Computation and Analysis of Texture-Induced Contact Information in Tire-Pavement Interaction

T. G. CLAPP and A. C. EBERHARDT

ABSTRACT

In tire-pavement interaction, road surface texture is an important parameter that influences many factors such as tire noise, skid resistance, vehicle performance, and rolling resistance. Efforts to understand and quantify the texture effects in tire-pavement interaction have been limited because of the difficulties in experimentally and theoretically determining the many individual contact areas and contact pressures produced by irregularly shaped asperities indenting the tire tread. A numerical method is developed and incorporated into a computational algorithm to approximate contact pressure resulting directly from road surface texture in tire-pavement interaction. Only 2-D road surface profile geometry and tire inflation pressure are required as input parameters. The purpose of this paper is to demonstrate application of the method. Several types of surface textures are analyzed using the contact approximation method. The road surfaces are characterized by analyzing the individual pressure distributions, contact lengths, and tire deformations that make up the pressure profiles. The contact length information is combined with the surface profile geometry to approximate the geometry of the deformed tire surface. Analysis of the deformed tire geometry provides information concerning factors such as void area and depth of penetration. Two-dimensional pressure profiles associated with the 2-D surface texture profiles are computed and transformed into force time-histories of tire input excitation.

The interaction between a rolling tire and a road surface has been a topic of wide research interest for many years. As the popularity and demand for automotive transportation have increased, research has been conducted by tire and pavement designers to understand and improve tire-pavement interaction for two primary reasons: vehicle performance and safety. The tremendous growth of the nation's transportation system and the ever present need to conserve energy have produced additional reasons for addressing the topic of tire-pavement interaction such as tire noise and rolling energy loss. Current research of tire-pavement interaction is directed toward understanding the contact forces that affect tire noise, vehicle performance, safety, and rolling resistance.

Road surface texture is an important parameter in the analysis of tire-pavement contact. Surface texture has always been an important consideration in the design and construction of pavements with good skid resistance characteristics (1). Surface texture is also shown to affect tire noise, a primary environmental noise source, by up to 6 dB on dry pavements and up to 15 dB on wet pavements (2). Surface texture also affects tire rolling resistance, an important component of vehicle fuel consumption, by up to 30 percent (3). The recent design of small, lightweight vehicles has increased the significance of the structure-born vibration and acoustic radiation affecting passenger comfort (4). Road surface texture creates fluctuating forces that excite the tire structure, resulting in vibrational response.

Sophisticated tire models are being developed to understand and predict the response of tires in contact with a variety of road surfaces. These models require an input excitation that reflects the true nature of tire-pavement contact. The contact information resulting from road surface texture must be included in the excitation mechanism.

Efforts to understand and quantify the texture effects in tire-pavement interaction have been limited as a result of difficulties encountered in experimentally or theoretically determining the many individual contact areas and pressures produced by irregularly shaped asperities indenting the tire tread. Global contact pressure and contact area associated with the tire footprint have been investigated (5), but the influence of surface texture is lost when averaged over the contact region. This global contact information is not sufficient to model the random, fluctuating forces that excite the tire structure and affect many factors related to tire-pavement interaction. This texture-induced contact information is required to represent realistic excitation forces produced by actual road surfaces.

Research has been performed to develop a method for predicting the normal contact forces that are created as a direct result of surface texture (6). Because the texture-induced contact information influences many topics of interest, a basic goal of the research has been to develop a method that is available to the tire and pavement research community.

The purpose of the research described here is to

T.G. Clapp, Textile Engineering and Science Department, P.O. Box 8301, North Carolina State University, Raleigh, N.C. 27695-8301. A.C. Eberhardt, Department of Mechanical and Aerospace Engineering, P.O. Box 7910, North Carolina State University, Raleigh, N.C. 27695-7910.

demonstrate the usefulness of the method by computing texture-induced contact pressure and length information from a variety of road surfaces. This contact pressure information is used to analyze individual peak pressures and construct force time-histories that excite tire models for predicting vibrational response and rolling resistance. The contact length information is used to approximate tire envelopment into the surface texture. This information contains skid-resistance parameters such as void area and depth of penetration resulting from surface texture geometry.

Researchers investigating topics such as skid resistance, tire noise, rolling resistance, and vehicle performance have an interest in the contact pressure and length information resulting directly from road surface texture in tire-pavement interaction. An analysis of experimental methods used to characterize pavement skid resistance by measuring texture-related parameters has demonstrated a need to define other surface texture parameters, such as microtexture, to adequately predict pavement skid resistance (7). In this paper information available from the approximation method developed for use by the general research community is described.

APPROXIMATION OF TEXTURE-INDUCED CONTACT PRESSURE

The development of an approximation method is based on an analysis of individual contact areas that are combined to form the total contact between a tire and a road surface. A contact model is developed to approximate the contact stress or pressure associated with individual contact areas. The contact stress produced by the model is mathematically described using the classical theory of elasticity (8,9). Contact pressure is approximated based on the model formulation and known input parameters.

An individual contact area associated with a surface asperity and the tire tread is modeled as a rigid indenter in contact with an elastic half-plane as shown in Figure 1. A line of continuous contact between points a and b is used to provide a two-dimensional model of the contact area. Working in two-dimensions reduces the complexity of the modeling process and is justified by the randomness of the road surface profile and the independence of parallel paths (10). The line of contact is called the displacement function, $f(x)$, and is assumed to be a known parameter. The vertical component of stress along the half-plane boundary is equal and opposite to the applied vertical pressure, $p(x)$, in the region of contact and equal to zero outside the contact region. This contact model provides the foundation on which tire-pavement contact is modeled.

The mathematical foundation used to develop the

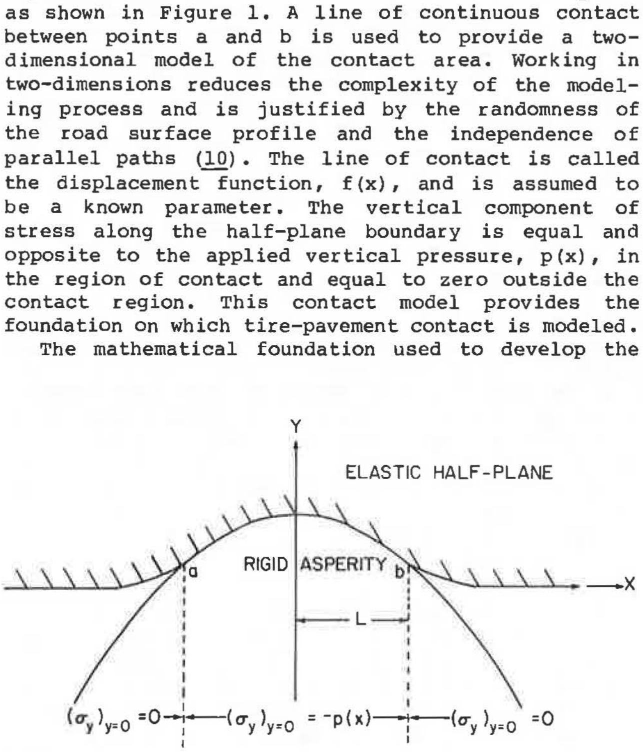

FIGURE 1 Two-dimensional model of the contact and boundary conditions between an elastic half-plane and a rigid object.

pressure distribution associated with tread-pavement contact is based on plane problems in the theory of elasticity. Galin (8) performed an exhaustive study on the topic of contact problems of the theory of elasticity. Specifically, Galin developed an analytic solution for a two-dimensional contact problem that is based on the same assumptions as the model for the tire-pavement contact problem. In that development, the following equation occurs:

$$\pi E f(x)/2(1 - \nu^2) + C0 = \int_a^b (\sigma_y)_{y=0} \ell n|t - x| dt \quad (1)$$

where

E = 1/2 plane modulus of elasticity,
ν = 1/2 plane Poisson's ratio,
t = dummy variable of integration,
x = horizontal contact position,
a,b = contact end points,
$(\sigma_y)_{y=0}$ = normal contact stress, and
$f(x)$ = contact displacement function.

C0 is a constant that describes the vertical distance from the half-plane boundary line to the initial point of contact. This formulation contains the displacement function, $f(x)$. Discrete samples that describe the road surface geometry are used to represent the displaced half-plane contact length, $f(x)$. The normal stress, σ_y, in the y-direction and on the half-plane boundary is equal and opposite to the externally applied vertical pressure, $p(x)$,

$$(\sigma_y)_{y=0} = -p(x) \quad (2)$$

Equation 2 is substituted into Equation 1 to obtain

$$\pi E f(x)/2(1 - \nu^2) + C0 = -\int_a^b p(t) \ell n|t - x| dt \quad (3)$$

Equation 3 is in terms of the displacement function, $f(x)$, which is described by 2-D road surface profiles.

With $f(x)$ previously defined, the problem becomes that of finding the corresponding pressure distribution, $p(x)$. The physics of the problem require the existence of a pressure distribution. Although unknown, the pressure is assumed to be some function with unknown coefficients that approximate the true pressure distribution.

The contact pressure distribution is approximated by a sequence of third-order polynomials connected by appropriate boundary conditions as shown in Figure 2.

The pressure distribution, $p_i(x)$, for each spline, i, is represented as follows:

$$p_i(x) = B_{i0} + B_{i1}x + B_{i2}x^2 + B_{i3}x^3 \quad (4)$$

where $X_i \leq x \leq X_{i+1}$. The coefficients, B_{in}'s, are unknown, and X_i and X_{i+1} are spline end points. Equation 4 is substituted into Equation 3 to determine the pressure distribution over an individual spline of contact length with end points X_i and X_{i+1}. The pressure is approximated over the entire contact length by a series of cubic splines to obtain

$$\pi E f(x)/2(1 - \nu^2) + C0 = -\sum_{i=1}^{I} \sum_{n=0}^{3} B_{in} \int_{X_i}^{X_{i+1}} (t - X_i)^n \ell n|t - x| dt \quad (5)$$

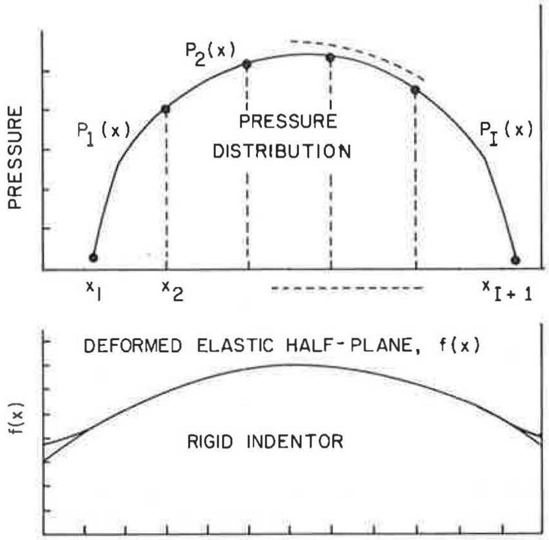

FIGURE 2 Sketch of the spline approximation of contact pressure associated with a deformed elastic half-plane.

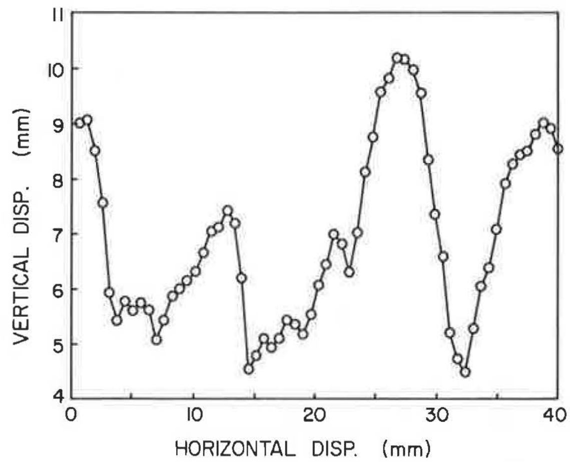

FIGURE 3 Typical section of 2-D road surface profile geometry.

where I is the total number of splines.

The splines are combined using appropriate interface conditions. Splines can be combined by imposing restrictions on the continuity of the pressure distribution, or restrictions on first, second, or third derivatives of the distribution (11). The interface condition imposed on combining splines is that the pressure must be continuous, this means that

$$B_{(i+1)0} = B_{i0} + B_{i1}h_i + B_{i2}h_i^2 + B_{i3}h_i^3 \quad (6)$$

where $i = 1, I - 1$ and $h_i = x_{i+1} - x_i$. This restriction assures a continuous distribution without introducing complexities that increase solution time and coefficient storage.

The unknowns in Equation 5 are C0 and the spline coefficients B_{in} ($i = 1, I$; $n = 0, 3$) to total 4 I + 1unknowns. With the interface conditions applied, there is a total of 3I + 2 unknowns. A total of 3 I + 2 equations are generated by selecting 3 I + 2 x-values along the contact length that correspond to discrete displacement values, f(x). A coefficient matrix formed by the 3 I + 2 equations is analyzed by using a singular value decomposition to décompose the matrix into singular values and vectors (12,13). The decomposed matrix information is used to compute the unknown spline coefficients. With the spline coefficients determined, the pressure distribution is approximated.

The method developed for approximating contact pressure also approximates the true contact length by producing negative pressures in the regions along the assumed contact length where no contact exists.

The approximation method is validated and incorporated into a computational algorithm to compute the contact information resulting directly from road surface texture in tire-pavement interaction (6). The input requirements for the algorithm consist of discrete samples that represent a two-dimensional road surface profile, as shown in Figure 3, and tire inflation pressure. The size and detail of the surface texture to be analyzed is limited primarily by the sample spacing of the surface profile. The algorithm computes multiple contact sections along the 2-D surface profile to incorporate the effects of adjacent asperities.

The algorithm computes the contact pressure and length information associated with 2-D surface texture profiles. The contact information consists of a series of individual contact lengths and pressure distributions associated with a 2-D road surface profile to form a 2-D pressure profile that characterizes the road surface. The pressure profile provides the basic contact information used to describe the effect of road surface texture in tire-pavement interaction. The amount of contact information produced by the algorithm is demonstrated by analyzing a variety of road surfaces. Details of the algorithm's computational process are included in the analysis.

APPLICATION OF COMPUTATIONAL ALGORITHM USING ROAD SURFACE TEXTURE

Surface profiles from four selected pavements are analyzed to predict the 2-D contact pressure profiles that contain the force and contact length information. Profile information was collected in previous research from four road surfaces located at Texas Transportation Institute (TTI), College Station, Texas (10). These surfaces are referred to in this report as Test Pads 2, 4, 7, and 8 to maintain consistency with previous research. The construction and skid resistance of the test surfaces are well-documented (14) and are given in Table 1.

TABLE 1 Pavement Description

Pad	SN_{40}	Description
2	18 ± 3	Asphaltic concrete with jennite flush seal
4	42 ± 5	Crushed gravel hot-mix asphaltic concrete
7	60 ± 5	Lightweight aggregate asphaltic chip seal
8	50 ± 5	Lightweight aggregate hot-mix asphaltic concrete

For each of the four pavements, 21 two-dimensional surface profile traces were collected using a profilometer developed at North Carolina State University (10). Each trace contains 560 points that describe the surface geometry. These points have a sampling increment of 0.635 mm (0.025 in.) over a total profile length of 35.56 cm (14 in.). Examples of the reproduced profiles from each pavement are shown in Figure 4. This figure shows the wide texture range investigated and the necessity of using a narrow sampling increment to accurately describe the profile geometry. The contact information is approxi-

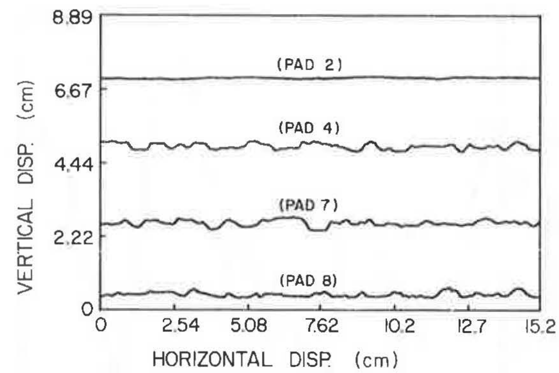

FIGURE 4 Computerized TTI pavement profile (vertical scale offset 2.22 cm).

mated for each road surface using the profile information as input into the computational algorithm.

The penetration or contact depth is determined by assuming total envelopment, computing the pressure profile, and comparing the average pressure of the profile to an equilibrium pressure. The depth of penetration is estimated based on the difference in pressure values. The iterative process is continued until the approximated average pressure is within 5 percent of the equilibrium pressure. If the average contact pressure of the total profile is less than the equilibrium or inflation pressure, then the surface is considered totally enveloped, and no modifications to the profile data are necessary. A particular example using a truck tire inflation pressure of 517 kPa (75 psi) is selected as the equilibrium pressure. The smoothest surface, Pad 2, has a totally enveloped average pressure of 131 kPa (19 psi) and is the only surface that is considered totally enveloped. Test Pads 4, 7, and 8 have average pressures of 1241 kPa (180 psi), 1344 kPa (194 psi), and 1034 kPa (150 psi). Because these average pressures, assuming total envelopment, are above the equilibrium pressure, Pads 4, 7, and 8 are considered only partially enveloped, and the depth of penetration must be determined.

Once the contact depth is determined for one surface profile, an empirical formula is constructed based on the mean surface depth and some fraction of the standard deviation to include the local variations in estimating the depth of penetration. The estimation of the penetration depth dramatically reduces the computation time and produces average pressures that are within 10 percent of the equilibrium pressure.

When the penetration depth is estimated for a particular surface profile, the profile data are modified by setting to zero displacement values below the contact depth equal to the contact depth value as shown in Figure 5. The modified profiles provide the necessary input into the approximation method to predict the contact information associated with each particular road surface.

COMPUTATION AND ANALYSIS OF CONTACT INFORMATION

Twenty-one pressure profiles from each of the four test pavements are generated by inputting the modified road surface profiles into the approximation algorithm. The texture-induced contact information is characterized by analyzing the contact length information, the individual pressure distributions, and the spectral content contained in the pressure profiles.

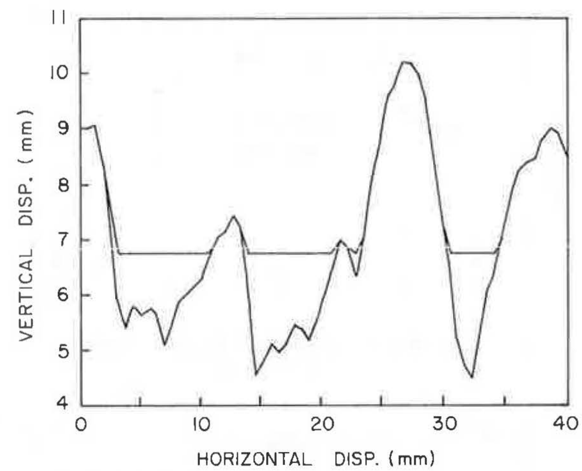

FIGURE 5 Modified surface profile based on an estimated depth of penetration over the original profile.

The area of contact associated with each pavement is contained in the approximated pressure profiles as indicated by the lengths of the profile over which positive pressure exists. The displacement information associated with each individual contact length is known and is used to construct an approximated enveloped half-plane. This information provides a means of understanding and quantifying the surface texture effect on parameters such as void area, percent contact length to total length, depth of penetration, and pressure distribution. Each test pavement is characterized by these parameters using the contact length information.

Pad 2, the smoothest pavement, is assumed to be totally enveloped, achieving full depth of penetration. The percent contact length to total length is 56 percent, which indicates that a large portion of the road surface is not in contact with the half-plane. An examination of the enveloped and original surface profiles shown in Figure 6 provides an explanation. Pad 2 contains low amplitude microtexture that produces a fluctuating pressure distribution as shown in Figure 7. The negative portions of the high frequency distribution are areas in which no contact exists, resulting in the 56 percent contact value.

Figure 6 also shows that the enveloped profile is practically identical to the surface profile. The area between the curves is called the void area and

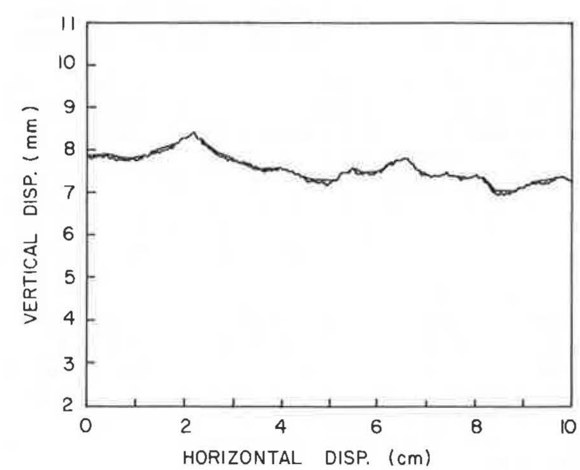

FIGURE 6 Comparison of original and enveloped surface profiles from Pad 2.

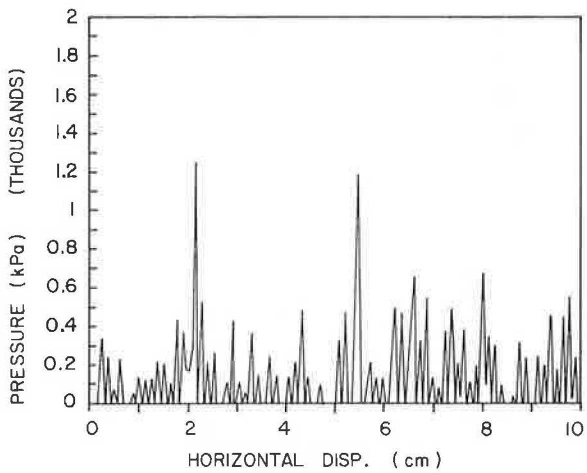

FIGURE 7 Contact pressure profile for Pad 2.

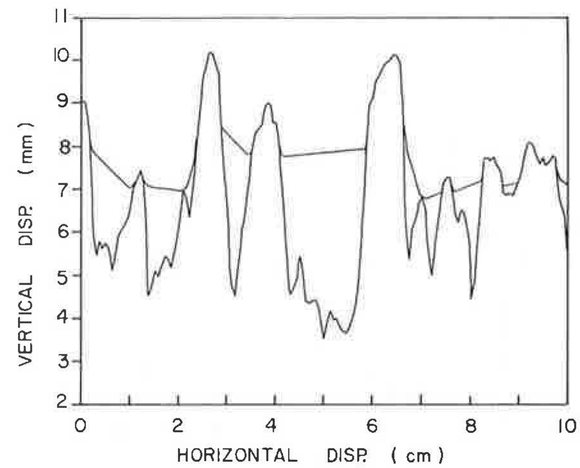

FIGURE 9 Comparison of original and enveloped surface profiles from Pad 7.

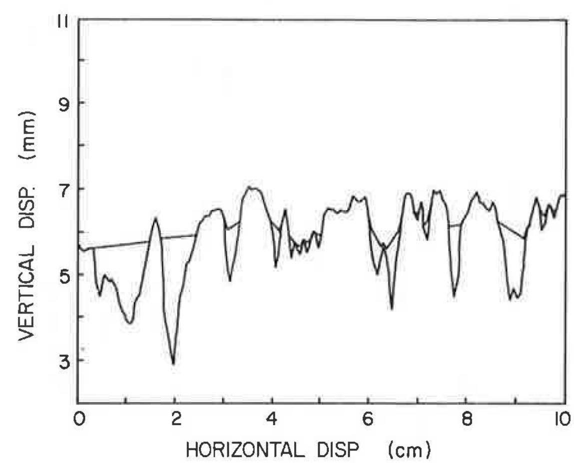

FIGURE 10 Comparison of original and enveloped surface profiles from Pad 8.

is an important safety consideration in pavement design. A large void area is desired to provide a path for water to exit from the tire-pavement contact region in wet highway conditions. Pad 2 has a very small average void area of 0.0010 cm^2/cm (0.0004 $in^2/in.$) that is measured in centimeters squared per centimeter of horizontal surface length. This small void area is a contributing factor in the low skid number of 18 ± 3.

The pressure profile for Pad 2 contains many low amplitude distributions. Analysis of the individual pressure distributions produces an average pressure of 180 kPa (26 psi) with average peak pressure of 380 kPa (55 psi).

Pads 4, 7, and 8 are partially enveloped as shown by the enveloped and original surface geometries in Figures 8 through 10. The figures show the different characteristics that describe each pavement. Pad 4 has widely spaced contact areas with similar depths of penetration. Pad 7 has widely spaced contact areas, but the depth of penetration varies from asperity-to-asperity because of the height variation of the asperities. Pad 8 has many sharp asperities in contact with the half-plane.

The pressure distributions associated with the enveloped profiles for Pads 4, 7, and 8 are shown in Figures 11 through 13. The microtexture roughness is reflected in the pressure profiles by the multiple peaks in the pressure distributions over individual contact lengths. Pad 8 reflects much more microtexture roughness than Pads 4 or 7. Additional information about the individual pressure distributions is given in Table 2, along with other parameters that characterize the three pavements.

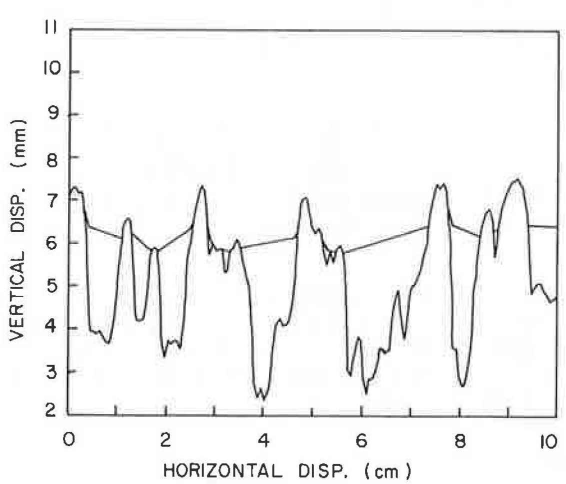

FIGURE 8 Comparison of original and enveloped surface profiles from Pad 4.

Pads 4, 7, and 8 all have high peak and average pressure values. Pad 8 contains 50 percent more peaks per centimeter than Pads 4 or 7, which may be reflected by the relatively higher skid number. Sharp peaks in the pressure distribution tend to improve tire-road surface adhesion by breaking the water film, thus diminishing the lubricating properties of the film. Pads 4 and 7 have a similar number of peaks and pressure values, but Pad 7 is superior to Pad 4 in terms of stopping traction as indicated by their skid numbers. The skid number difference is believed to be a result of the depth of penetration generated by the surfaces.

It is also assumed from this observation that handling (lateral tractive response) is also improved to some extent as the skid number increases. The primary resistive force that prevents skidding at high speeds in wet conditions is the hysteresis component of friction caused by the elastic half-plane material being deformed over the road surface asperities. Pad 7 is embedded approximately 32 percent deeper than Pad 4. This additional penetration increases the resistive forces that are created

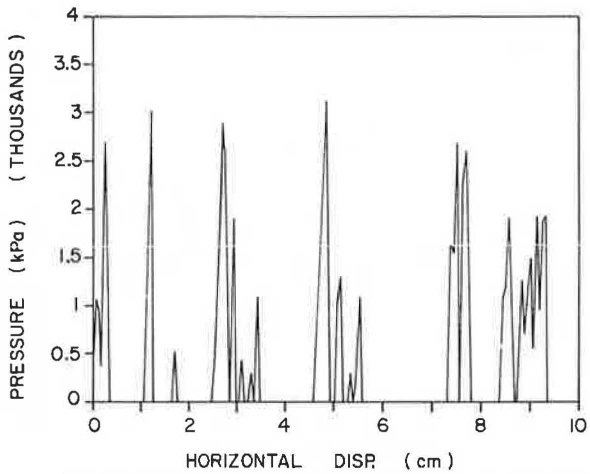

FIGURE 11 Contact pressure profile for Pad 4.

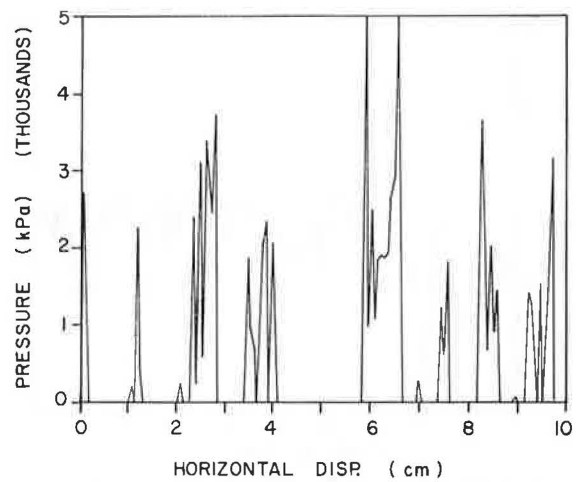

FIGURE 12 Contact pressure profile for Pad 7.

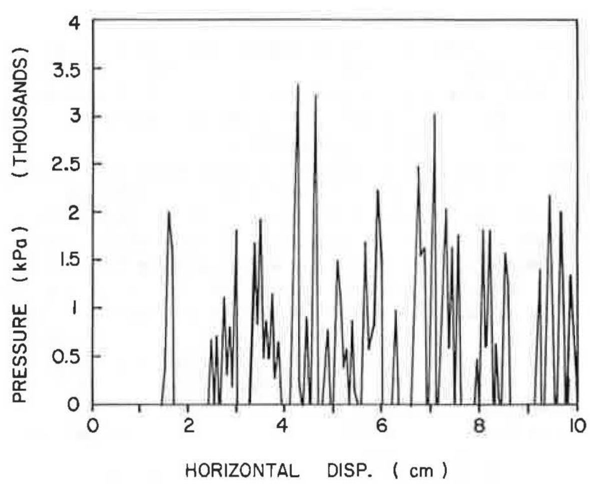

FIGURE 13 Contact pressure profile for Pad 8.

under sliding or skidding conditions. A detailed investigation of the contact information from many road surfaces can provide a definitive relationship to predict pavement skid resistance based on the analysis of road surface geometry using the methodology developed in this paper.

TABLE 2 Contact Information Analysis Results

	Pad 4	Pad 7	Pad 8
Individual avg.			
pressure, kPa	1179	1234	1055
psi	171	179	153
Individual peak			
pressure, kPa	2165	2227	1882
psi	314	323	273
No. peaks/cm	2.6	2.4	3.9
in.	6.6	6.2	9.8
Avg. depth of			
penetration, mm	1.17	1.55	0.89
in.	0.046	0.061	0.035
Standard deviation of			
penetration, mm	0.71	0.97	0.38
in.	0.028	0.038	0.015
Percent contact	32.4	32.0	45.3
Void area, cm^2/cm	0.10	0.10	0.036
$in.^2/in.$	0.04	0.04	0.014
Skid number (SN_{40})	42 ± 5	60 ± 5	50 ± 5

The pressure profiles are transformed into force time-histories by multiplying the pressure times incremental areas to obtain incremental forces, and dividing the displacement increment by vehicle velocity to obtain a time increment. The two-dimensional time-histories can be combined to produce a three-dimensional forcing function that can be used to excite the tire-pavement contact region.

The force time-histories are also transformed into the frequency domain to determine the spectral energy contained in each road surface. Examples of each pavement's spectral energy in 1/3-octave bands are shown in Figure 14. This spectral energy can be used to characterize road surfaces and excite tire models.

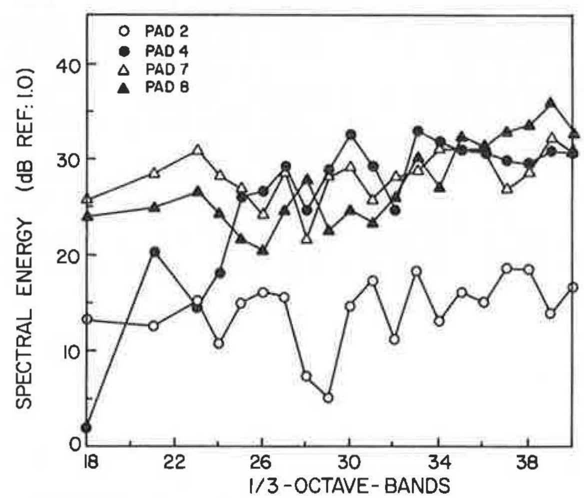

FIGURE 14 Comparison of 1/3-octave-band power spectra of the four test pad contact pressures.

Other contact information can also be extracted from the contact pressure profiles and the enveloped tire geometry as required to provide insight into factors influenced by road surface texture in tire-pavement interaction.

SUMMARY

Demonstrated in this paper are the capabilities of a computational algorithm for approximating contact information resulting directly from road surface texture in tire-pavement interaction. The methodology incorporated in the algorithm is developed to operate on a microcomputer and to use input information that is accessible, or obtainable, by the research community. The texture-induced contact information produced by the algorithm can be applied to understand and predict factors influenced by surface texture such as tire noise, pavement skid resistance, rolling resistance, and vehicle performance.

Current research is directed toward incorporating the computational algorithm into a generally available software package that can be implemented by the research community to compute texture-induced contact information given the road surface profile data and relate this information to factors such as skid resistance, tire noise, and rolling resistance. Efforts are also directed toward predicting the total forcing function in the tire-pavement contact region by combining the texture-induced forces with the effects of tread pattern and global pressure distribution over the tire footprint.

ACKNOWLEDGMENTS

The authors wish to thank the Federal Highway Administration, U.S. Department of Transportation, for support of this research and for its administration through the Office of University Research.

REFERENCES

1. D.F. Moore. The Friction of Pneumatic Tyres. Elsevier Scientific Publishing Co., Amsterdam, The Netherlands, 1975.
2. A.C. Eberhardt. An Experimental and Analytical Investigation of the Vibration Noise Generation Mechanism in Truck Tires. Report DOT-HS-8-02020. U.S. Department of Transportation, 1981.
3. L.W. DeRaad. The Influence of Road Surface Texture on Rolling Resistance. SAE Paper 780257. Society of Automotive Engineers, Warrendale, Pa., 1978.
4. S.K. Jha. Identification of Road/Tyre Induced Noise Transmission Paths in a Vehicle, International Journal of Vehicle Design and Components, Vol. 5, No. 1-2, Jan. 1984, pp. 143-158.
5. A. Browne, K.C. Ludema, and S.K. Clark. Contact Between the Tire and Roadway. Mechanics of Pneumatic Tires. NHTSA, U.S. Department of Transportation, 1981.
6. T.G. Clapp. Approximation and Analysis of Tire-Pavement Contact Information Resulting from Road Surface Roughness. Ph.D. dissertation, North Carolina State University, Raleigh, 1985.
7. T.J. Yeager and F. Buhlmann. Macrotexture and Drainage Measurement on a Variety of Concrete and Asphaltic Surfaces. Pavement Surface Characteristics and Materials. ASTM STP 763. C.M. Hayden, ed., American Society for Testing and Materials, 1982, pp. 16-30.
8. L.A. Galin. Contact Problems in the Theory of Elasticity. Department of Mathematics, North Carolina State University, Raleigh, Oct. 1961.
9. N.I. Muskhelishvili. Some Basic Problems of the Mathematical Theory of Elasticity. P. Noordoff Ltd., Groningen, The Netherlands, 1953.
10. T.G. Clapp. Spectral Correlation of the Surface Profile in the Development of a Tire and Pavement Interaction Force Model. Master's thesis, North Carolina State University, Raleigh, 1983.
11. A. Ralston and P. Rabinowitz. A First Course in Numerical Analysis, McGraw-Hill Book Co., New York, 1978.
12. J.E. Dennis and R.B. Schnabel. Numerical Methods for Unconstrained Optimization and Nonlinear Equations. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1983.
13. G.H. Golub and C.F. VanLoan. Matrix Computations. Johns Hopkins University Press, Baltimore, Md., 1983.
14. R.D. Kilmer. Truck Noise I-C. Report DOT-TST-76-48. U.S. Department of Transportation, 1975.

Publication of this paper sponsored by Committee on Surface Properties--Vehicle Interaction.