in the base of the case allows the laser to be projected onto the road surface and viewed by the video camera from inside the case. This portable unit is connected by a long cable to a 486 Compac PC that controls the operation. The components of the texture measuring device are the laser source, the camera, and the laser-camera transport.

Transport

The laser and the camera are fitted to a cross carriage that is sequentially moved into three alternative positions by fixed slides.
situated at each end of the main slide. The main carriage carrying the cross slide is driven by a motor through a lead screw for a distance of 20 cm as shown in Figures 4 and 5. In this way, three parallel profiles each 20 cm long can be recorded automatically in one operation.

**Laser Source**

The laser source is a 5-mw, 670-nm laser diode. Its fine cylindrical beam is changed to a flat knife by passing it through a cylindrical lens. It impinges on a mirror, which reflects it onto the road surface in view of the video camera. See Figures 4 and 5.

**Camera and Lens**

The black-and-white video camera views the laser line impinged on the road surface through powerful magnifying lenses. The laser beam and the line of sight of the camera are mutually at right angles so the line is always in focus. The aperture of the lens is adjusted automatically. The magnification of the lens is such that 1 cm of the surface is viewed at a time.

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**Intermediate Result Summary for Current Measurement**

Number of asperities in sample = 13
Weight per asperity = 10.76923lb
Texture depth = 1.02558mm
Max water holding depth (dl) = 0.01791ins
Film thickness ratios for speeds 10.30, 50mph
1. Locked wheel 0.95120 0.94226 0.93668
2. Sideways force 0.96427 0.93691 0.91792
Absolute slope of frequency bands 1(coarsest) to 4(finest)
0.15493 0.38320 0.40388 0.35559
Partial friction coefficients for frequency bands 1 to 4
1. Locked wheel at 10mph: 0.0640 0.2176 0.2368 0.1933 Sum = 0.7117
2. Locked wheel at 30mph: 0.0639 0.2170 0.2362 0.1928 Sum = 0.7099
3. Locked wheel at 50mph: 0.0667 0.2291 0.2495 0.2034 Sum = 0.6820
4. Sideways force (spd.ind): 0.0665 0.2194 0.2308 0.1949 Sum = 0.7176

**FIGURE 10** Example of output point file.
Computer Operation and Output

The texture measuring device is placed on the road. Upon initiation, the computer quickly tracks the edge of the laser line to give a profile of texture 10 mm long, as shown in Figure 6. Of these profiles, 60 are sequentially shown on the monitor and recorded while the carriage is automatically transported 1 cm at a time. Once the profile data are stored in the PC, the processing is effected as described earlier. The 60 parts of the profile are accurately connected and missing pieces are filled in. All the ordinates are divided by \( \sqrt{2} \) to give the vertical resolution of the 45-degree view of the profile.

Figure 7 shows the total texture and its four components as shown on the monitor screen. Figure 8 shows the main screen display with coefficient of friction values, average and peak texture depths, and the menu for other operations. The inappropriate three decimal places will be modified to a more appropriate accuracy.

The contents of other files also can be shown on the screen or printed, or both. For example, Figure 9 is an example of a block file showing the nozzle, texture depth, and locked-wheel and sideways force friction for any number of readings along a road. Figure 10 is an example of a point file that gives the six friction readings plus film thickness ratios and dry hysteretic friction values.

CORRELATION WITH DIRECTLY MEASURED FRICTION

A large number of devices that measure pavement friction directly with a test tire are available. There is seldom complete agreement between any two that measure friction on the same surfaces. For example, a runway friction tester (B. Miley, Florida Department of Transportation, unpublished data) and a pavement friction tester yielded an R-squared value of 0.02 for readings on about 25 wet open-graded textured roads using ribbed tires and an R-squared value of 0.75 on a large variety of wet asphalt surfaces using a smooth tire. Whitehurst (15) showed a 30 percent variation among seven different ASTM skid trailers reading identical surfaces. There are many reasons for this lack of agreement, among which are the vagaries of tread rubber behavior.

Relation Between Y-M Texture Friction Meter and Direct Measurement

A British pendulum friction tester and a Y-M texture friction meter were used to measure the friction on a number of wet rolled asphalt surfaces and also on very smooth surfaces such as floor tiles—surfaces where contact macrotexture was low. The correlation is shown in Figure 11 where the R-squared value was 0.9, which is high partly because of the inclusion of a large range of texture "harshness" and the absence of macrotexture.

A test truck that measures sideways force friction was used at 48 km/hr on a range of wet asphaltic and Portland cement concrete surfaces. The results are seen plotted against the Y-M texture friction meter readings for SFC_{4a} in Figure 12. The R-squared value was 0.7, which is similar to the agreement between the two peak friction tester results from Florida (B. Miley, Florida Department of Transportation, unpublished data).

Although the terms micro- and macrotexture are used, the texture is assumed to be continuous in scale, with no clear borderline between micro- and macrotexture. Others have developed devices for measuring road surface texture. For example, U.K. Transport Research Laboratory has a portable macrotexture measuring device. In addition, work by Henry and Hegmon (16) has led to the building of a fast texture-measuring van by the Pennsylvania Transportation Institute.

CONCLUSION

The main advantage to predicting tire-road friction from total texture measurements is based on the fact that the smooth pneumatic tire—the behavior of which is being simulated—has fixed characteristics. The initial hypothetical water film thickness is also fixed at 0.5 mm. Any variation in the predicted friction for a particular speed is solely a result of a change in the road surface texture. The surface texture is under the control of the road authority and so can be used as a trigger in pavement maintenance management. The recorded texture also can be used for other investigations, such as tire-road noise generation. A disadvantage,
of course, is the need for the measured surface to be free from water and detritus where tire contact occurs.

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