

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle <b>VEHICLE-PAVEMENT INTERACTION STUDY</b>		5. Report Date <b>October 1974</b>	
7. Author(s) <b>R. M. Olson, J. H. Johnson, and B. M. Gallaway</b>		6. Performing Organization Code	
9. Performing Organization Name and Address <b>Texas Transportation Institute Texas A&amp;M University College Station, Texas 77843</b>		8. Performing Organization Report No. <b>Research Report 138-7F</b>	
12. Sponsoring Agency Name and Address <b>Texas Highway Department P. O. Box 5051 Austin, Texas 78763</b>		10. Work Unit No.	
		11. Contract or Grant No. <b>Study 2-8-69-138</b>	
15. Supplementary Notes <b>Research done in cooperation with DOT, FHWA. Research Study Title: "Vehicle-Pavement Interaction Study"</b>		13. Type of Report and Period Covered <b>Final - September 1968 October 1974</b>	
		14. Sponsoring Agency Code	
16. Abstract <p>This final report describes methods, procedures, and results of a study commenced in September 1969. Investigations were made in the laboratory on selected pavement surfaces, measurements were made on pavement surfaces on Texas highways and on control surfaces constructed at the Texas A&amp;M Research Annex. The effect of rainfall was examined and an equation was developed to relate water depth to other variables. Finally, an expression was developed relating pavement characteristics, water depth, vehicle speed, and tire tread depth to skid or friction number.</p>			
17. Key Words <b>Microtexture, macrottexture, cross slope, pavement water depths, skid resistance</b>		18. Distribution Statement	
19. Security Classif. (of this report) <b>Unclassified</b>	20. Security Classif. (of this page) <b>Unclassified</b>	21. No. of Pages <b>65</b>	22. Price

VEHICLE-PAVEMENT INTERACTION STUDY

by

R. M. Olson, J. H. Johnson,

and

B. M. Galloway

Research Report Number 138-7F

Vehicle-Pavement Interaction Study  
Research Study Number 2-8-69-138

Sponsored by

the Texas Highway Department

in Cooperation with

U. S. Department of Transportation

Federal Highway Administration

October 1974

TEXAS TRANSPORTATION INSTITUTE  
Texas A&M University  
College Station, Texas



## DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

## TABLE OF CONTENTS

	Page No.
Introduction . . . . .	1
Microtexture Measurements of Pavement Surfaces . . . . .	2
Preliminary Measurements with Surfindicator . . . . .	6
Recommendations . . . . .	8
Macrottexture, Friction, Cross Slope, and Wheel Track Depression Measurements on 41 Typical Texas Highway Pavements . . . . .	10
Highway Friction Measurements with Mu-Meter and Locked Wheel Trailer . . . . .	17
Effects of Pavement Surface Characteristics and Textures on Skid Resistance . . . . .	24
The Effects of Rainfall Intensity, Pavement Cross Slope, Surface Texture, and Drainage Length on Pavement Water Depths . . . . .	30
Influence of Water Depths on Friction Properties of Various Pavement Types . . . . .	46
Analysis and Discussion of Test Results . . . . .	57
References . . . . .	64

## LIST OF FIGURES

Figure	Page No.
1. Surface Tracer Recordings and Governing Equations . . . . .	5
2. Average Friction-Velocity Comparisons For Different Test Conditions . . . . .	20
3. Skid Test Layout for Highway Pavement Section . . . . .	26
4. Diagrammatic Representations of Zero and Water Depth Measurements . . . . .	37
5. Plot of Water Depths Versus Variables for Combined Surfaces . . . . .	40
6. Plot of Average Surface Detention Versus Variables for the Combined Surfaces . . . . .	42
7. Frictional Trends for Slipping and Skidding Tires on Dry and Wet Pavements . . . . .	48
8. The Three Zones of the Contact Area of a Tire . . . . .	49
9. Drawing of the Test Pads . . . . .	50
10. Gradient and Percentage Gradient Calculations . . . . .	56
11. Effects of Pavement Texture Depths (TXD), Tire Tread Depths (TD), and Water Film Depths (WD) on the Skid Number at Various Speeds for the ASTM-14" Tire at 24 psi Tire Inflation Pressure, TAMU Annex Data. . . . .	62

## LIST OF TABLES

Table	Page No.
1. Skid Number and Macrotexture Values . . . . .	15
2. Cross Slope and Wheel Track Depression Summary Data . . .	15
3. Descriptions of the Surfaces Placed on the Beams . . . .	33
4. Testing Series . . . . .	35
5. Tabular Representation of the Relative Effects of Cross Slope, Texture, Drainage Length, and Rainfall Intensity on Water Depth . . . . .	39
6. Tabular Representation of the Relative Effects of Cross Slope, Texture, and Rainfall Intensity on Average Surface Detention . . . . .	41
7. Descriptions of the Test Surfaces . . . . .	51
8. Experimental Finishes of Portland Cement Concrete Test Sections . . . . .	53





## IMPLEMENTATION

The findings of this study have been given extensive exposure, and partly as a result of these findings, specifications for drainage at the tire-pavement interface have been included in an ever increasing number of design and construction procedures.

Data from this study have conclusively shown that skid numbers obtained by use of locked wheel trailers of the ASTM 274-70 type can be misleading as barometers of pavement performance at high speeds under inclement weather conditions. Efforts are now being made to determine whether correlations exist between skid number and speed using the standard internal watering system of the ASTM trailer and skid number speed gradients under simulated rain. From information presented in the study, the researchers confirmed a previous conclusion that the widely used skid trailer is primarily a survey and inventory device and is not necessarily suitable for determining possible hazards in the actual skid characteristics of pavements during rainy weather. The need for continued and extended implementation of wet weather advisory speed warnings is emphasized. Macrotexture values in the 0.04 to 0.05 range are recommended for high speed traffic and values above this range should be sought wherever technically and economically practical. Adequate microtexture is considered necessary at all reasonable vehicle speeds.



## INTRODUCTION

This final report describes methods, procedures, and results of a study commenced in September 1969. A more detailed description of the work conducted may be found in six reports submitted previously (1, 2, 3, 4, 5, 6). Investigations were made in the laboratory on selected pavement surfaces, measurements were made on pavement surfaces on Texas highways and on control surfaces constructed at the Texas A&M Research Annex. The effect of rainfall was examined and an equation was developed to relate water depth to other variables. Finally, an expression was developed relating pavement characteristics, water depth, vehicle speed, and tire tread depth to skid or friction number. The several efforts and significant results will be discussed in the following sections, entitled:

1. Microtexture Measurements of Pavement Surfaces.
2. Macrotecture, Friction, Cross Slope, and Wheel Track Depression Measurements on 41 Typical Texas Highway Pavements.
3. Highway Friction Measurements with Mu-Meter and Locked Wheel Trailer.
4. Effects of Pavement Surface Characteristics and Texture on Skid Resistance.
5. The Effects of Rainfall Intensity, Pavement Cross Slope, Surface Texture, and Drainage Length on Pavement Water Depths.
6. Influence of Water Depths on Friction Properties of Various Pavement Types.



## MICROTEXTURE MEASUREMENTS OF PAVEMENT SURFACES

The texture of a pavement surface is that characteristic of the surface profile consisting of a series of rather abrupt changes in elevation. Variation in textures can result from different sizes of aggregates on the pavement surface and from various pavement finishing operations. In general, textures can be categorized into three groups:

- a. Large-scale macroscopic texture
- b. Small-scale macroscopic texture
- c. Microscopic texture

A review of some of the available methods of texture measurements was made, and a brief preliminary investigation was conducted to evaluate the device and to determine its applicability to microtexture measurements of pavement surfaces.

Research Report 138-1 presents the results of these investigations, along with some recommendations. Some of the techniques described can be used for microtexture as well as macrotexture measurements. However, the techniques are primarily applicable to microscopic textures and are as follows:

### 1. Subjective Method, Dial Gauges and Light

The senses of touch and sight have been used for many years to determine the texture of finished surfaces. A system of dial gauges for evaluating the textures of finished surfaces has been developed. The major disadvantage of the dial gauge evaluation is the requirement for a large number

of laborious and time-consuming measurements.

Light can be used in several ways to help analyze surfaces. A technique known as light sectioning is a simple method used to obtain a representation of a surface texture. A beam of light is passed between two parallel, optically flat plates spaced by means of shims. The resulting slit of light is focused on the surface at an angle, and the reflection which is the apparent profile height is photographed through a microscope. The actual profile height is then mathematically determined.

## 2. Stylus Tracer

A technique using a stylus tracer is the most accurate method of surface texture analysis. With this method, a stylus is passed over the surface to be evaluated. By electrical, mechanical, or optical connection to the stylus, the response is transferred to a recorder or to an averaging meter. The result is a representation of the surface in the form of a profile picture, profile graph or an average value. For a simple mechanical linkage connecting the stylus to a recorder pen, the magnification can be controlled by the lever ratio in the system. In an optical-mechanical instrument, the oscillating stylus is mechanically connected to a tilted mirror that reflects a beam of light to a photographic paper and records a trace of the oscillating stylus.

## 3. True-Datum and Surface-Datum Pickups

Pickups for the two electronic measuring devices discussed previously fall into two categories: true-datum and surface-datum pickups. The true-datum pickup measures surface textures with respect to an optically flat datum, parallel to the surface being measured. A continuous plot is obtained of continuously amplified distances between the surface and the datum.

The surface-datum pickup has a shoe or a rider which passes over the

surface being measured. This shoe is very near or for some instruments surrounds the stylus. The measurement obtained is a plot of the position of the surface in relation to the shoe.

#### 4. Surface-Tracer Recordings

Surface-tracer recordings must be evaluated and characterized preferably by a numerical value. Two methods of assessing the surface-tracer recordings mathematically involve integration of the curve representing the surface as shown in Figure 1. Both methods use a centerline placed through the curve by a least squares fit.

Some instruments are equipped with dial gauges indicating the  $H_{CLA}$  and  $H_{RMS}$ .

Other methods involving simple measurements of tracer recordings include distance between lines representing average peak height and average valley depth or simply the average depth. These measurements neglect the influence of peak spacing.

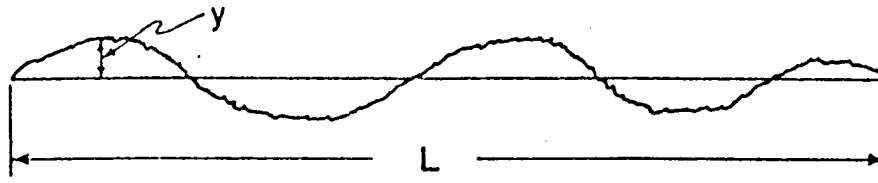
#### 5. Surfindicator

From the review of available literature and printed information, the following characteristics of the Clevite Model BL-185 Surfindicator can be listed:

1. The Surfindicator is a potential-generating device for measuring, in general, milled, ground or sanded surfaces;

2. It has a stylus with a diamond tip of 0.0005 inch in diameter; the stylus can move vertically through a maximum distance of approximately 0.06 inch.

3. It provides  $H_{CLA}$  or  $H_{RMS}$  readings, depending on the calibration from one to 1,000 microinches on a dial gauge;



$$H_{CLA} = \frac{1}{L} \int_0^L y \, dL$$

$$H_{RMS} = \sqrt{\frac{1}{L} \int_0^L y^2 \, dL}$$

Where:  $H_{CLA}$  = average distance from the centerline to the curve (centerline average), and

$H_{RMS}$  = root mean square distance.

Figure 1. Surface Tracer Recordings and Governing Equations.



4. It provides peak-to-peak spacing cutoff of 0.003, 0.010, and 0.030 inch (0.030 is generally used); and

5. It is reported to provide a limited compensation for variations in readings caused by changes in speed of stylus movement. (A precision constant speed traversing instrument, Surfdrive-70 designed to mechanically traverse the probe used with the BL-185, is available for purchase but was not used in this investigation.

#### PRELIMINARY MEASUREMENTS WITH SURFINDICATOR

In December 1969, the Texas Highway Department forwarded an electronic device that may be applicable for measuring the textures of pavement surfaces and referred to as the Surfindicator, Model BL-185, manufactured by the Clevite Corporation. The device is used to measure the textures of uniformly machined surfaces such as those on metallic products. It is capable of sensing both small-scale macroscopic and microscopic textures.

Preliminary microtexture measurements were made with the Clevite Surfindicator BL-185 on the surfaces of 4-inch diameter asphaltic concrete cores and small sawed sections obtained from various highways and marked areas (approximately one foot by two feet) of the standard skid test surfaces at the Texas A&M Research Annex. An extensive program of measuring microtexture of various road surfaces depended on the results of the preliminary measurements and their correlation with skid-resistant values.

In general the test procedure recommended by the manufacturer was followed in measuring the microtexture of the surfaces with the BL-185 Surfindicator. Briefly, the procedure consisted of providing a brief period of equipment warm-up followed by zeroing and balancing. A standard calibration block with a tex-

ture of 125 microinches was then used to calibrate the Surfindicator. The pickup with the holder was placed on the standard surface, and the pickup was moved by hand in a steady oscillating manner with a speed in a range from 1/3-inch to 1/4-inch per second. No mechanical means of measuring the speed was available, and the operator had to rely on judgement. The stroke was 3/4-inch. A dial gauge displayed the  $H_{CLA}$  reading in microinches. The calibration screw was adjusted until a deliberate increase in the speed of movement caused only a minimum increase in the reading from the standard 125 microinches.

The instrument was separately calibrated at peak-to-peak spacing cutoff of 0.003, 0.010, and 0.030 inch to obtain readings in  $H_{CLA}$ . However, the 0.030-inch cutoff value was used for most of the tests, since it is the one normally specified. The other cutoff values were used to determine if the results trended similarly to the 0.030 cutoff.

A minimum of three texture measurements were taken on each of the test specimens or test areas and were averaged to obtain the results. Test locations were randomly selected on the test specimens and surfaces. However, locations with apparent deep holes were avoided. The number of test specimens available per highway ranged from one to eight. Four test locations per test surface were selected at the Research Annex. For test surfaces and specimens with exposed flat aggregates, measurements were made on the aggregates as well as on the composite surfaces.

It was found from the investigation that since the Surfindicator was built primarily to measure textures of uniform surfaces such as machined, ground, or sanded metallic parts with a roughness up to 1,000 microinches, the instrument has some undesirable features for measuring microtextures of pavement surfaces. The major undesirable features include the sensitivity

to speed of tracing or of stylus movement, and the readings displayed on a dial gauge. The possible effects of these features result in fluctuating readings and in obtaining questionable measures of microtextures.

The measured microtexture values increased with increasing skid numbers, but the results of a statistical analysis did not indicate a high correlation between skid numbers and microtexture. Results of another statistical analysis indicated, however, that the Surfindicator is capable of showing differences in microtextures of pavement test surfaces at the Research Annex.

#### RECOMMENDATIONS

The following recommendations were made:

1. Further microtexture measurements with the BL-185 Surfindicator should be limited to occasions when testing can be done with a minimum of cost. That is, an extensive microtexture testing program on surfaces of various test sections together with skid measurements appears unwarranted at this time. However, if possible, testing with the Surfindicator should be considered and included as additional work associated with other test programs.

2. A texture-measuring device should be developed incorporating all the desirable features found in this investigation and others based on past experience. Such a device would incorporate the following features:

- a) A framework similar to the THD Profilograph,
- b) A mechanism consisting of LVDT, oscillating device, and an interchangeable pointer mounted on the framework, and,
- c) Appropriate electronic devices and a recorder to record the tracings of the surface profile, and the centerline average heights or the distribution of the various texture heights in a given traverse length.

In the operation of the device, the mechanism will move along a plane

nominally parallel to the surface. The oscillating device will move the pointer up and down with a certain amplitude during the translation to prevent any binding of the pointer. Tracings and centerline average heights will be recorded with two sizes of the pointer, the larger measuring macrotexture and the smaller measuring both the macro- and microtextures. Difference of the two measurements should provide the microtexture of the pavement surface.

3. Consideration should be given to the extent to which the tire tread rubber "wets" the surface aggregate as it passes or is dragged over the road surface. In general the device visualized should reflect only that part of the pavement microtexture that would normally be touched by the tire rubber. If, for example, the surface being evaluated possessed considerable macrotexture, actual rubber contact would be limited primarily to the upper segments of the large stones in the pavement surface; whereas on a relatively smooth surface with little macrotexture, the tire rubber might "wet" or contact essentially all the surface as it passed over it.

Additionally, such factors as tire tread depth, tread configuration, rubber hardness, tire inflation pressure, vehicle speed, and environmental effects among others would influence the evaluation. These factors and other considerations will be discussed in more detail later in this report.

MACROTEXTURE, FRICTION, CROSS SLOPE, AND WHEEL TRACK DEPRESSION  
MEASUREMENTS ON 41 TYPICAL TEXAS HIGHWAY PAVEMENTS

Friction properties of pavement surfaces have become factors of major importance to traffic safety. It must be assumed, human nature being what it is, there will be drivers who, for various reasons, will contribute to the hazards of the driving public. Selected changes in design and construction specifications may compensate for such behavior.

Pavement surface texture refers to the distribution and the geometrical configuration of the individual surface aggregates, as discussed earlier. Friction measurements are used for evaluating skid resistant properties of pavement surfaces; however, standard skid measurements may be misleading as barometers of performance under inclement weather conditions. Skid resistant properties, such as macrotexture, drainage characteristics of the surface, and aggregate size, shape, microtexture and mineralogy, need to be characterized. Tests with the Texas Highway Department skid trailer, and macrotexture tests utilizing four methods were conducted on 41 pavement surfaces, which exhibited widely different friction levels, friction-speed gradients, drainage capabilities, mineralogical properties, and texture classifications.

The role of macrotexture in imparting friction capabilities to pavement surfaces is of major concern. Macrotexture is one of several variables that affect the interaction at the tire-pavement interface; however, at present its relative importance is questioned. Macro- and microtexture provide for gross surface drainage and subsequent puncturing of the water film. Internal drainage of the pavement surface also acts in combination with macro- and microtexture.

It is the opinion of the authors that the combined effects of macro- and micro-texture and internal drainage largely determine the friction levels of pavement surfaces. The effects of macrotexture will be considered herein.

Agencies in the United States and other countries are engaged in developing methods for measuring pavement surface macrotexture to more fully evaluate its role in vehicle braking, cornering, and accelerating maneuvers. These different methods for measuring pavement surface macrotexture were analyzed and compared. The various methods are:

- |                       |  |
|-----------------------|--|
| 1. Sand Patch         | 7. Casting or Molding                      |
| 2. NASA Grease        | 8. Impression                              |
| 3. Drainage Meter     | 9. Centrifuge Kerosene Equivalent (CKE)    |
| 4. Foil Piercing      | 10. Wear and Roughness Meter               |
| 5. Linear Traverse    | 11. Mineralogical Studies and Profilograph |
| 6. Stereophotographic | 12. Photo-Interpretation                   |

Four methods employed in this study produced five measures of macrotexture. Two measures of average peak height and two measures of average texture depth were obtained, and these measurements were reduced to equivalent units. In addition, one measure of accumulative peak height was obtained. A brief description of each method is as follows:

1. Profilograph Method. The instrument is designed to scribe a magnified profile of the surface texture as a probe is drawn across the surface. The probe is placed on the pavement surface and, as the probe is drawn over the surface irregularities, the vertical movement of the probe is magnified through a linkage system. The probe and linkage system are attached to a carriage that is forced to move in a horizontal manner parallel to the pavement surface. The vertical and

horizontal movement produces a magnified texture profile which is scribed on a chart, from which average peak height can be determined. Also, the upward vertical excursions are recorded on a counter which permits reading, at any time, of the cumulative vertical peak heights of the texture through the length traversed by the probe.

2. Texturemeter Method. The instrument consists of a series of evenly spaced, parallel rods mounted in a frame. The rods can be moved vertically, independently of one another, against spring pressure. At either end of the series of movable rods is a fixed rod rigidly attached to the frame. Each movable rod is pierced by a hole through which passes a taut string, one end of which is fixed to the frame and the other to the spring loaded stem of a dial gauge mounted on the frame. When the instrument is in use, the rods are held in a vertical position with their ends resting against the pavement surface. If the surface is smooth, the string will form a straight line, and the dial will read zero. Any irregularities in the surface will cause the string to form a zig-zag line and will produce a dial reading; the coarser the pavement texture, the larger the dial reading. Average peak height can be calculated from the dial reading. The readings given by an instrument of this kind are affected by the size and spacing of the rods and the distance spanned by these rods.

3. Modified Sand Patch Method. Equipment consists of 100 grams of fine grained sand, a rectangular metal plate having a rectangular hole in it, and a straight edge. The technique involves determining the volume of sand required to fill the cavity of a non-textured surface. When the plate is placed on a textured surface, the bottom of the plate will rest on the upper asperities of the aggregate. The more irregular the surface

texture, the larger the resulting weight of sand required to fill the cavity. The average texture depth is defined as the ratio of the increased volume of sand to the area of the patch.

4. Putty Impression Method. The measurements are made by using a ball of silicone putty weighing 15.90 grams, and a cylindrical metal plate which has a recess machined in one side. Calibration is made on a flat, smooth surface. The silicone ball is formed by hand into a spherical shape and placed on the flat surface. The plate recess is centered over the ball of putty and pressed downward by hand until the plate comes into firm contact with the smooth surface. The putty will completely fill the recess. The process is the same on a pavement surface; however, since the pavement is not smooth and flat, the putty will not completely fill the recess in the plate. The more irregular the surface texture (the higher the macrotexture), the smaller the resulting putty diameter because some of the silicone is pressed into the surface texture. Average texture depth, based on volume per unit area, is calculated from an average of four diameter measurements.

#### Cross Slope and Wheel Track Depression Measurements

A 1-3/4-inch by 4-inch by 12-foot long aluminum box channel marked at one foot increments was used.

For the cross slope measurements, a bubble level was attached to the channel. The channel was leveled transversely to the direction of travel and the difference in elevation from the inside to the outside of the lane was measured directly with a ruler. The average cross slope, expressed in inch per foot and foot per foot across the total width of the lane was computed.

The channel was placed flush with the pavement surface for wheel track



depression measurements. A ruler was used to measure directly the inner and outer wheel track depressions.

The pavement surfaces included 21 hot mix asphalt concrete surfaces, 9 portland cement concrete surfaces, 9 surface treatments and 2 seal coats. The test surfaces were selected with regard to level of service, degree of polish, and traffic volume. In addition, the test sample included at least ten surfaces from each major surface category of the Texas Highway System. The array of surface types included the various mineralogical types and aggregate size configurations commonly used in Texas. A summary of information obtained is presented in Tables 1 and 2.

A series of 20, 40, and 60 mph skid tests was conducted at four locations on each surface. Ten texture measurements were taken at each location for a total of forty measurements per surface. All measurements were made in the outer wheel path.

Average skid numbers at 20, 40, and 60 mph, respectively, with appropriate temperature corrections were calculated for each test surface. In addition, for use in subsequent comparisons, average skid numbers between 20 and 60 mph were calculated.

Gradients (denoted by G) of the skid number speed curve between 20 and 60 mph and between 20 and 40 mph were calculated. Percentage gradients were also calculated to reflect the relative position of the curve. Curves of a given gradient positioned low on the graph would have higher percentage gradients than curves with the same gradient positioned higher on the graph. Therefore, percentage gradient is defined as the percentage of the gradient, obtained under test conditions, to a theoretical gradient if the skid number at the higher speed were zero. Statistical analyses were conducted to determine the correlation coefficients, coefficients of determination and regression lines

Table 1. Skid Number and Macro-Texture Values

Surface Type	Number Tested	Range Skid Number, 40 mph	Range Macro-Texture, inches
Hot Mix Asphalt Concrete	21	29-59	0.01 - 0.04
Portland Cement Concrete	9	36-45	0.01 - 0.04
Surface Treatment	9	29-65	0.02 - 0.07
Seal Coat	2	18-27	0.00 - 0.01

TABLE 2. CROSS SLOPE AND WHEEL TRACK DEPRESSION SUMMARY DATA

Service Category	Number of Surfaces Tested	Field Measurements				
		Average Rate of Cross Slope			Wheel Track Depression	
		Inch per Foot	Inch per Foot	Foot per Foot	Inside Wheel Track, Inch	Outside Wheel Track, Inch
<u>Interstate (IH)</u> Marked Routes	11	.15	5/32	.013	1/64	1/64
<u>Federal (US)</u> Marked Routes	9	.15	5/32	.013	3/64	7/64
<u>State (St)</u> Marked Routes	7	.18	3/16	.015	3/64	5/64
<u>Farm (FM)</u> Marked Routes	9	.22	7/32	.018	1/8	5/32
Test Surfaces Texas A&M Annex	5	.14	9/64	.011	0	0

for the comparisons established in the study.

The four methods used to evaluate pavement surface macrotexture provide acceptable data and furthermore texture values obtained by the several methods compared favorably. The profilograph method for measurement of macrotexture is preferred because of its simplicity, reproducibility, and better correlation with friction parameters. Statistically, however, results with the profilograph do not relate favorably with friction parameters.

For the water film thicknesses used in this study, no correlation was found between 20, 40 and 60 mph skid numbers and macrotexture. Poor correlation was found between gradients of the friction speed curve and macrotexture. Fair correlation was found between percentage gradients of the friction-speed curve and macrotexture. A relationship between gradient and skid number was not developed. These findings among others led to further investigations which are reported in the following sections of this summary report.

One conclusion deserves emphasis: An increase in cross-slope of pavements is indicated, particularly on pavements having a low level of macrotexture and which are zoned for vehicle operation at high speed.

## HIGHWAY FRICTION MEASUREMENTS WITH MU-METER AND LOCKED WHEEL TRAILER

The principal causes of pavement slipperiness are: (1) the presence of water in the tire-pavement contact area which, with increasing vehicle speeds, lowers the obtainable friction drag and raises the frictional demand, and (2). higher traffic volumes which, through pavement wear and aggregate polish, drastically reduce built-in friction potential of most new pavement surface types.

Friction measurements of the tire-pavement combination are widely accepted for evaluating the skid-resistant properties of pavement surfaces, and are essential to the determination of what occurs at the tire-pavement interface under different environmental conditions. Many agencies rely on coefficient of friction values derived from skid mode friction tests for evaluating pavement surface types and other factors relative to their effect on achieving adequate contact forces between wet pavement surfaces and vehicle tires. However, standard skid measurements may be misleading as indicators of performance under inclement weather conditions.

The objectives of this study were to investigate, through field studies on operational pavements, the effects of water drainage on friction values obtained from two devices, one operating in the slip mode and one operating in the skid mode.

Two series of 20, 40, 60, and 80 mph friction tests were conducted, with a Mu-Meter and the Texas Highway Department research skid trailer, under wet and dry conditions, at four places on each surface. The tests involved smooth

and treaded tires inflated to pressures of 10 and 24 psi. These conditions were used in an attempt to better evaluate their relative effects on the slip and skid modes. Other variations were incorporated into the study to gain a better insight to the overall problems.

The Soiltest ML-400 Mu-Meter Friction Recorder is a continuous recording friction-measuring trailer that determines the frictional characteristics of treadless tires operating in the cornering slip mode. It is used to measure the cornering-force friction coefficient generated between the test surface and the pneumatic tires on two running wheels that are set at a fixed 7 1/2-degree toe-out (yaw) angle to the line of drag.

The Research Skid Trailer, an instrument of the Texas Highway Department, is used to measure skid resistance. The trailer utilizes E-17 circumferentially grooved treaded tires inflated to 24 psi. The drag forces are measured with strain gauges, and a self-watering system used a centrifugal pump that applies approximately 0.020-inch water film thickness to the pavement surface.

The testing sequence at each site was as follows: (1) a series of 20, 40, 60, and 80 mph tests with the Mu-Meter on dry pavement, (2) a series of 20, 40, 60, and 80 mph tests with the trailer on pavement wetted by the trailer's self-contained internal watering system, and (3) a series of 20, 40, 60, and 80 mph tests with the trailer and Mu-Meter on pavement wetted by a water truck. In the third sequence the measurements were taken concurrently with the Mu-Meter lagging approximately 100 feet behind the trailer at each respective test speed. Measurements were made in the wheel path with the position of the Mu-Meter wheels nearly the same as the skid trailer wheels.

Fifteen surfaces were tested using the following equipment and conditions:

1. Mu-Meter -- 10 psi, smooth (or treadless) tire, surface dry

2. Trailer -- 24 psi, E = 17 circumferentially grooved tire, surface wet internally.
3. Trailer -- 24 psi, E = 17 circumferentially grooved tire, surface wet externally.
4. Mu-Meter -- 10 psi, smooth tire, surface wet externally.

Tests were also conducted on several of the surfaces using the following additional conditions:

5. Mu-Meter -- 24 psi, smooth tire, surface dry
6. Trailer -- 24 psi, smooth tire, surface wet externally
7. Mu-Meter -- 24 psi, smooth tire, surface wet externally

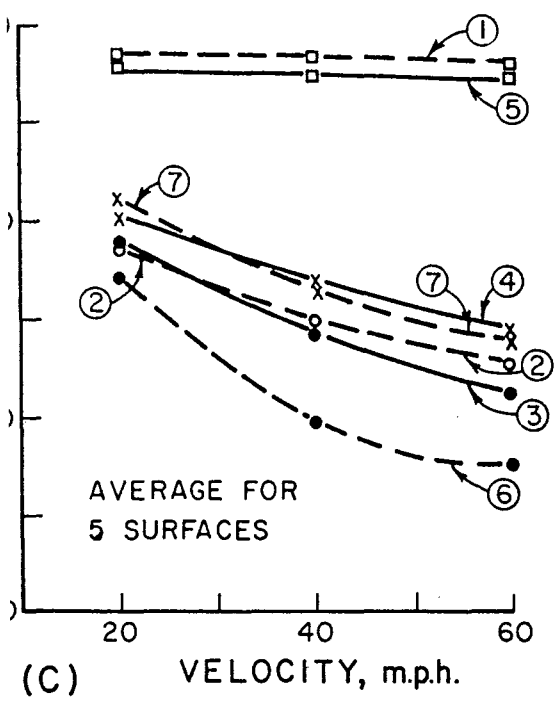
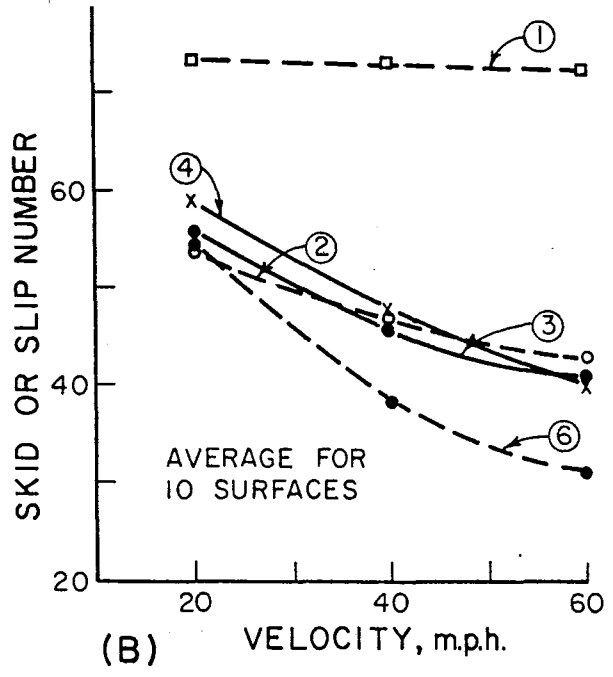
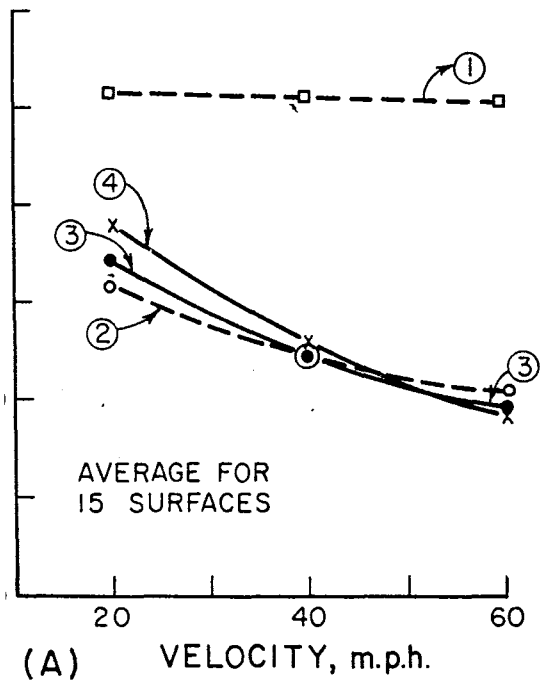
Macro-texture tests by profilograph or putty impression methods were made.

Individual test spots at each location were located in the outer wheel path, spaced approximately 50 feet apart.

The variables introduced under controlled conditions for the tests were:

1. Test surfaces, classified with respect to type, mineralogical classification, and aggregate size configuration.
2. Friction mechanism and method, cornering slip with the Mu-Meter, and skidding slide with the trailer. Values are reported as slip and skid numbers respectively.
3. Pavement condition with respect to absence or presence of water film; dry implies no water film, wet implies approximately 0.020-inch water film thickness.
4. Process of wetting pavement, internal implies utilization of the skid trailer's self-contained watering system, external implies use of a water truck as a separate operation.
5. Tire crown configuration with respect to absence or presence of grooves - smooth (or bald) tire implies no tread, E-17 tire implies the standard circumferentially grooved tread.
6. Tire inflation pressure, 10 or 24 psi as indicated.

Average friction number-velocity values for the test surfaces are plotted with respect to the seven test conditions in Figure 2. Ten of the surfaces were



**LEGEND**

- 1. MU-METER, SMOOTH TIRE 10 psi, SURFACE DRY
- 2. THD TRAILER, E-17 TIRE 24 psi, SURFACE WET-INTERNAL
- 3. THD TRAILER, E-17 TIRE 24 psi, SURFACE WET-EXTERNAL
- 4. MU-METER, SMOOTH TIRE 10 psi, SURFACE WET-EXTERNAL
- 5. MU-METER, SMOOTH TIRE 24 psi, SURFACE DRY
- 6. THD TRAILER, SMOOTH TIRE 24 psi, SURFACE WET-EXTERNAL
- 7. MU-METER, SMOOTH TIRE 24 psi, SURFACE WET-EXTERNAL

**FIGURE 2. AVERAGE FRICTION-VELOCITY COMPARISONS FOR DIFFERENT TEST CONDITIONS.**

tested under five different test conditions; these data are shown in Figure 2-B.. Data were obtained on an additional five surfaces with only four test conditions; these results are given in Figure 2-A. Figure 2-C contains complete data as obtained with the seven conditions on five surfaces.

The Mu-Meter results indicate that slip numbers are not affected by velocity increase on dry pavements. On wet pavements both the Mu-Meter (smooth tire) and trailer (E-17 tire) results reflect the characteristic decrease in friction with increase velocity. On the average, at 20 mph, both instruments indicate the same magnitude. (See Figure 2-A, condition 3 and 4.) Results from the trailer operating with a smooth tire (condition 6) compared favorably with both the Mu-Meter (smooth tire) and the trailer (E-17 tire) at 20 mph; however, much lower values were obtained at higher speeds. (See Figure 2-B). This is to be expected when consideration is given to the fact that the Mu-Meter is operating in the slip mode, whereas the trailer is operating in the skid mode, thus, higher friction values are expected in the slip mode if other conditions are maintained constant.

The use of a treaded tire on the trailer will generally provide sufficient drainage at high speeds to increase the friction to that of an instrument operating in the slip mode with a smooth tire. At the lower speeds, however, drainage effects are reduced and the overriding effects of the slip mode prevail; thus, the Mu-Meter records slightly higher friction values. (See Figure 2-A and B, conditions 3 and 4.) However, these conclusions are specific and will not necessarily be true for all surface types, equipment, variables and/or environmental conditions. For example, in Figure 2-C, the curves for conditions 3 and 4 differ appreciably when the average curves represent only five surfaces.

The summary statements listed below are tentative and therefore subject to revision as data from this and other studies are accumulated and evaluated.



Furthermore, these statements are predicated on the test procedures, equipment, and environmental conditions associated with the data gathering process.

1. The Mu-Meter and skid trailer correlate rather well when smooth-treaded tires are used on both instruments. Correlation coefficients of 0.94, 0.92, and 0.96 were obtained at 20, 40, and 60 mph respectively. Average results reveal slightly higher friction when measured with the Mu-Meter as compared to the trailer. This is expected since available friction in the slip mode is greater.

2. Friction numbers obtained with the E-17 treaded tire (trailer) correlated poorly with those obtained with smooth tires on both the trailer and Mu-Meter. Nearly identical correlation coefficients, averaging 0.86, 0.80, and 0.75 at 20, 40, and 60 mph, respectively were obtained for both comparisons. The decrease in correlation with increased speeds is a function of the relative drainage capabilities of the E-17 (tread) and smooth tires, with relative differences greater at higher speeds when drainage becomes very critical for surfaces with poor drainage capabilities. Friction does not differ greatly on surfaces with good drainage capabilities when measured with either treaded or smooth tires.

3. Comparison of external versus internal pavement wetting processes for the skid trailer tests revealed correlation coefficients of 0.92, 0.93, and 0.93 at 20, 40, and 60 mph, respectively. At 20 mph, the external process gave a slightly higher average value, whereas, at 60 mph the reverse was true. At 40 mph the averages were identical.

4. Extremely poor correlation was obtained between dry and wet pavement friction tests with the Mu-Meter. Dry pavement friction was unaffected by test speed variations and in addition, was only affected to a small extent by surface type. All surfaces exhibited high friction properties when tested in the

dry condition.

5. Variations in tire pressure had little influence on Mu-Meter values on wet roads.

6. Gradients of the friction velocity curves as obtained with both instruments correlated poorly. Better correlations were obtained for percentage gradients comparisons, with the Mu-Meter and trailer (smooth tire) having a correlation coefficient of 0.92. This also points up the relative drainage capabilities of E-17 (treaded) and smooth tires.

7. Skid number-gradient correlations were poor for the Mu-Meter and extremely poor for the trailer. Better correlations were obtained between skid numbers and percentage gradients, with the Mu-Meter again having the highest correlation coefficient of 0.87.

8. Forty mph skid numbers obtained with each instrument correlated poorly with macrotexture. The highest correlation coefficient of 0.56 was obtained with Mu-Meter results.

9. Relatively poor correlation coefficients were obtained for gradient-macrotexture comparisons. Substantially higher coefficients ranging from 0.60-0.85 were obtained with both instruments for wet pavement percentage gradient-macrotexture comparisons.

## EFFECTS OF PAVEMENT SURFACE CHARACTERISTICS AND TEXTURES ON SKID RESISTANCE

Improvements in highway design have permitted increased volumes of traffic at higher speeds on our highways. At the same time, the high volumes also have resulted in increased numbers of highway accidents. Many of the accidents on wet highways have been attributed to slippery conditions or lack of sufficient forces between tires and pavement to properly decelerate, corner, or accelerate the vehicles. Some of the factors that influence the forces between the tire and the pavement are: (1) design and composition of the tire, (2) operating mode of the tire, (3) pavement surface texture, and (4) thickness of water film on the pavement.

Various methods have been developed to measure the texture of pavement surfaces, and efforts have been made to correlate the textural properties with the skid resistance parameters. The large-scale macroscopic texture that affects the value of the void area between the tire tread and pavement is reported to be related to the decrease in skid number as speed increased, whereas the small-scale macroscopic texture and the microscopic texture to a lesser extent are related to the skid number.

Some Texas pavement surfaces have sufficient macrotextures to provide decreases in skid numbers below ten percent; however, many of the pavement surfaces have low values of microtexture. Certain types of aggregates retain microtextures better than others. Therefore, for prolonged high skid resistant pavements, maintenance efforts should be directed toward the construction of pavements with ample surface macrotexture and the coarse aggregates in these surfaces should wear or abrade in such a manner as to provide adequate microtexture.

The purpose of this research was to determine the relationships between skid numbers and small-scale pavement textures combined with macrotexture parameters.

By means of multiple regression analyses skid numbers were related to independent variables consisting of small-scale textures, macrotextures, and aggregate size. The test equipment consisted of the THD locked wheel research trailer, the Clevite Model BL-185 Surfindicator, the THD profilograph, the modified sand apparatus, and the putty impression apparatus.

Highway pavement test surfaces were selected to include surface courses and surface treatments with rounded gravels and crushed aggregates. A typical test section is shown in Figure 3. The purpose of selecting the test path as a diagonal across the highway was to obtain an indication of the differences in the skid number and the texture values among the center wheel path, between wheel path, inner wheel path, and the centerline of the highway. A 6-inch core specimen was obtained from each location for texture measurements with the putty impression method and with the Clevite BL-185 Surfindicator. Test speeds of 20- to 40-mph with a standard E-17 test tire and with a smooth tread tire were used in the experiments. A total of eight tests were conducted on each site.

Two macrotexture measurements of the pavement surfaces were obtained at each location with the THD Profilograph. Macrotexture measurements determined by the putty impression method were taken on the surfaces of two of the four cores obtained from the OWP, BWP, and the IWP of a selected test section. One of the two cores from the highway centerline was selected for measurement.

Texture measurements with the Clevite BL-185 Surfindicator were taken on the surfaces of all the 6-inch cores obtained from the highway pavement section,

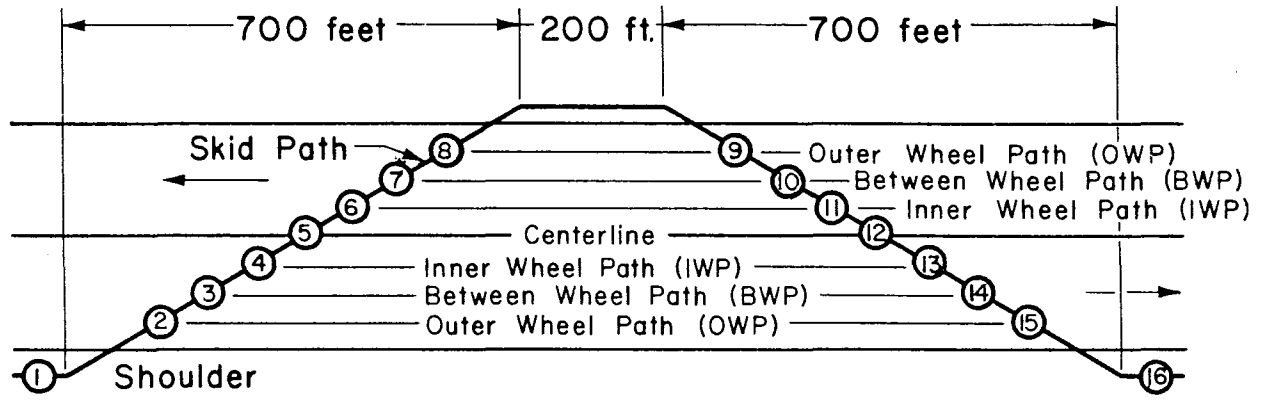


Figure 3. Skid test layout for highway pavement section.

except those taken from the shoulders. A total of 24 measurements was made on the surface of each core.

By means of multiple regression analyses, skid numbers were related to independent variables consisting of small-scale textures, macrotextures, and aggregate size. The results of the analyses of skid numbers versus small-scale pavement surface textures indicate that the 20 mph skid numbers measured with a standard ASTM E 274-65T skid trailer equipped with a standard E-17 tire provide the highest correlation coefficients. Skid numbers measured with the E-17 tire at 40 mph, and skid numbers measured with a smooth tread tire at 20 mph or 40 mph provide a lower correlation coefficient. The small-scale textures on the surfaces or on exposed aggregate particles in terms of center-line average heights can be measured with the Clevis BL-185 Surfindicator. The correlation coefficients for the  $SN_{E20}$  - Surfindicator texture relationships are statistically significant at the one percent level. However, the coefficients are not very high.

Microtextures and small-scale macrotextures were significantly correlated with 20 mph skid numbers measured with a standard skid trailer. Macrotexture and aggregate particle size factors impose the correlation coefficients. A correlation coefficient of 0.87 was obtained by relating the skid number at 20 mph to a combined independent variable consisting of: (1) the small-scale textures measured on aggregate particles by the Clevis BL-185 Surfindicator, (2) macrotexture measured by the Texas Highway Department Profilograph, and (3) the weighted particle-size factor.

Equations, used to estimate the skid numbers at 20 mph from the values of pavement surface textures and aggregate sizes are given as follows:

$$1. \text{SN}_{E20} = 0.053t_s^{1.109} T_{\text{pro}}^{-0.093}$$

$$2. \text{SN}_{E20} = 1/.725t_a^{0.523} T_{\text{pro}}^{-.0144} (\text{WPS})^{-0.291}$$

where

$\text{SN}_{E20}$  = skid number measured with the E-17 tire and at the speed of 20 mph

$t_s$  = Surfindicator texture measured on the surfaces,

$t_a$  = Surfindicator texture measured on exposed aggregate particles,

$T_{\text{pro}}$  = Profilograph texture, and

WPS = weighted particle-size factor.

The percent decrease in skid number caused by an increase in the skidding speed from 20 to 60 mph,  $G$ , may be estimated by any one of the following empirical equations:

$$1. G = 223.748 (0.002369)^{A_V}$$

$$2. G = 146.304 (0.002569)^{A_V}$$

$$3. G = 79.106 (0.046095)^{A_V}$$

$$4. G = 118.518 (0.011774)^{A_V}$$

where

$G$  = percent decrease in skid number, and

$A_V$  = total void area that includes the void area of the tire grooves and the pavement surface void area

The surface void area is determined from the Profilograph texture, Texturemeter texture, modified sand-patch texture or the putty impression texture for the first, second, third, and the fourth equation, respectively.

The results of this research stress the importance to driver safety of the microtextures and the small-scale macrottextures of aggregate particles exposed on pavement surfaces. These textures together with the macrottextures as measured by the Profilograph and the distribution of the aggregate size

have a decided influence on the skid number measured by a locked-wheel trailer and hence on driver control. The results also show that low values of macro-textures are indicative of poor drainage from the tire-pavement interface. Low values of void areas result in large reductions in skid numbers as the skidding speed increases.



THE EFFECTS OF RAINFALL INTENSITY,  
PAVEMENT CROSS SLOPE, SURFACE TEXTURE,  
AND DRAINAGE LENGTH ON PAVEMENT WATER DEPTHS

Safety on our nation's highways is a topic of utmost importance to the driving public. Among those topics that have received considerable attention over the past 30 to 40 years is the problem of providing roadway pavement surfaces that will provide adequate tire-gripping capabilities under all operating conditions, thus reducing the occurrence of accidents attributed to skidding, the phenomenon occurring when frictional demands on the vehicle wheels exceeds that available. Skidding results in an increased stopping distance, loss of directional stability, and loss of operator control. The skidding situation is of the utmost danger to the occupants of the skidding vehicle as well as to other persons or property within range of the skidding vehicle.

A pavement becomes slippery when the prevailing conditions are such that water lubricates the tire-roadway surface contact area after the inherently high skid resistance of a new surface has been worn and polished away by traffic, and/or when vehicle speeds are high enough to hydrodynamically reduce or eliminate the tire-surface contact (and thus the available friction) below the level required for vehicle maneuvers.

This study was concerned with determining the amount of water that can be expected to exist on various pavement types under normal ranges of pavement cross slope, rainfall intensities, pavement textures, and drainage lengths. Equations have been developed to relate these variables and their relative effects to water depth. The objectives of the research were to:

1. Examine the relative effects of various rainfall intensities, pavement cross slopes, drainage lengths, and surface textures on resultant pavement water depths.

2. Develop an equation relating rainfall intensity, pavement cross slope, drainage length and surface texture to pavement water depth.
3. Recommend means by which the findings and conclusions contained in the report can be implemented by the highway engineer in determining proper geometric designs and paving materials commensurate with acceptable pavement water depths and service demands.

In 1966, Authur D. Little, Inc., in The State of the Art of Traffic Safety, reported the following:

Skidding has emerged as a factor of major importance to the overall traffic safety problem, and the surface characteristic of principal concern appears to be the frictional properties of the road surface, both wet and dry. While there is evidence that skidding is involved in a high proportion of accidents, current methods of reporting accidents are believed to be inadequate to determine the true extent of this factor. Since skidding occurs in many accidents, either before or after braking, it is generally overlooked as a 'cause' in most accident reports. There is a tendency to list more obvious 'causes' such as 'failure to negotiate the curve' or 'lost control of car' which are in fact not causes but results; therefore, no accurate record is maintained of the kind and the degree of skidding involvement.

Thus, it may be inferred from the above quote that skidding and associated problems are actually contributing causes of more accidents than are attributed by current methods of reporting accidents. Analyses of accident records indicate that the incidence of total accidents, as well as accidents directly involving skidding, increases significantly with decreasing friction coefficients between the pavement and the tire.

The achievement of adequate pavement skid resistance is a result of the driver's responses and the interaction between the pavement and tire. This report, however, deals only with the pavement disregarding variations in friction which may be due to variations in tire design, vehicle parameters, and driver characteristics.

The main causes of pavement slipperiness are many and varied, but in very general terms are due to 1) the presence of water or other friction reducing materials in the tire-pavement contact area, which, with increasing vehicle speeds, lowers the available friction and raises the frictional demand, and 2) higher traffic volumes which, through pavement wear and aggregate polish, drastically reduce built-in friction potential of most new pavements. Many parameters affect the interactions at the tire-pavement interface. Considered to have major effects are: 1) mode of operation, i.e., rolling, slipping, or sliding, 2) pavement-surface characteristics, mainly macro- and microscopic roughness and drainage capability, 3) water-film thickness at the interface, 4) tire-tread depth and elastic and damping properties of the tire rubber, and 5) vehicle speed.

The shorter the distance required to stop a vehicle in emergency situations, and the higher the available force to provide adequate cornering, the better the resultant chance to avoid or reduce the severity of accidents. And, as stopping distance and cornering capability are direct functions of a friction coefficient, a high value of friction coefficient is important. The study of factors affecting water-film thickness is of paramount importance.

Nine test surfaces were placed on individual 28 1/2-foot long by 4-foot wide concrete beams. Each surface represented a section of a highway surface two lanes wide taken perpendicular to the direction of travel. A leveling course of concrete was applied to each beam prior to placement of the test surface. Descriptions of the test surfaces are shown in Table 3.

Tests were conducted using two 30-foot long by 9-foot frames that supported a system of 58 nozzles, which could be directed over the test surface. The nozzles, located approximately 1 foot to the sides and 5 feet above the test surface, were equally spaced 1 foot apart on the two frames.

TABLE 3

## DESCRIPTIONS OF THE SURFACES PLACED ON THE BEAMS

Surface Number	Surface Type	Aggregate Maximum Size, in.	Texas Highway Department Specifications	Average Texture Depth, ** in.
1	Rounded Siliceous Gravel Portland Cement Concrete (Transverse drag)*	3/4	Class A Item 364	0.035
1A	Rounded Siliceous Gravel Portland Cement Concrete (Longitudinal drag)*	3/4	Class A Item 364	0.036
2	Clay Filled Tar Emulsion (Jennite) Seal	No Aggregate	—	0.009
3	Crushed Limestone Aggregate Hot Mix Asphalt Concrete (Terrazzo Finish)	1/2	Type D Item 340	0.003
4	Crushed Siliceous Gravel Hot Mix Asphalt Concrete	1/4	Type F Item 340	0.019
5	Rounded Siliceous Gravel Hot Mix Asphalt Concrete	5/8	Type C Item 340	0.039
6	Rounded Siliceous Gravel Surface Treatment (Chip Seal)	1/2	Grade 4 Item 320	0.141
7	Synthetic Lightweight Aggregate Surface Treatment (Chip Seal)	1/2	Grade 4 Item 320	0.164
8	Synthetic Lightweight Aggregate Hot Mix Asphalt Concrete	1/2	Type L Sp. Item 2103	0.020

\*With respect to direction of vehicular travel

\*\*Obtained by Putty Impression Method (31)

Every fourth nozzle had the same size orifice. This pattern was followed on each side; however, the spacing of similar orifices was offset by two nozzles so that when nozzles of a given size orifice were operating the rainfall spray would tend to be more uniform on the surface. The two hose-type nozzles were placed directly over the test surface. One was centered at the upper end and the other centered nine feet from the lower end of the surface. This placement permitted uniform water spray over the surface.

A metal tank collected the runoff water. A Stevens Type F Recorder was used for maintaining a graphic record of water-level rise in the tank plotted against time. After the rate of water rise in the tank becomes constant, the rainfall intensity over the surface was deduced from the time rate of water level rise in the tank.

A Leopold and Stevens point gage was used for measuring water depths on the surfaces. The metric scale vernier can be read directly to the nearest 0.2 mm. The silicone putty impression method was used for assessing the degree of surface macrotecture.

A methodical test procedure was used for each surface. Five water depth measurements, spaced equidistant across the width of the surface, were taken at four locations approximately 6, 12, 18, and 24 feet measured from the upper end of the drainage area. These 20 measurements were repeated for each cross slope-rainfall intensity combination. Twenty-five series as indicated in Table 4 were used. An additional five series at a cross slope of 1 in/ft (1:12) were taken on three surfaces. A minimum of 500 depth measurements were taken on each surface.

Zero measurements were first taken at each test location to establish a datum plane at the top of the texture from which subsequent water-depth measurements could be referenced. Diagrammatic representations of the zero

TABLE 4  
TESTING SERIES

Series	Cross Slope			Approximate Rainfall Intensities
	in/ft	ft/ft	percent	in/hr
A1 - A5	1/16	1:192	0.52	0.50, 1.00, 2.00, 3.50, 5.50
B6 - B10	1/8	1:96	1.04	0.50, 1.00, 2.00, 3.50, 5.50
C11 - C15	1/4	1:48	2.08	0.50, 1.00, 2.00, 3.50, 5.50
D16 - D20	3/8	1:36	2.78	0.50, 1.00, 2.00, 3.50, 5.50
E21 - E25	1/2	1:24	4.17	0.50, 1.00, 2.00, 3.50, 5.50
F26 - F30*	1	1:12	8.33	0.50, 1.00, 2.00, 3.50, 5.50

\* Only taken on three surfaces.

reading and water-depth readings are shown in Figure 4. A metal disk was incorporated into the zero measurements however, its thickness was added to the gage reading as depicted in Figure 4a. Both positive (i.e., above top of texture) and negative (i.e., below top of texture) water depths were recorded.

It was desirable for the rain drop size to increase as the rainfall intensity was increased. This requirement necessitated the use of different size nozzle-orifices; the larger orifices produced higher intensities and correspondingly larger drop sizes. The intensity could also be varied by regulating the water pressure and changing the number of nozzles.

At the conclusion of each set of measurements, the rainfall was immediately stopped with the aid of the bleeder valve. At the same instant, a trough was placed under the flume and the water held in detention on the surface was diverted to a separate bucket. A rubber squeegee was used to remove the water stored in texture depressions.

#### Summary of Findings and Results

1. The experimentally determined equation relating water depth, surface texture, length of drainage path, rainfall intensity, and pavement cross slope is:

$$d = [3.38 \times 10^{-3} (1/T)^{-.11} (L)^{.43} (I)^{.59} (1/S)^{.42}] - T$$

where

d = water depth above top of texture (in.);

T = average texture depth (in.);

L = drainage-path length (ft);

I = rainfall intensity (in/hr); and

S = cross slope (ft/ft).

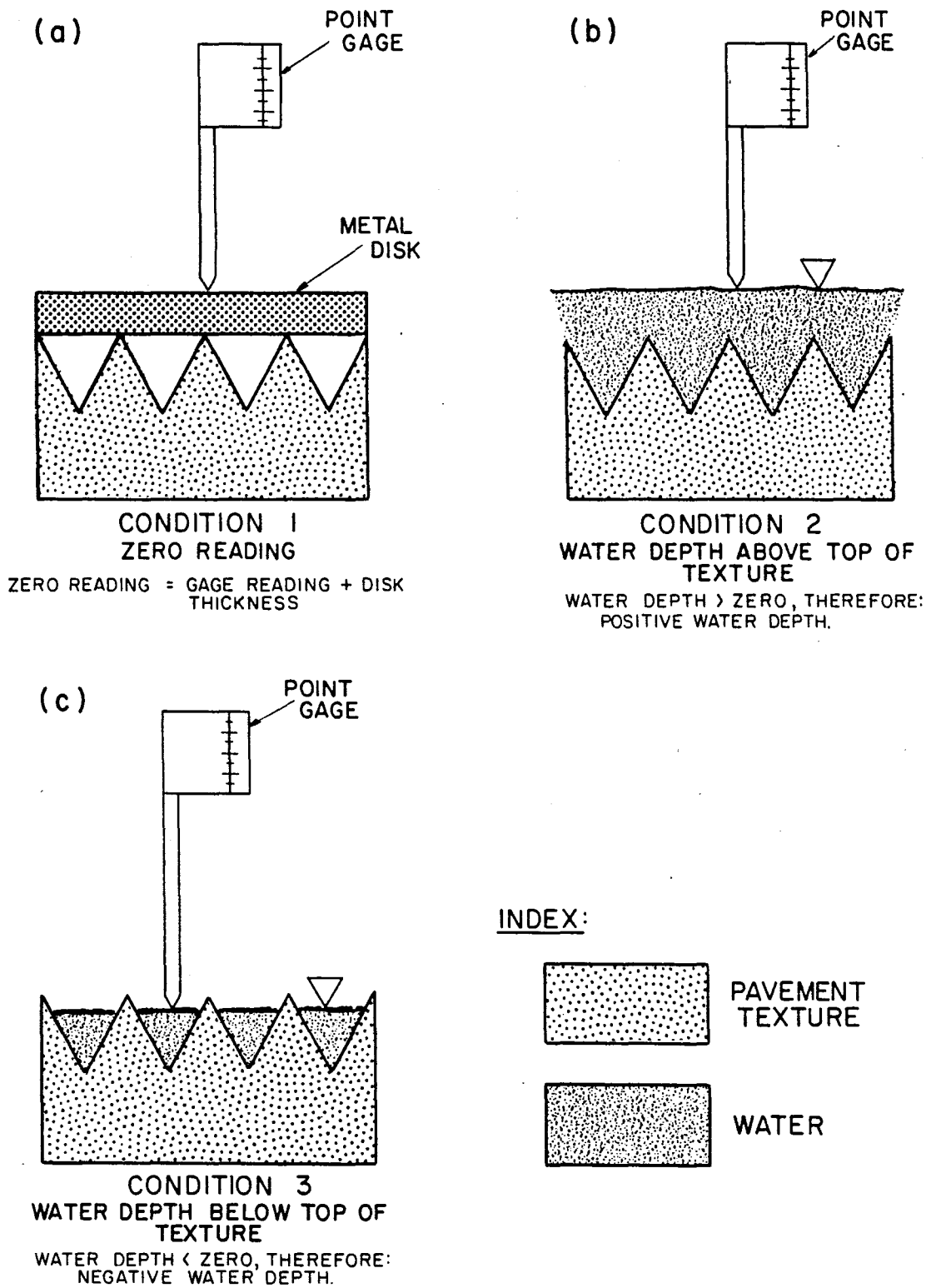


Figure 4. Diagrammatic representations of zero and water depth measurements.



2. Increasing surface texture resulted in a decrease in water depth for a given rainfall intensity, cross slope, and drainage length. This effect was more pronounced at the flatter cross slopes and lower rainfall intensities.

3. Greater drainage lengths increased water depths; however, the rate of increase in water depth, became smaller as drainage lengths increased.

4. Greater water depths were associated with higher rainfall intensities; notwithstanding, the adverse effect of rainfall intensity was quite pronounced, even at the lower rainfall intensities.

As noted in Table 5 and Figure 5, increases in cross slope result in corresponding decreases in water depths. The effect is more pronounced at the flatter cross slopes. For example, increasing cross slope rate from 1/16 in/ft to 1/4 in/ft will decrease the corresponding water depth by 62 percent of its 1/16 in/ft value in the outside wheel path. Note, however, that cross slopes in excess of 1/4 in/ft do not reflect as much effect on resultant water depths, particularly when the magnitude of the cross-slope increments are given consideration.

An inverse relationship between macrotexture and water depth was also found. The effect increased at the higher macrotexture levels and was more pronounced at macrotexture levels greater than 0.050 inches.

As expected, water depths increased as drainage lengths increased.

As also expected, water depths decreased as rainfall intensities decreased. A rainfall intensity of about 0.3-in/hr would be required to encapsulate the asperities on a pavement surface having 0.03-in. texture, 24-foot drainage length, and 1/8 in/ft cross slope.

Tabular representations and graphical plots of the relative effects of the variables on average surface detention are given in Table 6 and Figure 6, respectively. These values were determined from the overall experi-

TABLE 5

TABULAR REPRESENTATION OF THE RELATIVE EFFECTS OF CROSS SLOPE, TEXTURE, DRAINAGE LENGTH, AND RAINFALL INTENSITY ON WATER DEPTH

Constants	Variable Cross Slope in/ft	Resultant Water Depth in.	Percent Decrease
Texture, 0.03 in. Length, 24 ft Intensity, 1.5 in/hr	1/16	0.074	
	1/8	0.048	35
	1/4	0.028	62
	3/8	0.021	72
	1/2	0.013	82
	1	0.002	97

Constants	Variable Texture, in.	Resultant Water Depth in.	Percent Decrease
Length, 24 ft Intensity, 1.5 in/hr Cross Slope, 1/8 in/ft	0.005	0.059	
	0.015	0.057	3
	0.030	0.048	19
	0.050	0.038	36
	0.075	0.011	81
	0.125	-0.034	158

Constants	Variable Drainage Length ft	Resultant Water Depth in.	Percent Increase
Intensity, 1.5 in/hr Cross Slope, 1/8 in/ft Texture, 0.03 in.	6	0.013	
	12	0.028	115
	18	0.039	200
	24	0.048	269
	36	0.062	377
	48	0.074	469

Constants	Variable Rainfall Intensity, in/hr	Resultant Water Depth in.	Percent Decrease
Texture, 0.03 in. Length, 24 ft Cross Slope, 1/8 in/ft	5.5	0.138	
	3.5	0.098	29
	2.0	0.062	55
	1.0	0.031	77
	0.5	0.011	92
	0.1	-0.014	110

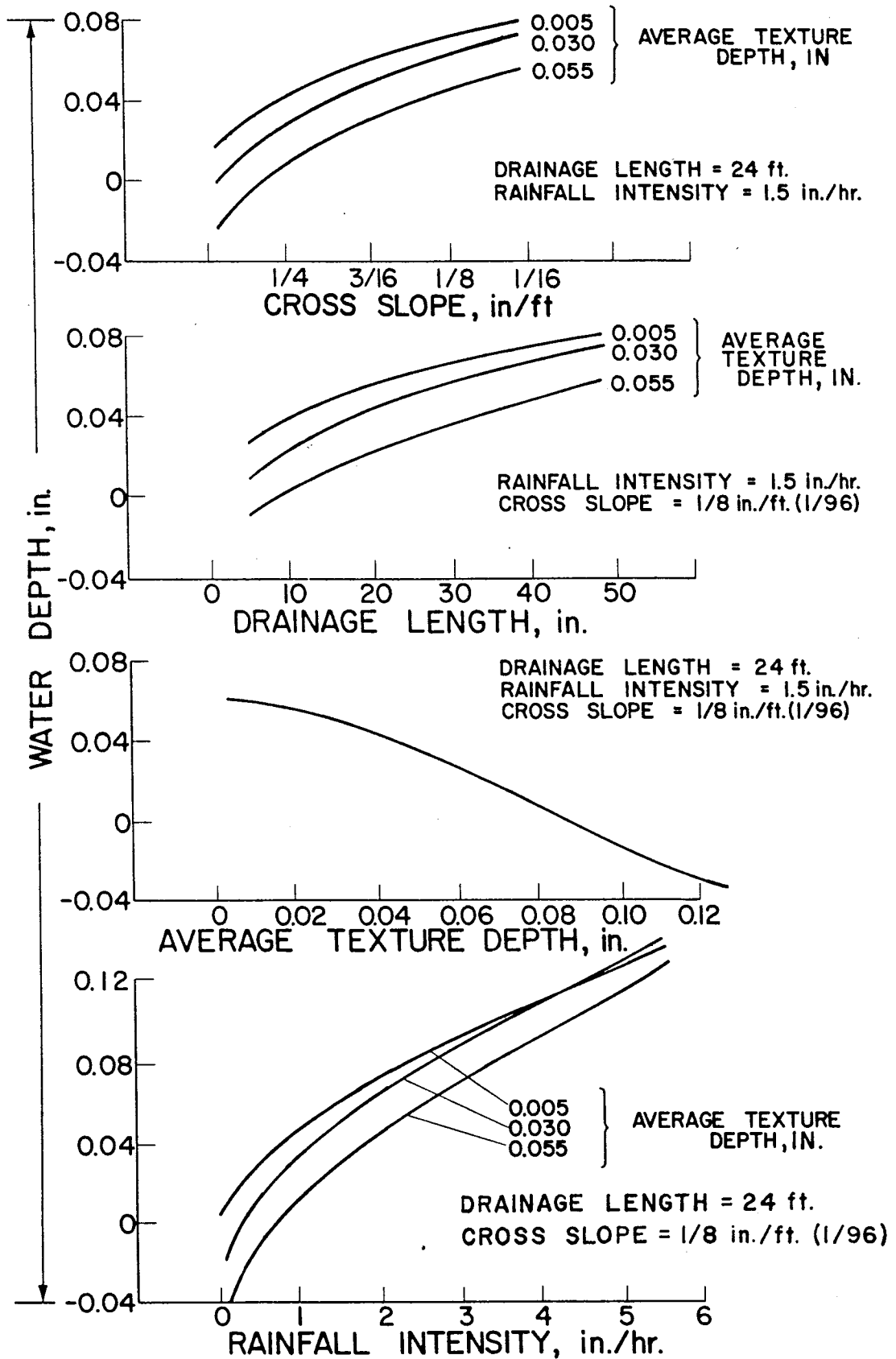


Figure 5. Plot of water depths versus variables for combined surfaces.

TABLE 6

TABULAR REPRESENTATION OF THE RELATIVE EFFECTS OF CROSS SLOPE, TEXTURE,  
AND RAINFALL INTENSITY ON AVERAGE SURFACE DETENTION

Constants	Variable Cross Slope in/ft	Resultant Average Detention in.	Percent Decrease
Texture 0.03 in.	1/16	0.022	
	1/8	0.012	45
	1/4	0.004	82
	3/8	0.001	95
Intensity 1.5 in/hr	1/2	-0.003	114
	1	-0.008	136

Constants	Variable Texture in.	Resultant Average Detention in.	Percent Decrease
Cross Slope 1/8 in/ft	0.005	0.029	
	0.015	0.024	17
	0.030	0.012	59
	0.050	-0.006	121
Intensity 1.5 in/hr	0.075	-0.029	200
	0.125	-0.076	362

Constants	Variable Rainfall Intensity, in/hr	Resultant Average Detention in.	Percent Decrease
Texture 0.03 in.	5.5	0.057	
	3.5	0.038	33
	2.0	0.019	67
	1.0	0.003	95
Cross Slope 1/8 in/ft	0.5	-0.008	114
	0.1	-0.021	137

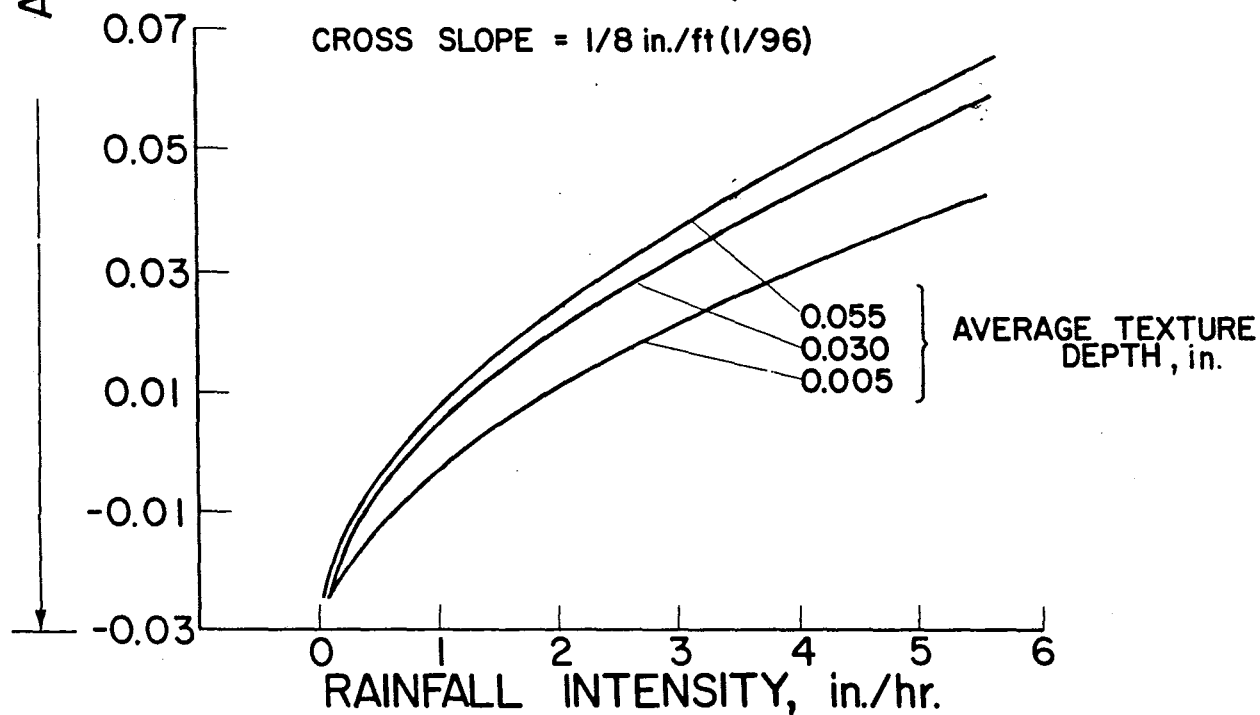
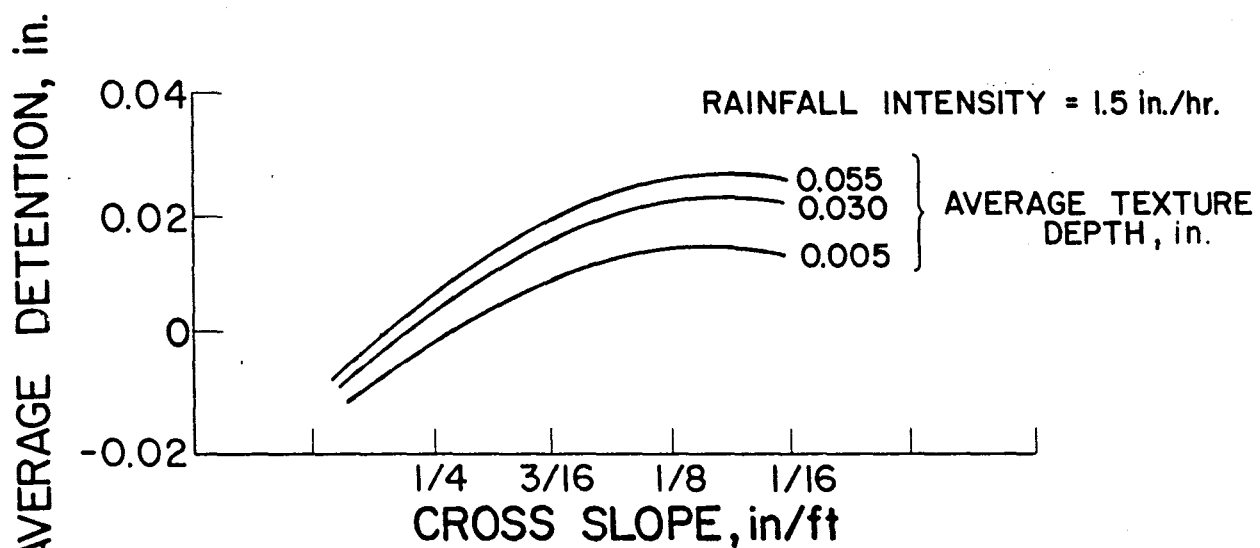
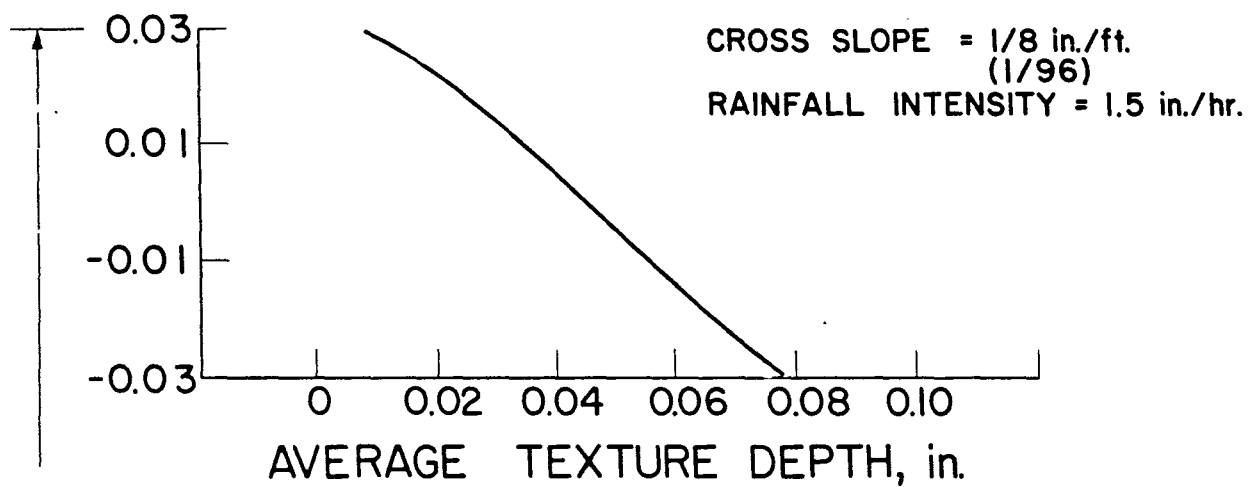


Figure 6. Plot of average surface detention versus variables for the combined surfaces.

mentally obtained equation

$$\text{Det} = [11.80 \times 10^{-3} (1/T)^{-0.11} (I)^{0.57} (1/S)^{0.31}] - T$$

where

Det = average surface detention (in);

T = average texture depth (in);

I = rainfall intensity (in/hr); and

S = cross slope (ft/ft).

In its original form the equation was based on a datum plane at the bottom of the texture (neglecting depression-storage water); however, subtraction of the texture from the obtained depth shifts the datum plane to the top of the texture. The equation is valid for drainage lengths of 28 feet and less with negative values indicating average water depths below the top of the texture.

Pavement cross slope, macrotexture, and rainfall intensity were found to affect average surface detention in the same manners as the variables affected water-depth measurements, discussed previously. Increases in pavement cross slopes and macrotextures and decreases in rainfall intensities resulted in corresponding decreases in average surface detention. The average surface-detention measurements are somewhat limited in scope, however, since they are only based on 28-foot long drainage lengths.

In addition to the previous discussion of the relative effects of cross slope on water depth, another major benefit of a steeper cross slope would be the reduced volume of water which could collect in pavement deformations. This is particularly so on flexible pavements where a certain amount of wheel-track depression almost always occurs because of compaction in the base and the surface. The use of paved shoulders may generally reduce the subsidence of the outside one-third of the traffic lane; such subsidence being caused

previously by less construction compaction near the pavement edge and subsequently greater permanent deformation during service. Where highly compacted shoulders are used, permanent deformation can still be occurring in the traveled lanes; thus, after a period of time, a portion of the cross slope can be lost. Steeper cross slopes will reduce the effect.

It was observed during the experimental tests that after the cessation of rainfall, the steeper cross slopes drained the remaining surface water more quickly than did the flatter slopes. This is another benefit of steep cross slopes; particularly in areas of high humidity, low wind speed, and/or low temperatures. These conditions serve to increase the drying time and thus the length of the time the surface is wet. Steeper cross slopes would serve only to remove the bulk of the water more quickly, and would facilitate drainage of low areas and deformations.

Another possible means of reducing the wet-pavement exposure-time would be the use of a permeable surface layer which would allow infiltration of some of the rainfall and subsequent drainage through the permeable layer to the pavement edge. Admittedly, this concept has some disadvantages.

### Conclusions and Recommendations

Increases in the minimum rates of pavement cross slopes appear to be warranted. It is recommended that cross slopes in the range 1/8 in/ft to 3/8 in/ft be used on high speed rural highways. The higher cross slope of 1/4 in/ft or more should be favored in areas with greater potential for wet weather accidents. This will not only reduce the water depth on pavements for a given rainfall intensity, but will also assist in providing for drainage of low areas and depressions that tend to lower the effectiveness of built-in cross slope. Steeper cross slopes will offer a margin of safety

against ponding and subsequently long, wet-pavement exposure times. The adverse effects of excessive cross slope are recognized.

Smooth-textured dense graded surfaces should not be used. Slight amounts of precipitation will result in water depths above the texture peaks and poor effective drainage on such surfaces. If such surfaces are used, a certain degree of permeability should be effected in the surface. The surface aggregate should be capable of puncturing the water film or drainage of the water into the surface should be possible.

It is suggested that research be conducted to determine the relative influences of ambient temperatures, wind velocities, and relative humidities on the drying rates of various pavement-surface types after rainfall of a given intensity has ceased. Drying rates are indicative of the time during which the pavement surface is wet. It is assumed that high relative humidity, low wind velocity, and low ambient temperature all contribute to increased exposure times and thus decreased drying rates for a given surface. Their relative effects and significance need to be determined in conjunction with the wind effects created by traffic.

An indirect method for measuring the friction contribution of microtexture would be helpful to the design engineer. Such a method should involve the use of presently used friction measuring equipment. From the research accomplished so far in this study it appears that the relationship between locked wheel skid and cornering slip at 40 mph may offer an indirect approach to the measurement of the contribution of microtexture.



## INFLUENCE OF WATER DEPTHS ON FRICTION PROPERTIES OF VARIOUS PAVEMENT TYPES

This report contains the results of the final phase of a study concerned with the determination of the effects of water depth on the friction properties of various pavement textures at different levels of vehicular speeds and tire-tread depths, tire pressures, and tire types. The objectives of the research were to:

1. Examine the effects of various water depths on the friction properties of various surface textures at different levels of vehicular speeds and tire-tread depths.
2. Develop an equation relating water depth, surface texture, vehicular speed, and tire-tread depths to friction number; and
3. Recommend means by which the findings and conclusions contained herein can be implemented by the highway engineer in determining proper geometric designs and paving materials commensurate with acceptable pavement friction characteristics and service demands.

Attempts have been made to characterize properties affecting friction of pavement surface types using qualitative terms such as surface macro-texture; aggregate size, shape, micro-texture, and mineralogy; and drainage characteristics of the total surface. Although the relative magnitude of their influence has not been universally accepted, it is generally agreed that these characteristics largely determine the friction properties of surfaces.

The importance of the type and magnitude of surface texture on the friction properties of pavement surfaces has been studied by several researchers. The term "macroscopic texture" is generally used to describe part of the pavement surface as a whole or the large-scale texture caused by the size and shape of the surface aggregate; whereas the term "microscopic texture"

refers to the fine-scaled roughness contributed by individual small asperities on the individual aggregate properties.

Macro- and microtexture provide for gross surface drainage and subsequent puncturing of the water film. Internal drainage of the pavement surface itself acts in combination with macro- and microtexture.

The shape of the aggregate particles is a significant factor in skid-resistance considerations. The individual particles should be angular and sharp to provide a gritty texture. Skid resistance measurements have been found to be about 25 percent higher for bituminous mixes containing angular aggregates than for those containing rounded aggregates.

The frictional force generated between the tire and the pavement is made up of two components: a force attributable to adhesion between tire and pavement, and a force attributed to hysteresis losses in the tire rubber caused by deformation of the tire as it rolls or slides across an irregular surface. Both forces are functions of molecular activity within the tire rubber.

The adhesion component is generated by the junctions of rubber and surface molecules created primarily by van der Waals force of attraction. These junctions produce a shearing resistance at the tire pavement interface. Adhesion forces, therefore, are dependent upon the magnitude of the shearing resistance and upon the area of contact between the tread rubber and the pavement surface. The hysteresis force produces a pressure difference between the two sides of the intruding surface projections (or asperities) when the rubber rebounds less vigorously than it is displaced. Hysteresis forces depend upon the quantity of rubber being deformed and on the damping properties of the rubber.

Figure 7 shows that the dry friction level of a pavement is either inde-

pendent of or increases slightly with vehicle speed. This is due to the complementary effects of the adhesion and hysteresis component of friction. The figure also illustrates the rapid decay of frictional resistance on wet pavements as speed increases, indicating the obvious danger of wet pavements with regard to skid resistance.

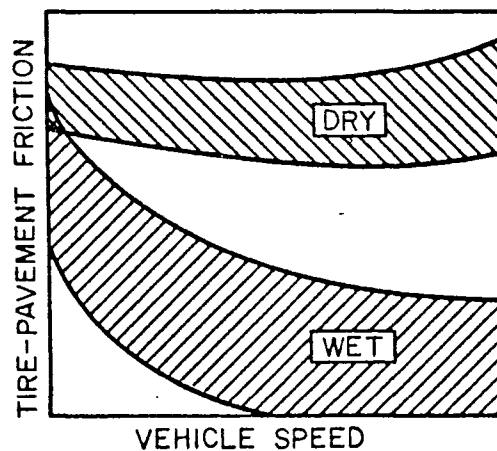


Figure 7. Frictional trends for slipping and skidding tires on dry and wet pavements (7).

The phenomenon of hydroplaning has received much attention. Hydroplaning occurs when the tire is completely separated from contact with the pavement surface by a water film, resulting in essentially zero friction being generated between the tire and pavement.

When a tire rolls or slides across a wet pavement, water is removed from the tire-pavement interface in three steps, as shown in Figure 8. As the tire moves over the surface, the bulk of the water is removed by the normal force of the tire squeezing the water outside the tire footprint through drainage channels in the pavement or into the grooves in the tire tread. However, a thin film of water, on the order of a thousandth of an inch, remains tenaciously bound to the pavement surface. Very high localized pressures caused by smaller pavement asperities against the tire surface then may serve to

puncture this thin water "squeeze-film" to permit intimate dry tire-pave-ment contact.

When the depth of water is too great to be removed by this action, "dynamic" hydroplaning occurs. A second type, "viscous" hydroplaning occurs when, either due to the smoothness of the tire or the lack of surface asperities, the tire rides on the microfilm of water remaining at the surface.

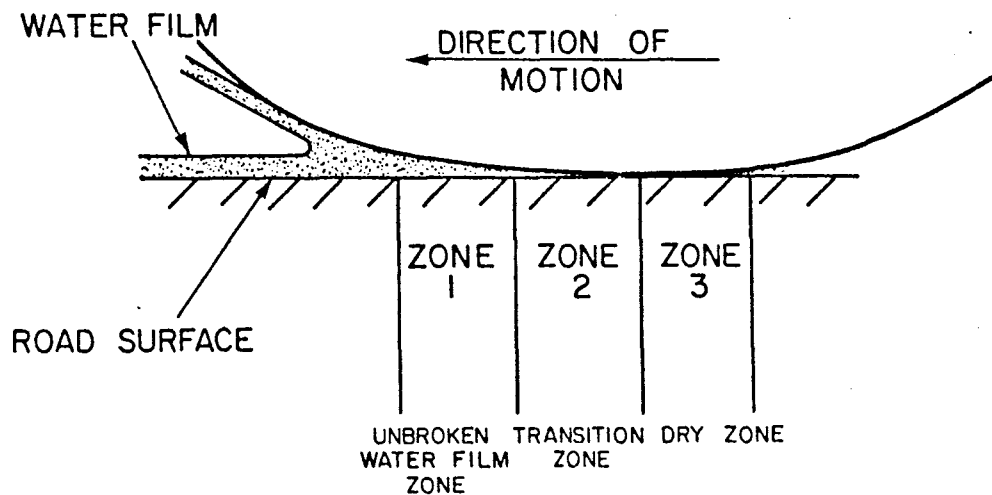


Figure 8. The three zones of the contact area of a tire (8).

In this study, nine different types of pavement surface were constructed at the Texas A&M Research Annex: four hot mix asphaltic concrete surfaces, one portland cement concrete surface, two surface treatments, a painted portland cement concrete surface, and one sealed surface (See Figure 9).

The surface types were chosen so as to exhibit widely different friction levels, friction-velocity gradients, drainage capabilities, mineralogical properties, and textural classification. Descriptions of each surface are presented in tabular form in Table 7.

Friction measurements with the skid trailer were conducted on surfaces Nos. 1 through 9. Preparation and conditioning of the surfaces had advanced sufficiently to permit locked-wheel skids, particularly at various

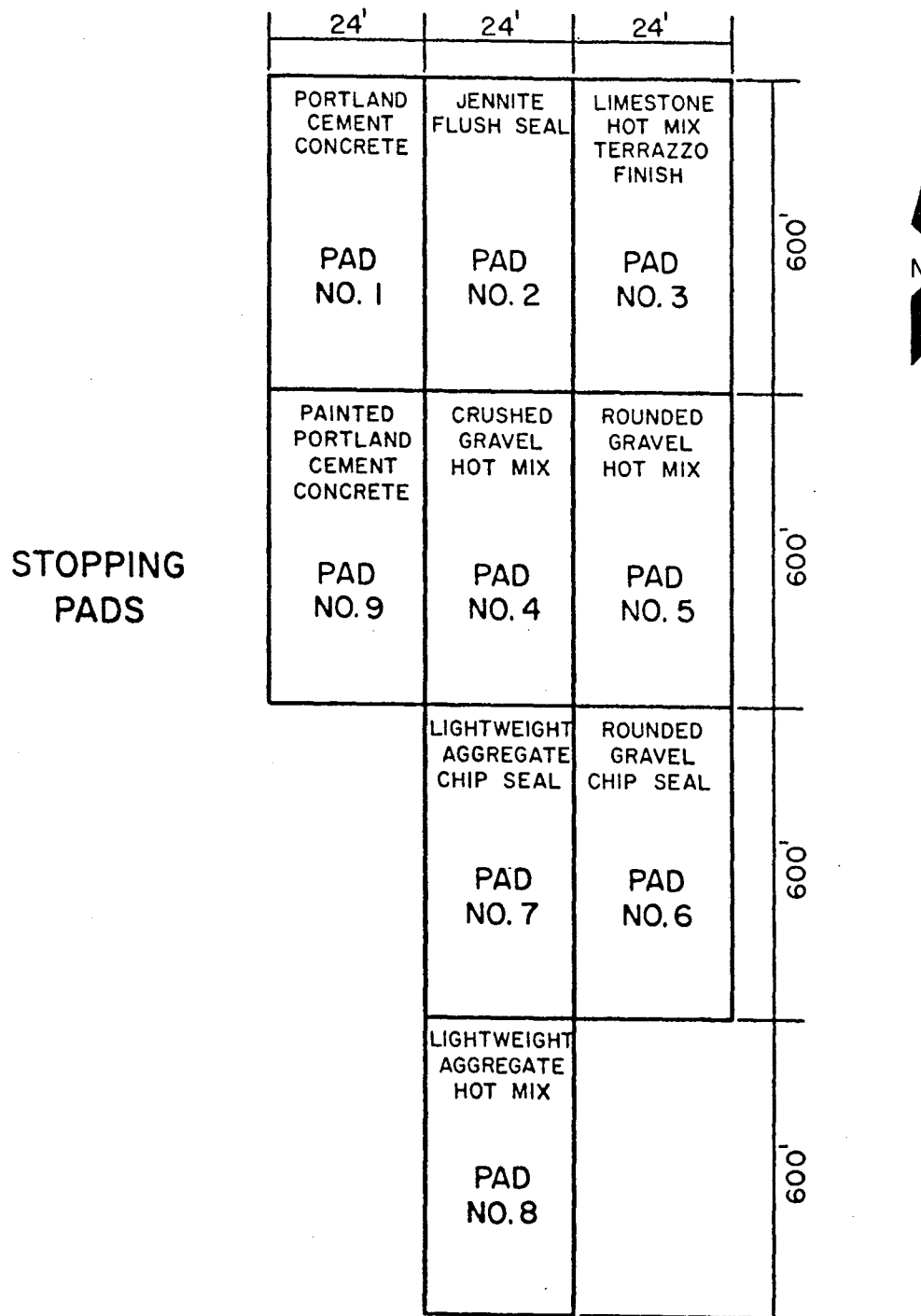


Figure 9. Drawing of the test pads.

TABLE 7  
Descriptions of the Test Surfaces

Test Pad Number	Surface Types	Aggregate			Texas Highway Department Specifications	Construction Date	Preparation Prior to Testing (September 1970)	Average Texture Depth,** In.
		Weight Percent	Type	Maximum Size, In.				
1	Rounded Siliceous Gravel Portland Cement Concrete (Belt Finish)	67	Rounded Siliceous Gravel	1-1/2	(Existing Runway Surfaces)	1953	Cleaned with water and power broom	0.019
		33	Siliceous Sand					
2	Clay Filled Tar Emulsion (Jennite) Flushed Seal		No Aggregate		Type E*	1968	Scrubbed with water and rubber float	0.005
3	Crushed Limestone Aggregate Hot Mix Asphalt Concrete (Terrazzo Finish)	35	Coarse Crushed Limestone	1/2	Type D	1968	Ground with terrazzo machine and polished with water, fly ash, and rubber float	0.014
		30	Medium Crushed Limestone					
		25	Fine Crushed Limestone					
		10	Field Sand					
4	Crushed Siliceous Gravel Hot Mix Asphalt Concrete	60	Coarse Crushed Siliceous Gravel	1/4	Type F	1968	Polished with water, fly ash and rubber float	0.029
		20	Fine Crushed Siliceous Gravel					
		20	Field Sand					
5	Rounded Siliceous Gravel Hot Mix Asphalt Concrete	30	Coarse Rounded Siliceous Gravel	5/8	Type C	1968	Polished with water, fly ash and rubber float	0.024
		25	Fine Rounded Siliceous Gravel					
		35	Crushed Limestone Fines					
		10	Field Sand					
6	Rounded Siliceous Gravel Surface Treatment (Chip Seal)	100	Rounded Siliceous Gravel	1/2	Grade 4	1970	None	0.119
7	Synthetic Lightweight Aggregate Surface Treatment (Chip Seal)	100	Lightweight Aggregate (Fired Clay)	1/2	Grade 4	1970	None	0.148
8	Synthetic Lightweight Aggregate Hot Mix Asphalt Concrete	40	Lightweight Aggregate (Fired Clay)	1/2		1970	Scrubbed with detergent, water and broom and polished with water, fine sand and rubber float	0.022
		40	Lightweight Slag Aggregate					
		20	Siliceous Field Sand					

\*A 1/16 maximum size Type E mix composed of slag and limestone screenings was used as a base for the seal.

\*\*Obtained by putty impression method.

TABLE 7 Continued

Test Pad Number	Surface types	Aggregate			Texas Highway Department Specifications	Construction Date	Preparation Prior to Testing (September 1970)	Average Texture Depth, ** in.
		Weight Percent	Type	Maximum Size, in.				
9	Rounded Siliceous Gravel Portland Cement Concrete (Belt Finish) Two coats of Traffic Paint	67	Rounded Siliceous Gravel	1-1/2	(Existing Runway Surfaces)	1953	Cleaned with water and power broom	0.033

water depths and although data from these surfaces were not processed at the termination of the study, subsequent effort made it possible to include the additional data.

Also during the final months of the study the number of pavement surface types was enlarged to include seven experimentally developed surfaces of portland cement concrete.

Summarized descriptions of the seven concrete surfaces are given in Table 8 of this report. It should be noted that the list includes a control which in this case represented the currently used burlap drag type of concrete pavement surfacing. The other surfacing technique employed represent technically feasible methods of texturing portland cement concrete pavements during construction, that is, texture formation while the concrete is still in the plastic state.

#### Tires Used in Field Studies

The tires used in the study included the ASTM 14-inch standard skid resistant tire, the 15-inch interim standard ASTM skid tire (the manufacture of this tire has been discontinued), and three commercial tires. All tires were tested at 24 and 32 psi inflation pressure.

The ASTM tires used included a range of tread depths from no tread to a full tread of 10/32 inches. The three commercial tires ranged in tread depth from no tread to tread depths of 9/32 inch.

Although samples of commercial tires used was quite limited, it is felt that the trends in performance on what might be considered typical wet pavement surfaces can be gained from the rather extensive data presented.

Tire tread patterns and rubber compounds have changed and these changes



TABLE 8. Experimental Finishes of Portland Cement Concrete Test Sections

Finish Type	Description	Test Section No.
Burlap Drag	A burlap drag finish is accomplished by passing a wet burlap cloth, with approximately two ft of burlap in contact with the surface until the desired texture is obtained.	F-17
Brush	Accomplished by passing a natural-bristle brush (strawlike) over the slab surface, slightly grooving the concrete. The broom is inclined at an angle of approximately 30 degrees to the surface.	F-20
Tines	Accomplished by passing a series of thin metal strips (tines), 1/8 in. by 5 in. long, over the section surface, producing grooves of approximately 1/8 in. depth in the concrete. The tine spacing was varied from 1/8 in. to 1/4 in. (clear distance between tines).	F-15, F-16, F-18, F-19
Burlap Drag Plus Longitudinal Tines	Accomplished by first passing burlap drag over the section surface, followed by one pass of the tines, 1/8 in. by 5 in. long, over the section surface, producing grooves of approximately 1/8 in. depth in the concrete. The tine spacing was varied from 1/4 in. to 1.0 in. (clear distance between tines).	F-11, F-12, F-13 F-14, F-21

are evidenced in their performance characteristics. However, from data presented at the General Motors Tire Traction Symposium (T2), it appears that tread improvements in the past decade have been meager. The current trend in rubber compounding is toward better wear characteristics and improved traction and both of these changes have strong public appeal.

### Equipment

Rain simulator equipment was used for wetting the pavement surface. The basic framework of the rain simulator was composed of 4-inch wide by 1-inch deep steel channels. A 4-inch diameter pipe served as the manifold with 2-inch diameter pipes used as feeder lines for the shrub-head nozzles. Eight 20-foot long sections of the rain simulator wetted an area approximately 210 feet long by 30 feet wide. Spray bars were spaced 6 feet apart with shrub-head nozzles directed downward and spaced at 6 foot intervals along the spray bar. Hose-type nozzles were attached to the upper side of the spray bar and used for low intensity rainfall for initial tests.

A 4000-gallon tank truck equipped with a high pressure pump was used for supplying water to the system. Desired water depths were measured at various distances along the drainage path. Rainfall intensities were deduced from the amount of water caught in metal cans during a twelve-minute interval.

The friction measurements reported herein were obtained with the Texas Highway Department research skid trailer which conforms substantially to ASTM standards (E27-65T)\* and utilizes 14-inch ASTM Standard tires (E229-66)\* inflated to 24 psi. The drag forces are measured with strain gages and the internal-watering system, when used, utilizes a centrifugal pump which applies a water film approximately 0.020-inches in thickness to the pavement surface.

Friction measurements were taken at 20, 40, and 60 mph with E-17 treaded

---

\*Part 11, 1970 Annual Book of ASTM Standards, American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pa.

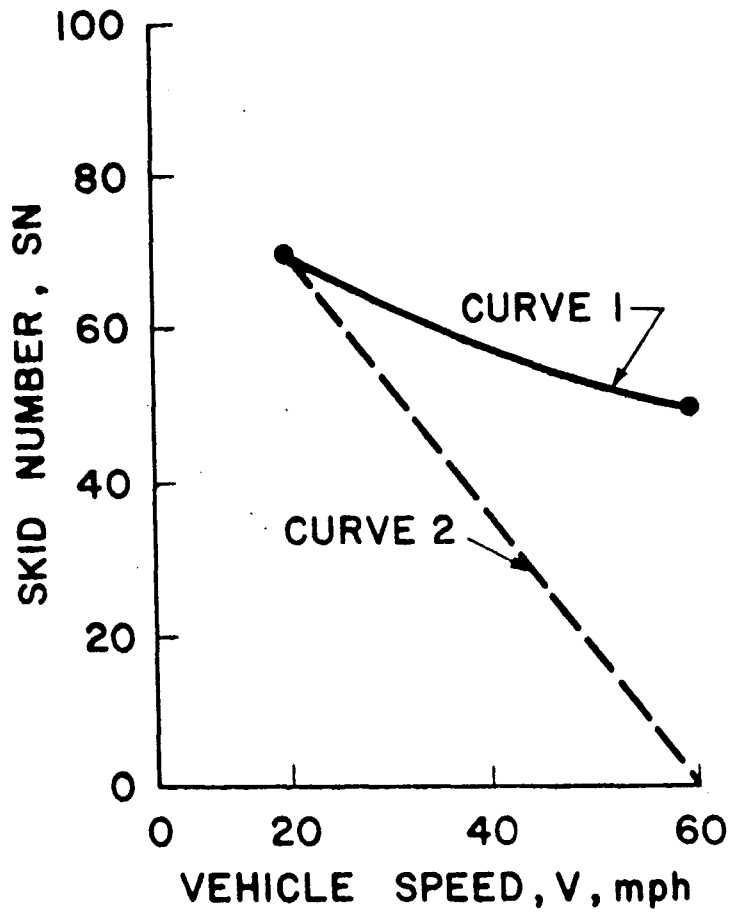
and smooth tires. The internal watering system was used for only a portion of the measurements, as indicated.

Additional friction measurements were taken with the British Portable Skid Tester in accordance with ASTM standard procedure (E303-69)\*. Four locations were tested on each surface. Water depth measurements were taken with the Leopold and Stevens point gage. A total of 15 measurements were taken for a given reported average water depth. Macrotexture measurements of the surfaces were taken by the putty impression method. Four measurements were taken on each surface and averaged.

Two series of 20, 40, and 60 mph skid tests at various water depths using both E-17 treaded and smooth tires were conducted with the trailer. A total of four measurements were taken at each speed-tire-water depth combination. Each surface was tested at 5 or 6 different water depths and additionally with the trailer's internal watering system. Average skid numbers at 20, 40, and 60 mph were calculated for each surface-tire-water depth combination. The series was repeated for tire inflation pressure of 24 and 32 psi. This entire series was repeated with three different commercial tires.

Gradients (denoted by  $G$  of the skid number-speed curve between 20 and 60 mph were calculated. In addition, in order to reflect the relative position of the curve, percentage gradients were calculated. Curves of a given gradient positioned low on the graph would have higher percentage gradients than curves with the same gradient positioned high on the graph. Thus, percentage gradient is defined as the percentage of the gradient, obtained under test conditions, to a theoretical gradient if the skid number at the higher speed were zero. Calculations appear in Figure 10.

Water depth and rainfall intensity measurements were also taken during the skid testing sequence.



$$\text{GRADIENT (G)} = \frac{SN_{20} - SN_{60}}{40}$$

$$\text{GRADIENT (G}_2) = \frac{SN_{20} - 0}{40}$$

$$\text{PERCENTAGE GRADIENT (PG)} = \frac{G}{G_2} \times 100 = \frac{SN_{20} - SN_{60}}{SN_{20}} \times 100$$

Figure 10. Gradient and percentage gradient calculations.

## ANALYSIS AND DISCUSSION OF TEST RESULTS

Friction data obtained on the Research Annex Test Pads was analyzed. Skid trailer measurements were obtained on seven highway surfaces.

The skid trailer friction data for the combined surfaces were analyzed using a computerized multiple-regression program to obtain the best fit of the data. Equations relating the relative effects of speed, water depth, texture, and tire-tread depth to skid number were developed. Tire-tread depths were assumed as 0.25-inch for the E-17 treaded tire and 0.02-inch for the smooth tire. ASTM specifications permit E-17 tread depth between 0.15 and 0.35-inch. A value slightly greater than zero was used for the smooth tire. Water depths were referenced at the top of the texture. Equations relating the same variables, excluding speed, to gradient and percentage gradient were also developed.

### Regression Analysis of Test Data

The data from Pads 1, 3, 4, 5, 6, 7 and 8 at the Research Annex were divided into four groups for regression analysis:

1. ASTM tire at 32 psi.
2. Commercial tires at 32 psi.
3. ASTM tire at 24 psi.
4. Commercial tires at 24 psi.

Pads 2 and 9 are analyzed separately from the above pads because the friction potential of these two surfaces is rather low. They do, however, represent real world surfaces such as flushed bituminous surfaces or polished surfaces of the flexible or rigid type.

Several constraints were placed upon the results of the regression analysis. The equations derived must

1. Be simple expressions which include all of the variables,
2. Include the most significant interactions between variables, usually with such interactions expressed as the product or quotient of variables,
3. Have as high a correlation coefficient ( $R^2$ ) as possible, while maintaining the other constraints, and
4. Be physically realistic.

The requirement of physical realism is imposed by specifying that only those statistical models which have the right kinds of relations among the variables are acceptable. In these cases, the signs of four "slopes" were specified.

1.  $\frac{d(SN)}{d(MPH)} < 0$ . The skid number (SN) decreases as the speed (MPH) increases.
2.  $\frac{d(SN)}{d(TD)} > 0$ . The skid number (SN) increases as the tread depth (TD) increases.
3.  $\frac{d(SN)}{d(WD)} < 0$ . The skid number (SN) decreases as the water depth (WD) increases.
4.  $\frac{d(SN)}{d(TXD)} > 0$ . The skid number (SN) increases as the texture depth (TXD) increases.

### Regression Procedures

A select regression program (Ref. 9), which implements the Hocking-Lamotte-Leslie's variable selection procedure (Ref. 10, 11), was utilized. Based on the experience obtained in implementing this computer program,

the decision was made to use a two-step regression analysis procedure.

Step 1:

A logarithmic model was assumed for each data group.

$$\ln(\text{SN}) = \ln(a_0) + a_1 \ln(\text{MPH}) + a_2 \ln(\text{TD}) + a_3 \ln(25.4\text{WD} + 2.5) \\ + a_4 \ln(\text{TXD}).$$

This equation is equivalent to

$$\text{SN} = a_0 \text{MPH}^{a_1} \text{TD}^{a_2} (25.4\text{WD} + 2.5)^{a_3} \text{TXD}^{a_4}$$

## Step 2: Linear Combination Model

The following linear combination model was assumed for each data group.

$$SN = b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6 + b_7 x_7 + b_8 x_8.$$

For Data Group 1 (ASTM tire at 32 psi),

$$x_1 = \frac{TD^{0.06} \quad TXD^{0.05}}{MPH^{0.72} \quad (25.4WD + 2.5)^{0.08}}$$

$$x_2 = \frac{TD^{0.06} \quad TXD^{0.07}}{MPH^{0.72}}$$

$$x_3 = \frac{TD^{0.06}}{MPH^{0.72} \quad (25.4WD + 2.5)^{0.15}}$$

$$x_4 = \frac{TD^{0.06}}{MPH^{0.72}}$$

$$x_5 = \frac{TXD^{0.05}}{MPH^{0.72} \quad (25.4WD + 2.5)^{0.08}}$$

$$x_6 = \frac{TXD^{0.07}}{MPH^{0.72}}$$

$$x_7 = \frac{1}{MPH^{0.72} \quad (25.4WD + 2.5)^{0.15}}$$

$$x_8 = \frac{1}{MPH^{0.72}}$$

The following equation is selected as the final model, based on  $R^2$ , the physical constraints, simplicity of expression and inclusion of all four independent variables, namely, MPH, TD, WD, and TXD.

$$\begin{aligned} SN &= 135.121 \quad x_4 + 563.655 \quad x_5 \\ &= 135.121 \quad \frac{TD^{0.06}}{MPH^{0.72}} + 563.655 \quad \frac{TXD^{0.05}}{MPH^{0.72} \quad (25.4WD + 2.5)^{0.08}} \\ &= \frac{135}{MPH^{0.72}} \left[ TD^{0.06} + \frac{4.18 \quad TXD^{0.05}}{(25.4WD + 2.5)^{0.08}} \right] \end{aligned}$$



Data groups 2, 3, and 4 were regressed using the same procedures, and final models for each data group were developed, and a typical plot is shown in Figure 11.

### Sensitivity Analysis

Sensitivity of each variable was obtained by applying the following differential analysis.

$$\begin{aligned} \Delta SN = & \left( \frac{\partial SN}{\partial MPH} \right) \Delta MPH + \left( \frac{\partial SN}{\partial TD} \right) \Delta TD + \left( \frac{\partial SN}{\partial WD} \right) \Delta WD \\ & + \left( \frac{\partial SN}{\partial TXD} \right) \Delta TXD \end{aligned}$$

### Application of Sensitivity Analysis

The sensitivity equation for each data group can be represented in the following general form.

$$\Delta SN = -c_1 \Delta MPH + c_2 \Delta TD - c_3 \Delta WD + c_4 \Delta TXD$$

The sensitivity of any variable can be estimated by the changes of the other four variables. For instance, in order to obtain the same SN ( $\Delta SN = 0$ ), when  $\Delta WD = \Delta TXD = 0$ ,  $\Delta MPH$  can be estimated by

$$\Delta MPH = \frac{c_2}{c_1} \Delta TD$$

This implies that if TD decreases one unit, then MPH must decrease  $\frac{c_2}{c_1}$  unit to obtain the same SN. Also, let  $\Delta SN = \Delta TD = \Delta TXD = 0$ , then

$$\Delta MPH = -\frac{c_3}{c_1} \Delta WD$$

This implies that if WD increases one unit, then MPH must decrease  $\frac{c_3}{c_1}$  unit to obtain the same SN.

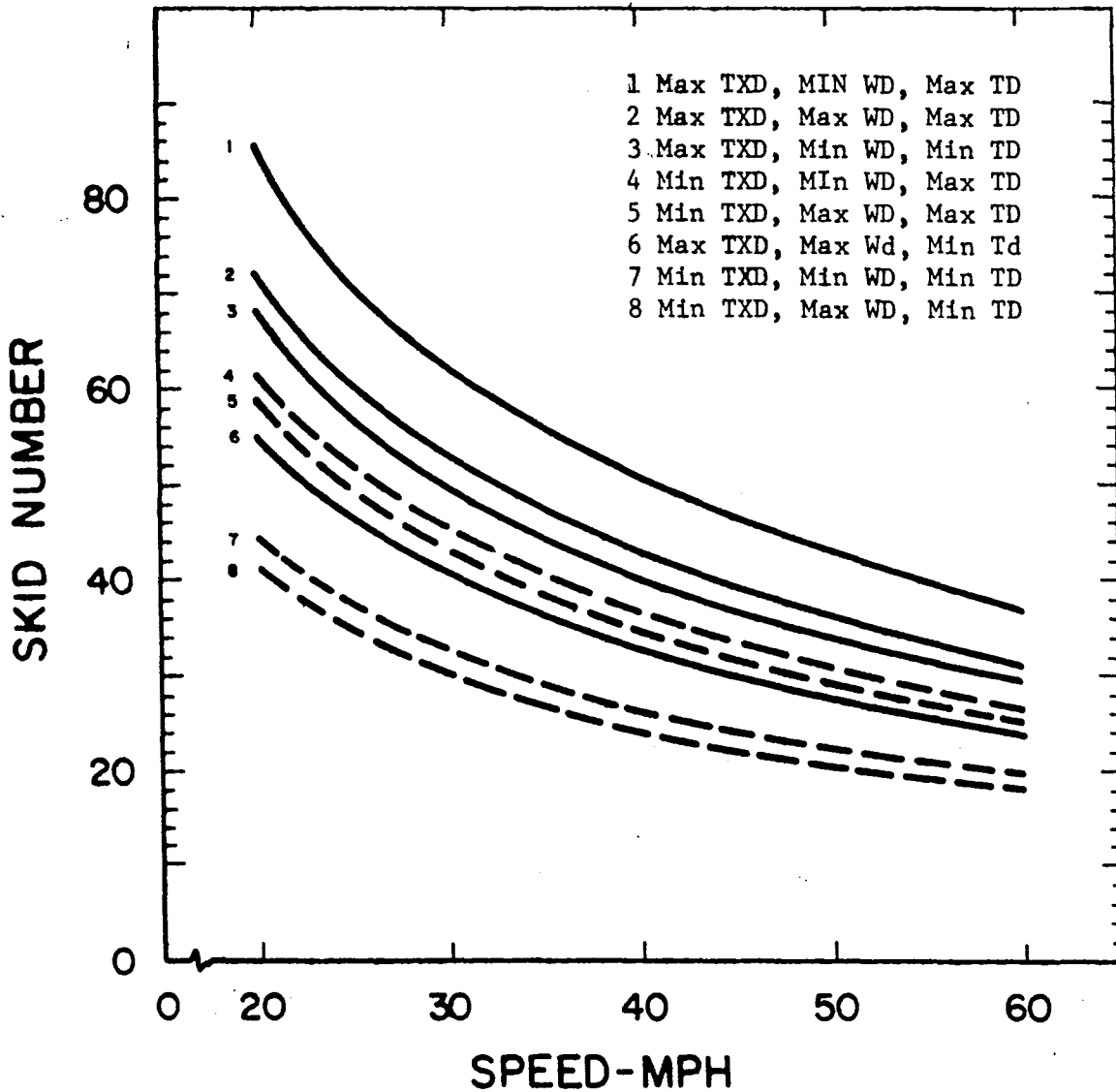


Figure 11. Effects of pavement texture depths (TXD), tire tread depths (TD), and water film depths (WD) on the skid number at various speeds for the ASTM-14" tire at 24 psi tire inflation pressure, TAMU Annex data.

### Stochastic Considerations

Because these equations have been derived by regression, there will always be values of skid number that will differ on a random basis from those predicted by the equation. As a consequence, it is important to know how reliably these equations predict that a skid number will be above a minimum acceptable level. The reliability of skid-resistance prediction is the degree of confidence (say 95 percent) one has that the predicted value of SN is above the minimum level. This reliability can be calculated from the statistical properties of the MPH, TD, WD, and TXD frequency distributions. The fact that it is not always 100 percent certain is because of the inherent uncertainty and variability of these variables. The regression equations are deterministic models. Stochastic models which include the variability of the variables can be composed based on the expected value and variance of SN.

### Discussion and Conclusion

- (1) The regression models satisfy physical constraints,

$$\frac{d SN}{d MPH} < 0, \frac{d SN}{d TD} > 0, \frac{d SN}{d WD} < 0, \frac{d SN}{d TXD} > 0$$

- (2) Experimental data are within following ranges:

$$20 \leq MPH \leq 60, 0 \leq TD \leq 10, -2.1 \leq WD \leq 3.61, \text{ and}$$

$0.0032 \leq TXD \leq 0.1590$ . The regression models may not be used to predict SN outside these ranges.

- (3) Sensitivity analysis and stochastic considerations can be utilized to establish criterion for skidding accident reduction.

## REFERENCES

1. Gallaway, B. M. and Tomita, H., "Microtexture Measurements of Pavement Surfaces," Research Report No. 138-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, February 1970, 20pp.
2. Gallaway, B. M. and Rose, J. G., "Macro-texture, Friction, Cross Slope and Wheel Track Depression Measurements on 41 Typical Texas Highway Pavements," Research Report No. 138-2, Texas Transportation Institute, Texas A&M University, College Station, Texas, June 1970, 57pp.
3. Gallaway, B. M. and Rose, J. G., "Highway Friction Measurements with Mu-Meter and Locked Wheel Trailer," Research Report No. 138-3, Texas Transportation Institute, Texas A&M University, College Station, Texas, June 1970, 58pp.
4. Gallaway, B. M., Epps, J. A. and Tomita, H., "Effects of Pavement Surface Characteristics and Textures on Skid Resistance," Research Report No. 138-4, Texas Transportation Institute, Texas A&M University, College Station, Texas, March 1971, 36pp.
5. Gallaway, B. M., Schiller, R. E., Jr. and Rose, J. G., "The Effects of Rainfall Intensity, Pavement Cross Slope, Surface Texture, and Drainage Length on Pavement Water Depths," Research Report No. 138-5, Texas Transportation Institute, Texas A&M University, College Station, Texas, May 1971, 69pp.
6. Gallaway, B. M., Rose, J. G., Scott, W. W., Jr., and Schiller, R. E., Jr., "Influence of Water Depths on Friction Properties of Various Pavement Types," Research Report No. 138-6, Texas Transportation Institute, Texas A&M University, College Station, Texas, June 1974, pp.
7. Kummer, H. W., and Meyer, W. E., "Tentative Skid Resistance Requirements for Main Rural Highways," NCHRP Report 37, Highway Research Board, 1967.
8. Keen, H. M., "Design for Safety," Highway Research Record 214, 1968.
9. Dubose, D. A. "Select Calling Program," Institute of Statistics, Texas A&M University, 1970.
10. Hocking, R. R., and R. N. Leslie, "Selection at the Best Subset in Regression Analysis," Technometrics 9, pp. 531-540, 1967.
11. LaMotte, L. R., and R. R. Hocking. "Computational Efficiency in the Selection of Regression Variables," Technometrics 12, pp. 83-93, 1970.
12. \_\_\_\_\_, The Physics of Tire Traction - Theory and Experiment, Plenum Press, New York, New York, 1974.