Prediction of Tire-Road Friction from Texture Measurements

W. O. YANDELL AND S. SAWYER

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 Ziess 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.

School of Civil Engineering, University of New South Wales, P.O. Box 1, Kensington, N.S.W. 2033, Australia.

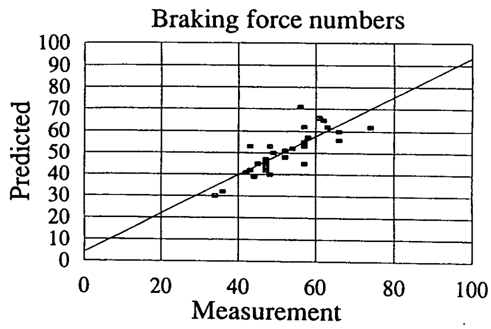

FIGURE 1 Braking force numbers at 48 km/hr versus those predicted from texture measured by light section microscope and profile former in 1982. $R^2 = 0.67$.

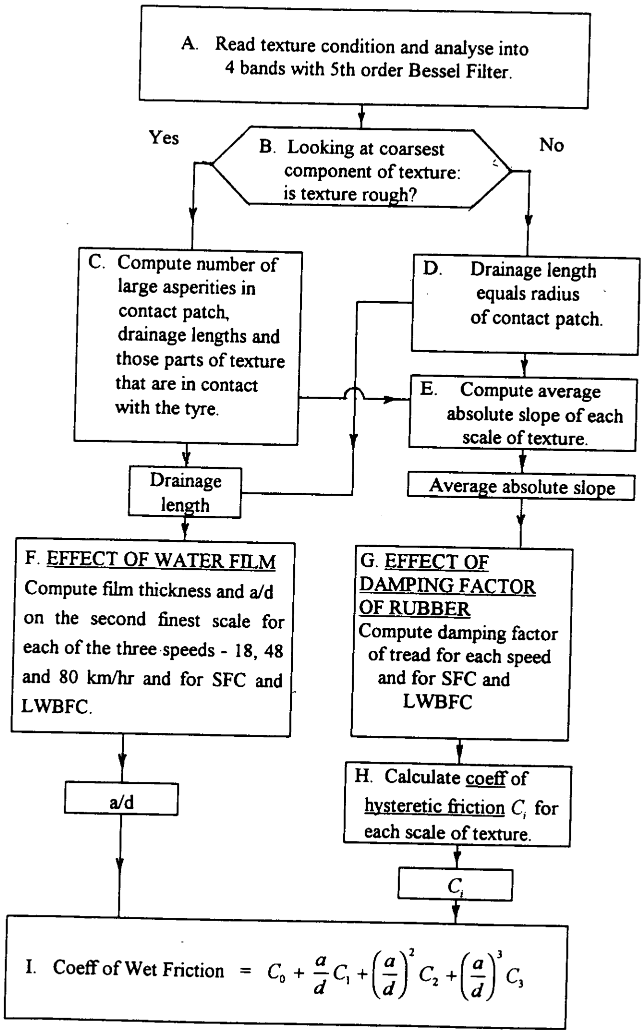

FIGURE 2 Simplified flow chart showing operation of the Y-M texture friction meter.

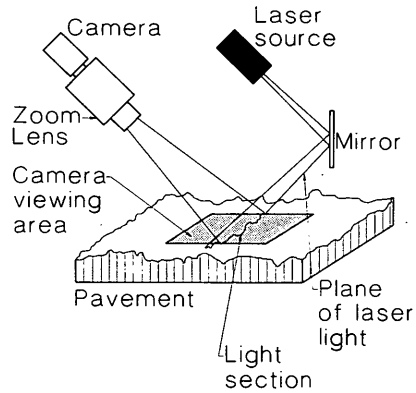

FIGURE 3 Schematic view of Y-M texture friction meter texture measurement.

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 $\sqrt{3}$.)

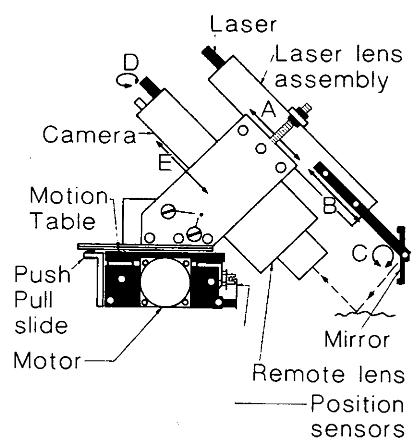

FIGURE 4 Side view of the laser camera carriage on the motion table.

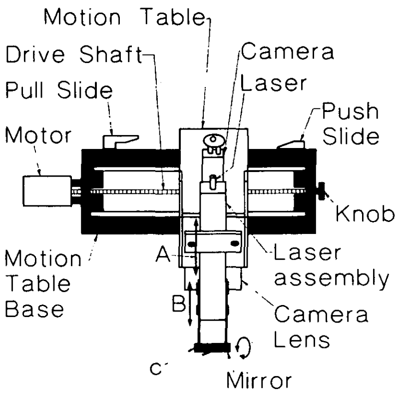

FIGURE 5 Plan view of the laser camera carriage on the motion table.

F. The average water film thickness and the ratio of *a/d* is computed: *a* is the asperity height *d* of the second-finest scale of texture minus the water film thickness. 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;

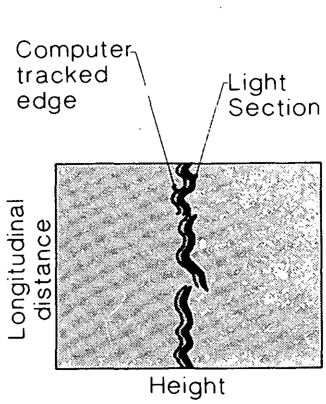

FIGURE 6 Monitor view of a laser image tracked by the computer.

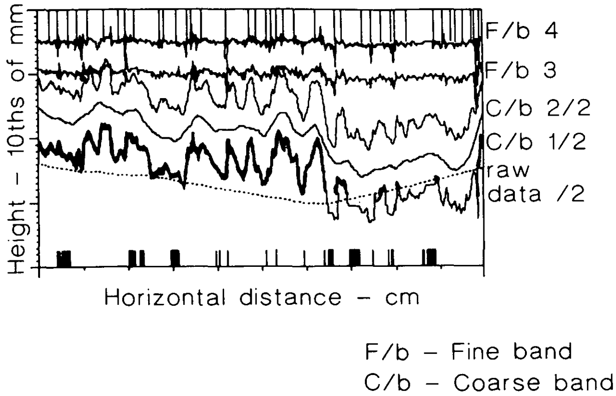

FIGURE 7 Monitor view of the total recorded texture and its four components.

- *d* = average depth of the coarsest component of microtexture; and
- *C* = 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 × 50 × 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

PLACE: DESCRIPTION:		SURFACE: AC CHAINAGE: 0.60 mm
Av. texture depth: .456 mm. Std. Dev:		Pk. texture depth: 137 mm.
SPEED	LOCKED WHEEL FRICTION	SIDEWAYS FORCE FRICTION
10mph (16kph)	.567	.589
30mph (48kph)	.543	.568
50mph (80 kph)	.523	.521
Edit Mondo Data	Files	The Works
Take a Measurement	Print Report	Change Screens
Calculate friction	Adjust Video	Special Operations
Quit to DOS		
Esc=main menu Ctrl-t=Time/date	F1=Erase line F2=Restore line	F3=Full Edit

FIGURE 8 Main display of menu and output.

Yandell Mee Friction Device Results

Date: 25 Jul 1989
Time: 2.32

Client:	Case study City Council
Id Number:	009
Place:	Parkinson Ave from Cominara Parkway to Hart St
Surface:	AC
Description:	10 metre intervals 1 metre from kerb

Chainage Km	Texture Depth mm	Locked Wheel Friction 10mph	Locked Wheel Friction 30mph	Locked Wheel Friction 50mph	Sideways Force Friction 10mph	Sideways Force Friction 30mph	Sideways Force Friction 50mph
0.00	.606	.461	.383	.369	.661	.618	.590
0.01	.564	.428	.349	.333	.658	.615	.586
0.02	.588	.458	.379	.364	.658	.615	.586
0.03	.580	.488	.403	.389	.702	.656	.626
0.04	.617	.532	.443	.430	.760	.714	.683
0.05	.559	.438	.360	.344	.634	.590	.561
0.06	.551	.466	.384	.369	.673	.628	.598
0.07	.547	.403	.335	.321	.577	.539	.514
0.08	.561	.392	.324	.310	.564	.525	.500
0.09	.566	.437	.358	.341	.636	.590	.560

FIGURE 9 Example of output block file (short form).

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.

Client: Case study City Council		The Yandell-Mee Friction Texture Meter	
Id. No.: 003	File: 478003 pnt	Time: 17:13	Date: 25 Jul 1989
Place: Parkinson Ave from Cominara Parkway to Hart St Description: 10 metre intervals 1 metre from kerb			Surface: AC Chainage: 6,000 km
Texture depth: .551 mm		Pk. texture depth: .878	

Speed	Locked wheel friction	Sideways force friction
10mph (16kph)	0.468	0.673
30mph (48kph)	0.384	0.628
50mph (80kph)	0.369	0.598

Intermediate Result Summary for Current Measurement

Number of asperities in sample = 13
Weight per asperity = 10.769231b
Texture depth = 1.02558mm
Max water holding depth (d1) = 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):	0.0645	0.2194	0.2388	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 chainage, 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.

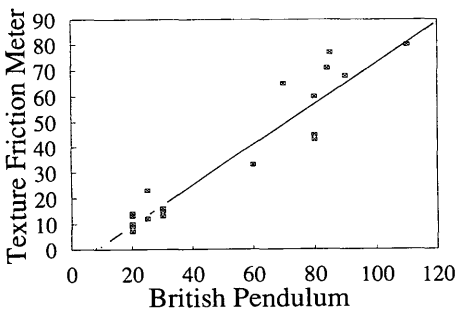

FIGURE 11 Relationship between friction numbers predicted with Y-M texture friction meter: braking force number at 16 km/hr and British pendulum numbers on rolled asphalt and floor tile surfaces, R^2 = 0.9.

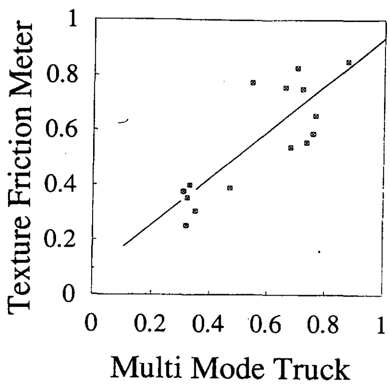

FIGURE 12 Relationship between friction coefficients predicted with the Y-M texture friction meter: sideways force coefficient at 48 km/hr and that measured by a friction test truck, R^2 = 0.7.

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_{48} 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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REFERENCES

1. Yandell, W. O. A Mathematical Simulation of Hysteretic Sliding Friction. *Proc., 4th Conference of the Australian Road Research Board*, Oct. 1968.
2. Yandell, W. O. The Effect of Surface Geometry on the Lubricated Sliding Friction and Polishing of Roadstones. *Australian Road Research*, Vol. 3, No. 10, 1969.
3. Yandell, W. O. A New Theory of Hysteretic Sliding Friction. *Wear*, Vol. 17, April 1971.
4. Yandell, W. O. The Use of Mechano-Lattice Analogy for Determining the Abrading Stresses in Sliding Rubber. *Rubber Chemistry and Technology*, June 1971.
5. Yandell, W. O. The Part Played by Microtexture in Skidding Resistance. *Proc., 6th Conference of the Australian Road Research Board*, 1972.
6. Yandell, W. O. The Simulated Traffic Polishing of Roadstones. In *Wear*, Vol. 21, 1972.
7. Yandell, W. O. The Relation Between the Stress Saturation of Sliding Rubber and the Load Dependence of Tire-Road Friction. Presented at International Symposium on the Physics of Tire Traction Theory and Experiment, Detroit, Mich., Oct. 1973.
8. Gopalan, M. K. and W. O. Yandell. Effect of Lubricants and Masking of Texture on Abrasion of Rubber. *Australian Road Research*, Vol. 5, No. 9, 1975, pp. 48–55.
9. Gopalan, M. K. and W. O. Yandell. The Relation Between the Surface Texture of Roads and the Friction and Abrasion of Tire Tread Rubber. *Proc., 8th Conference of the Australian Road Research Board*, Perth, Aug. 1976.
10. Taneerananon, P. and W. O. Yandell. Micro-Texture Roughness Effect on Predicted Road-Tire Friction in Wet Conditions. *Wear*, Vol. 69, 1981, pp. 321–337.
11. Zankin, V. and W. O. Yandell. High Speed Rolling Friction on Viscoelastic Substrates—Determination of the Hysteretic Damping Factor. *Wear*, Vol. 72, No. 2, 1981, pp. 157–185.
12. Yandell, W. O., P. Taneerananon, and V. Zankin. *Prediction of Tire-Road Friction from Surface and Tread Rubber Properties.* ASTM Special Technical Publication 793. ASTM, Philadelphia, Pa., 1982.
13. Tabor, D. *Philosophical Magazine*, Vol. 43, 1952, p. 1055.
14. Kummer, H. W. and W. E. Meyer. New Theory Permits Better Frictional Coupling Between Tire and Road. Presented at Conference of Federation Internationale des Sociétés d'Ingenieurs des Techniques de l'Automobile, Munich, 1966.
15. Whitehurst, E. A. Field Test Center's Experiences with Skid Trailer Problems. TRANSPLEX College of Engineering, Ohio State University, Columbus, 1978.
16. Henry, J. J. and R. R. Hegmon. *Pavement Texture Measurement and Evaluation.* ASTM Special Technical Publication 583, ASTM, Philadelphia, Pa., pp. 3–17.

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