U.S. Department
of Transportation

**Federal Highway
Administration**

WET WEATHER EXPOSURE MEASURES

Research, Development, and Technology
Turner-Fairbank Highway Research Center
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FOREWORD

It is common knowledge that driving on wet roads requires extra caution. "Slippery When Wet" signs are posted by highway departments at some locations, although it is not known if such signs have any effect on driver behavior or on accident rates. There is no question that tire-pavement friction is much lower on wet pavements than on dry ones. Friction on wet pavements decreases with increasing speed, and this decrease (friction-speed gradient) is greatest when both the tire and the pavement are relatively smooth. Thus one way of reducing the skidding hazard is to provide pavements with adequate macrotexture, and make sure that tires have adequate tread depth. However, since drainage is never complete, a very thin waterfilm remains which can be pierced by harsh microtexture. Therefore, pavements must have both micro- and macrotexture for providing adequate friction under wet conditions.

The research reported here concentrated on the effects of very thin waterfilms on pavement-tire friction. A computer program, WETTIME, was developed for estimating wet-time exposure as a function of rainfall and local conditions. The program can be used to draw contour maps of pavement wetness, with some examples given in the report. Using these contour maps instead of average rainfall, in conjunction with accident records, should give a better estimate of the contribution of skidding to the total accident occurrence.

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and Highway Operations
Research and Development

NOTICE

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16. Abstract

Accident surveillance programs require a measure of wet-pavement exposure to determine whether the wet-pavement accident rates of particular highway sections are higher or lower than expected. This research program used the results of laboratory and field tests, together with available weather data to construct a model for estimating the percentage of time a pavement would be wet. The laboratory and field testing program addressed (1) the minimum level of pavement surface wetness that substantially reduces tire-pavement friction and (2) the time required for a pavement to dry following rainfall. A computer model, known as the WETTIME model, was developed in the research to estimate the monthly and annual hours of wet-pavement exposure. The model can be used to estimate wet-pavement exposure in the vicinity of any first-order weather station from data that can be obtained from the National Climatic Data Center in Asheville, North Carolina. Procedures were also developed to use the output of the WETTIME model to prepare isoexposure contour maps for entire States or regions.

A companion volume, Report No. FHWA/RD-87/106, is a Users Guide for the WETTIME exposure estimation model.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

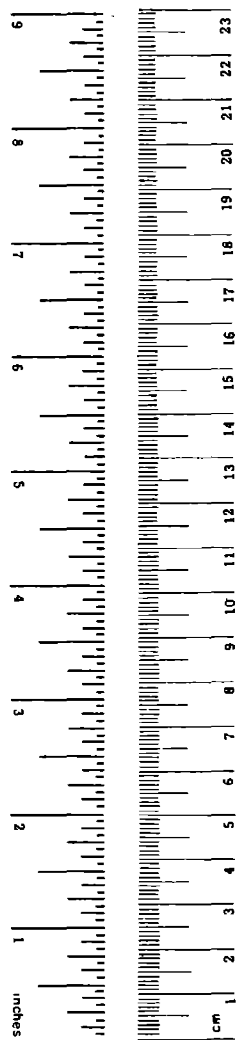
VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac

MASS (weight)

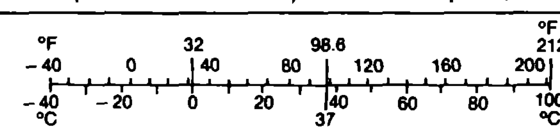
Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

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I. INTRODUCTION

Wet weather accidents constitute an important element of the safety problem on American highways. Recent research has found that approximately 13.5 percent of fatal accidents[1] and as many as 25 percent of all accidents[2] occur under wet pavement conditions. The presence of water on the pavement reduces the available friction at the tire-pavement interface and may increase accident rates associated with maneuvers involving high friction demand -- particularly accelerating, braking, and cornering.

The estimation of wet pavement exposure is critical to the assessment of wet weather accident experience. Wet pavement exposure estimates are needed both to assess the overall priority that should be assigned to wet weather accidents in highway safety programs and to provide a reliable means to compare wet weather accident rates of highways located in different climatological regions.

A. Study Objectives

Midwest Research Institute (MRI) and the Pennsylvania Transportation Institute (PTI) have undertaken a study for the Federal Highway Administration (FHWA) to improve the ability of highway agencies to estimate wet weather exposure measures. The objectives of this study are to:

- Establish the minimum levels of wetness at which tire-pavement friction is substantially reduced;
- Develop a model for predicting how many hours per year this minimum wetness level is exceeded, as a function of regional meteorological and pavement characteristics; and
- Demonstrate use of the model by developing wetness maps for some representative regions.

B. Study Overview

The study involved a series of laboratory and field investigations to develop the basic building blocks of a wet-pavement exposure estimation model. The primary issues investigated in laboratory and field experiments were:

- The minimum water film thickness on a pavement surface that substantially reduces tire-pavement friction; and
- The time required for a wet pavement to dry following the end of rainfall, as a function of ambient environmental conditions.

Analytical and observational studies were also conducted to investigate:

- The relationship between the total amount of rainfall in a given period and the duration of rainfall within that period;
- The conditions under which pavement drying cannot occur due to saturated or nearly saturated atmospheric conditions;
- The conditions under which pavement wetness may result from condensation on the pavement during fog; and
- The conditions under which pavement wetness may result from ice and snow conditions.

The findings of these studies are summarized in Section I.C.

The results of these investigations were used to develop a computer model, known as the WETTIME model, to predict the number of hours of wet-pavement exposure per year from readily available weather data. This model is suitable for direct application by highway agencies and is available from the Federal Highway Administration. This report describes the development and application of the WETTIME model. Instructions for use of the model is provided in a companion volume, "Users Guide for the WETTIME Exposure Estimation Model."[3]

C. Summary of Findings

The laboratory and field investigation of pavement surface friction conducted during the research concluded that the minimum level of wetness that substantially reduces pavement surface friction is between 0.001 and 0.009 in. (0.025 and 0.23 mm) of water on the pavement surface. This conclusion is based primarily on the results of locked-wheel friction tests conducted at 40 mi/h (64 km/h) with a full-scale tire on typical pavement surfaces. This minimum level of wetness is likely to be exceeded during any hour in which there is at least 0.01 in. (0.25 mm) of rainfall.

Laboratory tests were conducted to measure pavement drying time under controlled environmental conditions. These results were used to develop a statistical model that predicts the pavement drying time as a function of solar radiation intensity, wind speed, temperature, relative humidity, and pavement type (asphalt/portland cement concrete). Field tests verified that the model predicts realistic pavement drying times under a variety of environmental conditions.

These laboratory and field results were used together with the results of analytical and observational studies as the basis for development of the WETTIME computer model. This program uses computer files of weather data available from the National Climatic Data Center (NCDC) in Asheville, North Carolina, to estimate the monthly and annual number of hours of wet-pavement exposure. The elements incorporated in the WETTIME computer model include:

- Minimum level of wetness that reduces pavement surface friction
- Rainfall intensity and duration
- Runoff period following rainfall
- Pavement drying period following rainfall and runoff
- Pavement wetness due to fog
- Estimation of exposure to ice-and-snow conditions

Procedures were also developed to use the output of the WETTIME model to prepare isoexposure contour maps for entire States or regions. Isoexposure contours are lines connecting locations of equal wet-pavement exposure.

D. Organization of This Report

Section II of this report provides background information on the need for wet-pavement exposure estimates and the existing estimation methods. This section focuses on the importance of wet-pavement exposure estimates in highway safety programs and the limitations of the current methods for making such estimates.

Section III presents an overview of the WETTIME exposure estimation model. This section focuses on the components of the WETTIME model and the type of output it can provide.

Section IV provides examples of the application of the WETTIME model including test cases for several geographic regions and isoexposure contour maps of several States.

The conclusions and recommendations from the research are presented in Section V and the references cited in the report are presented in Section VI.

Appendix A discusses the laboratory and field investigation of the minimum level of wetness that reduces pavement surface friction. Appendix B discusses the laboratory and field investigation of pavement drying time following rainfall.

II. BACKGROUND

This section of the report defines wet-pavement exposure and discusses the need for wet-pavement exposure estimates, the types of weather data available to make exposure estimates, and the strengths and weaknesses of existing methods for making exposure estimates.

A. Definition of Exposure Measures

Exposure estimates are used in highway safety studies as a measure of the opportunities for traffic accidents to occur. Typical exposure measures for traffic accidents include the number of sites considered, the duration of the time period for which accident data are available, the total length of the sites, or the total vehicle-miles of travel on those sites. The greater the exposure, the greater the number of accidents that would be expected to occur. To determine whether there are more accidents than expected at a site (or a group of sites), both an accident frequency and an exposure measure are needed. Thus, safety measures used in accident surveillance often combine both accident and exposure measures for a given time period into an accident rate:

$$R = \frac{A}{E} \tag{1}$$

where: R = accident rate (accidents per million veh-mi)
A = number of accidents
E = exposure (million veh-mi)

Thus, accidents form the numerator and exposure forms the denominator of the accident rate expression.

Wet-pavement exposure measures represent the portion of the total exposure that occurs under wet-pavement conditions. If the numerator of the accident rate expression is annual wet-pavement accidents, then the denominator should be annual vehicle-miles of travel under wet-pavement conditions, as shown below:

$$R_w = \frac{A_w}{E_w} \tag{2}$$

where: R_w = wet-pavement accident rate (accidents per million veh-mi)

A_w = number of wet-pavement accidents

E_w = wet-pavement exposure (veh-mi)

Wet-pavement accidents are defined by the road surface condition at the time of the accident as recorded by police officers and/or motorists on the accident report form. The categories used for road surface condition on accident report forms typically consist of (1) dry, (2) wet, and (3) ice and snow. Wet-pavement accidents are those which occur when the road surface is wet, whether or not it is actually raining at the time of the accident.

The annual wet-pavement exposure (E_w) can be estimated most directly as the product of total annual vehicle-mile of travel (E) and the proportion of annual hours during which the pavement is wet. Previous wet-pavement exposure estimation methods have focused on how to estimate this latter proportion.

B. Need for Wet-Pavement Exposure Estimates

Most highway agencies have an existing program of identifying and treating locations with high wet-pavement accident experience, often as part of their computerized accident surveillance system. The locations identified by the program are reviewed through engineering studies to determine whether a correctable safety problem exists. These locations become candidates for improvement projects (such as pavement resurfacing) to increase the supply of tire-pavement friction and improvement projects (such as realignment or other geometric modifications) to reduce the demand for tire-pavement friction.

Accident surveillance programs identify potential improvement locations by comparing the accident frequencies or rates at specific locations with average values or with selected critical values. Typically, the computer analysis may evaluate the accident experience of a fixed-length section (say, 0.3 mi or 0.5 km) that moves along the highway in 0.01-mi (0.02-km) increments. For example, a 0.3-mi (0.5-km) highway section might be classified as a high-accident section if it had either a wet-pavement accident rate at least 20% higher than the average wet-pavement accident rate or more than 5 wet-pavement accidents per year.

A review of wet-pavement accident surveillance programs by the National Transportation Safety Board[1] (NTSB) in 1980 found that most States do not use any wet-pavement exposure measure in their wet-pavement accident surveillance programs. If no wet-pavement exposure measure is available, the wet-pavement accident rate is typically defined with wet-pavement accidents in the numerator and total exposure in the denominator; as follows:

$$R'_w = \frac{A_w}{E} \qquad (3)$$

where: R'_w = modified wet-pavement accident rate (accidents per million veh-mi)

A_w = number of wet-pavement accidents

E = total exposure under all pavement conditions (veh-mi)

This hybrid measure (R'_w) has been used both in many State accident surveillance systems and in past wet-pavement research.[4] The potential problem with R'_w as a measure of wet-pavement accident rate is that it is not sensitive to the geographic variations in climate within a State or the variations in climate from year-to-year. An accident surveillance program that monitors R'_w or the raw frequency of wet-pavement accidents will tend to identify as problem sections those highways in areas that get the most rainfall. Highway sections with low pavement surface friction that are located in drier areas might go untreated even if they experience unusually high accident rates when the pavement is wet.

Precipitation amounts vary markedly between regions in many States. At the extreme, the Pacific Coast States include areas of both rain forest and desert. A few States perform accident surveillance separately for different parts of the state to account for the diversity of climate. For example, the Washington State DOT has divided their State into eight climatic regions for application of their wet-pavement accident surveillance program and has used different criteria to select high-accident locations in each region. Some States have computed average wet-pavement accident rates separately for each highway district.

Precipitation amounts also vary from year-to-year within each State and across the nation. It would be erroneous to interpret an increase in wet-pavement accident frequency as a developing safety problem if it resulted, in fact, from an increase in rainfall from one year to the next year. Thus, wet-pavement exposure estimates are also needed to account for year-to-year changes in climate.

C. Available Weather Records

The development of an explicit method to estimate wet-pavement exposure requires detailed weather records. The most detailed weather records that are normally available for major weather stations are recorded on an hourly basis. All previous efforts to estimate wet-pavement exposure have been based on the hourly weather data available from the National Climatic Data Center (NCDC) in Asheville, North Carolina.

The most commonly used weather records for exposure estimation are the Hourly Precipitation Data available on computer tape from NCDC. These data contain a record of the hourly precipitation amount (in inches) for each hour in which a measurable amount of precipitation (at least 0.01 in. or 0.25 mm) occurred. The Hourly Precipitation data make no distinction between frozen and nonfrozen precipitation; for frozen precipitation, the precipitation amount is given as a water equivalent in inches. A review by MRI found these data to be complete and reliable at first-order weather stations, typically located at major airports. However, the data for many of the minor stations appear to be incomplete and unreliable for exposure estimation. The reliability of the Hourly Precipitation Data for estimating wet-pavement exposure of minor weather stations is addressed further in Section IV.C. of this report.

Most previous attempts to estimate wet-pavement exposure have been based solely on the Hourly Precipitation Data described above. However, there are other forms of weather records available on an hourly basis that provide a valuable supplement to the hourly precipitation amounts. NCDC publishes a two-page printed monthly summary of hourly weather records for approximately 250 first-order weather stations. This summary, known as Local Climatological Data, provides hourly precipitation amounts, identifies hours with trace amounts of precipitation, and identifies the type of weather that occurred (rain, snow, fog, etc.).

Even greater detail in hourly weather data is found in the Hourly Surface Observations available on computer tape from NCDC. These data are also available for first-order weather stations and include hourly data on:

- Air temperature
- Dewpoint temperature
- Relative humidity
- Wind speed
- Cloud cover
- Occurrence of rain, snow, or fog

These data provide a more complete understanding of hourly weather than precipitation amounts alone.

D. Existing Wet-Pavement Exposure Estimation Methods

There have been several previous attempts by highway agencies and researchers to develop a wet-pavement exposure estimation method. It has been obvious to all investigators that annual precipitation totals by themselves are not adequate to estimate wet-pavement exposure. Some climatic regions commonly experience cloudbursts where large amounts of rain fall in a very short time period. Other regions experience drizzle, where small rainfall amounts are spread over a long time period. Therefore, all previous attempts to estimate wet-pavement exposure have, in one way or another, examined the number of hours in which rainfall occurred.

A 1972 study by the California Department of Transportation[5] defined wet-pavement exposure as the total number of hours during which a measurable amount (0.01 in. or 0.25 mm or more) of rainfall occurred. Trace amounts of rainfall were not considered. This method was used to estimate wet-pavement exposure from the NCDC Hourly Precipitation Data described above. A similar definition of wet-pavement exposure has been used in studies by NTSB[1] and the States of Arizona[6] and Michigan.[7]

An alternative wet-pavement exposure estimation technique was developed by MRI in earlier research. The MRI method was developed in NCHRP Project 6-11, "Economic Evaluation of the Effects of Ice and Frost on Bridge Decks."[8] The method was further refined by MRI in a 1978 FHWA study entitled, "Effectiveness of Alternative Skid Reduction Measures."[2] The technique differed from the California/NTSB technique in that it included explicit consideration of the drying period during which pavements remain wet after rainfall ceases and the period that pavements are wet due to melting of snow and ice. The original MRI technique also considered wet time due to trace amounts of rainfall (less than 0.01 in. or 0.25 mm per hr) that are part of a longer period during which measurable rainfall occurs, but ignored periods of rainfall composed entirely of trace amounts. The development of the technique included field observations of pavement drying times, and the technique was validated using wet pavement exposure data from a moisture sensor implanted in an Interstate highway bridge near Iowa City, Iowa.

Both the California/NTSB model[1,5] and the original MRI model[2] have strengths and weaknesses which are summarized in Table 1. A major strength of the California/NTSB approach is its simplicity, since it considers only the NCDC Hourly Precipitation Data. This method can be applied to numerous weather stations throughout each State. However, the simplicity of the model makes it tempting to apply it to minor weather stations which have questionable data.

Another weakness of the California/NTSB approach is that it makes no distinction between frozen and non-frozen precipitation. This distinction is important in an exposure measure, because accidents classified by road surface conditions have separate categories for wet pavements and for ice- and snow-covered pavements. Thus, the California/NTSB method is only applicable to snow-free areas or to data from which the winter months have been excluded. This limitation may not be critical in California, where snowfall is rare in most populated areas, but it is important for nationwide application as attempted by NTSB.[1]

Finally, the California/NTSB approach does not explicitly consider possible variations in the duration of rainfall within each hour, possible variations in pavement drying time, pavement wetness due to melting ice and snow, and pavement wetness due to fog.

The original MRI model attempted to account for many of the weaknesses described above, but did so imperfectly because of the lack of research concerning the role of these factors in pavement wetness. The MRI model was more complex than the California/NTSB model because it considered both Hourly Precipitation Data and the weather observations available from the Local Climatological Data published by NCDC.

Pavement drying time following rainfall was originally estimated as 1 hr;[8] this estimate was later reduced to 30 min based on limited field observations.[2] However, no research was available to indicate how pavement drying time might vary with environmental and atmospheric conditions.

During each hour of measurable rainfall, the duration of rainfall was assumed to last for the entire hour. No data were available to indicate how the duration of rainfall might vary with rainfall amounts or other environmental variables.

TABLE 1

STRENGTHS AND WEAKNESSES OF PREVIOUS WET-PAVEMENT EXPOSURE ESTIMATION TECHNIQUES

Model	Strengths	Weaknesses
California/NTSB Model	Simple model. Only one data source required (Hourly Precipitation Data) No reliance on trace amounts of rainfall which may not completely wet the pavement	No distinction between frozen and nonfrozen precipitation No consideration of variations in duration of rainfall within an hour with measurable precipitation No consideration of variations in pavement drying time based on environmental conditions, etc. No consideration of pavement wetness due to melting ice and snow No consideration of pavement wetness due to fog No validation on independent data Easily applied to weather stations with questionable data
Original MRI Model	Pavement drying time estimate based on limited field observations Explicit distinction made between frozen and nonfrozen precipitation Explicit consideration of pavement wetness due to melting ice and snow Limited validation on independent data	Complex model Two data sources required (Hourly Precipitation Data and Local Climatological Data) Overemphasis on trace amounts of rainfall Overemphasis on pavement wetness due to fog No consideration of variations in duration of rainfall within an hour with measurable precipitation No considerations of variations in pavement drying time based on environmental conditions, etc.

The model attempted to account for pavement wetness due to fog by classifying all hours when fog occurred as wet-pavement time. This resulted in an overestimate of the duration of pavement wetness due to fog.

The original MRI model did provide separate estimates for wet-pavement exposure time and ice and snow exposure time. The model also treated the pavement drying time following snowfall as wet time, rather than as ice and snow time. This feature of the model recognized that pavement wetness can result from melting ice and snow.

The original MRI model considered some periods with trace amounts of precipitation as wet time and the inclusion of these trace amounts may have resulted in unnecessarily high exposure estimates.

The preceeding discussion and the summary in Table 1 indicate that the weaknesses of both previous models outweigh their strengths. Thus, there is a need for development of an improved wet-pavement exposure estimation model, which was accomplished in the research reported here.

III. DEVELOPMENT OF THE WETTIME EXPOSURE ESTIMATION MODEL

This section of the report describes the development of the WETTIME model for estimating wet-pavement exposure. The section first presents a brief overview of the model scope and then describes the individual components or elements of the model and the research findings on which they are based. The complete formulation of the model is then presented, followed by a discussion of the input data required and the output provided by the model.

A. Model Scope

The WETTIME model is intended to provide a tool for use by highway agencies to estimate wet-pavement exposure. The elements of the model draw upon the strengths of both the California/NTSB model[1,5] and the original MRI model,[2,8] described in Section II.D., while correcting their weaknesses through laboratory and field testing, as well as analytical and observational studies. The model is based to the greatest possible extent on valid research findings rather than on engineering judgment.

The model development recognized the need to distinguish clearly between wet-pavement exposure time and ice-and-snow exposure time. The NCDC Hourly Precipitation Data alone cannot be used for this purpose, because these data do not distinguish frozen and non-frozen precipitation. The most readily available data source in which this distinction can be made is the NCDC Hourly Surface Observations. These observations also include hourly measurements of air temperature, dew point temperature, relative humidity, wind speed, and cloud cover that can be used to enhance the accuracy of the exposure estimation model. However, the need for both types of input data limits the direct application of the model to first-order weather stations. There are only about four to ten first-order stations in each State, typically located at major airports. A method for extending the WETTIME model estimates to additional weather stations was developed so that isoexposure contour maps of selected states could be developed; this process is discussed in Section IV.C. of the report.

B. Model Elements

The following elements have been incorporated in the WETTIME model:

- Minimum level of wetness that reduces pavement surface friction
- Rainfall intensity and duration
- Runoff period following rainfall

- Pavement drying period following rainfall and runoff

- Pavement wetness due to fog

- Estimation of exposure to ice-and-snow conditions

Each element of the model is discussed below.

1. Miminum level of wetness that reduces pavement surface friction: None of the earlier wet-pavement exposure estimation models explicitly addressed whether the rainfall amounts considered by the model were sufficient to reduce pavement surface friction to the point of slipperiness. The existing exposure estimation techniques assume that 0.01 in. (0.25 mm) of rainfall in an hour, or in some cases a trace amount of rainfall in an hour, is sufficient to result in slipperiness. However, neither of the existing models provides any justification for this assumption on the basis of valid research findings.

A critical review of the literature related to the relationship between tire-pavement friction and waterfilm thickness was undertaken as part of the development of the WETTIME model. Because no satisfactory relationships were found in the literature, laboratory and field studies were undertaken to determine the minimum level of wetness that substantially reduces friction. The literature review and the laboratory and field testing are summarized briefly in the following discussion and are presented in greater detail in Appendix A.

a. Literature review: A critical review of the literature indicates two reasons why the amount of rainfall that results in slipperiness had not been previously determined. First, the relationship between tire-pavement friction and waterfilm thickness is elusive, especially for low speeds. Second, even if this relationship were known, there is no accepted definition of what level of friction constitutes slipperiness.

Locked-wheel friction tests conducted in accordance with ASTM Standard E 274 at 40 mi/h (64 km/h) use a water flow rate of 3.6 gal/min/in. of wetted width (0.54 L/min/mm). This flow rate results in a nominal waterfilm thickness of 0.02 in. (0.5 mm) on the pavement during friction testing. Figure 1 illustrates that, on most pavement surfaces, friction is relatively insensitive to waterfilm thickness at thicknesses of 0.015 in. (0.38 mm) or more.[9] The 0.02-in. (0.5-mm) thickness was selected as a convenient value for friction testing, since it assures an actual waterfilm thickness of at least 0.015 in. (0.38 mm) despite variations in water flow rates.

Research concerning the relationship between tire-pavement friction and waterfilm thickness has been conducted for relatively thin waterfilms, less than 0.02 in. (0.5 mm) thick, by Besse,[9] Giles,[10] Gegenbach,[11] Veith,[12] Pelloli,[13] Williams and Evans,[14] and Rose and Gallaway.[15] Each of these researchers found some sensitivity of friction to waterfilm thickness for speeds of 25 mi/h (40 km/h) or higher. However,

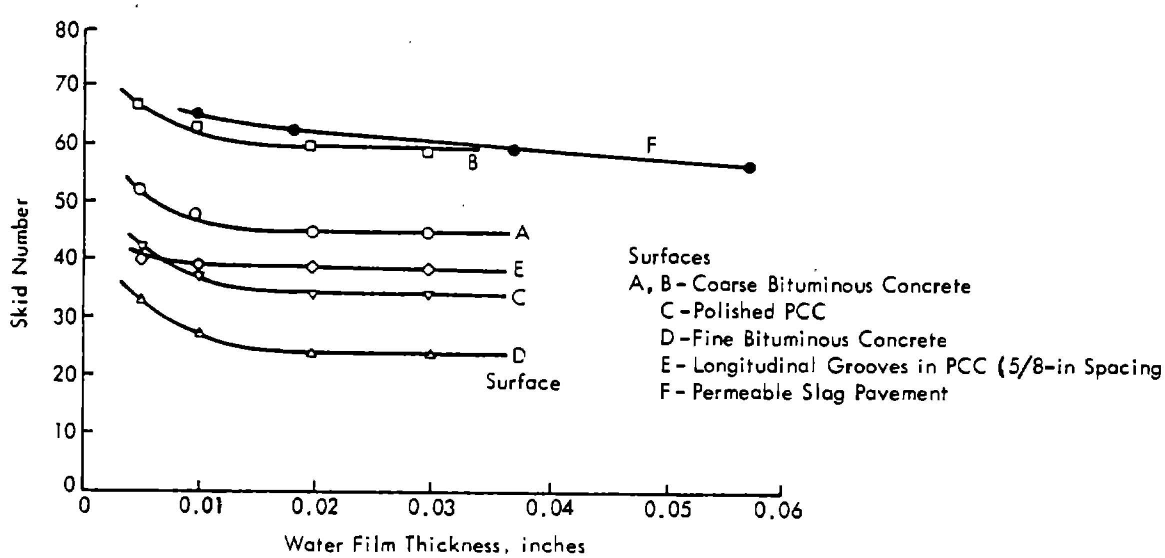


Figure 1 - Skid Resistance at 40 mi/h as Function of Waterfilm Thickness on Various Surfaces[9]

none of the studies found any sensitivity of friction to waterfilm thickness at speeds of less than 25 mi/h (40 km/h). The study results varied widely and none was found to be satisfactory for establishing the minimum level of wetness.

Veith[12] and Pelloli[13] concluded that the relationship between friction and waterfilm thickness at higher speeds was described by a negative exponential, with the general form:

$$\mu = ae^{-bd} + c \qquad (4)$$

where: μ = coefficient of friction
d = waterfilm thickness
a,b,c = regression coefficients to be determined

Besse,[9] Giles,[10] and Gegenbach[11] also obtained relationships that appear to be of a negative exponential form, at least for some pavement types and speed ranges.

It is also known that contaminants on the pavement, such as oil and grease and deicing chemicals, may influence friction.[18,20] The influence of such contaminants may depend on the length of time since the last substantial rainfall. Some contaminants are washed away by continued rainfall or by the forceful application of water during a skid test. Thus, the relationships between friction and waterfilm thickness in Figure 1, which were established through conventional skid testing, are probably indicative of conditions at the onset of rainfall on a relatively clean surface or during rainfall after the contaminants have been washed away.

b. Definition of minimum level of wetness: There is no accepted definition of the minimum level of wetness that substantially reduces pavement surface friction. Thus, a definition had to be developed during the research.

One approach to defining the minimum level of wetness would be to use the waterfilm thickness corresponding to a specified coefficient of friction or a specified reduction from the dry-pavement friction. Though appealing, such concepts are simplistic, since there is no agreement on a rational basis for defining acceptable and nonacceptable levels of friction. Instead, it was decided that the criterion for the minimum level of wetness should be based primarily on the shape of the friction versus waterfilm thickness curve.

Figure 2 shows the conceptual relationship between coefficient of friction and waterfilm thickness, for a negative exponential relationship of the form shown in Equation (4). In Figure 2, the pavement friction coefficient under dry conditions is represented by c+a, while the pavement friction coefficient for thick waterfilms asymptotically approaches the value of c. The minimum level of wetness should be a waterfilm thickness at which pavement friction has decreased substantially from the dry value and is approaching, but not yet reached, the relatively insensitive relationship between pavement friction and waterfilm thickness for thick waterfilms. There is no unique point on a continuous function that meets this criterion. Several candidate definitions were considered. A decision was reached to define the minimum level of wetness as the waterfilm thickness at which the pavement friction coefficient has fallen 75 percent of the way from the dry friction coefficient for thick waterfilms (i.e., the waterfilm thickness at which the pavement friction coefficient is equal to c+a/4). For a negative exponential relationship, the minimum level of wetness is then defined as:

$$d_{min} = -\frac{1}{b}\,\ell n\,\frac{1}{4} = \frac{1.386}{b} \qquad (5)$$

where: d_{min} = minimum level of wetness at which friction is substantially reduced

b = regression coefficient from Equation (4)

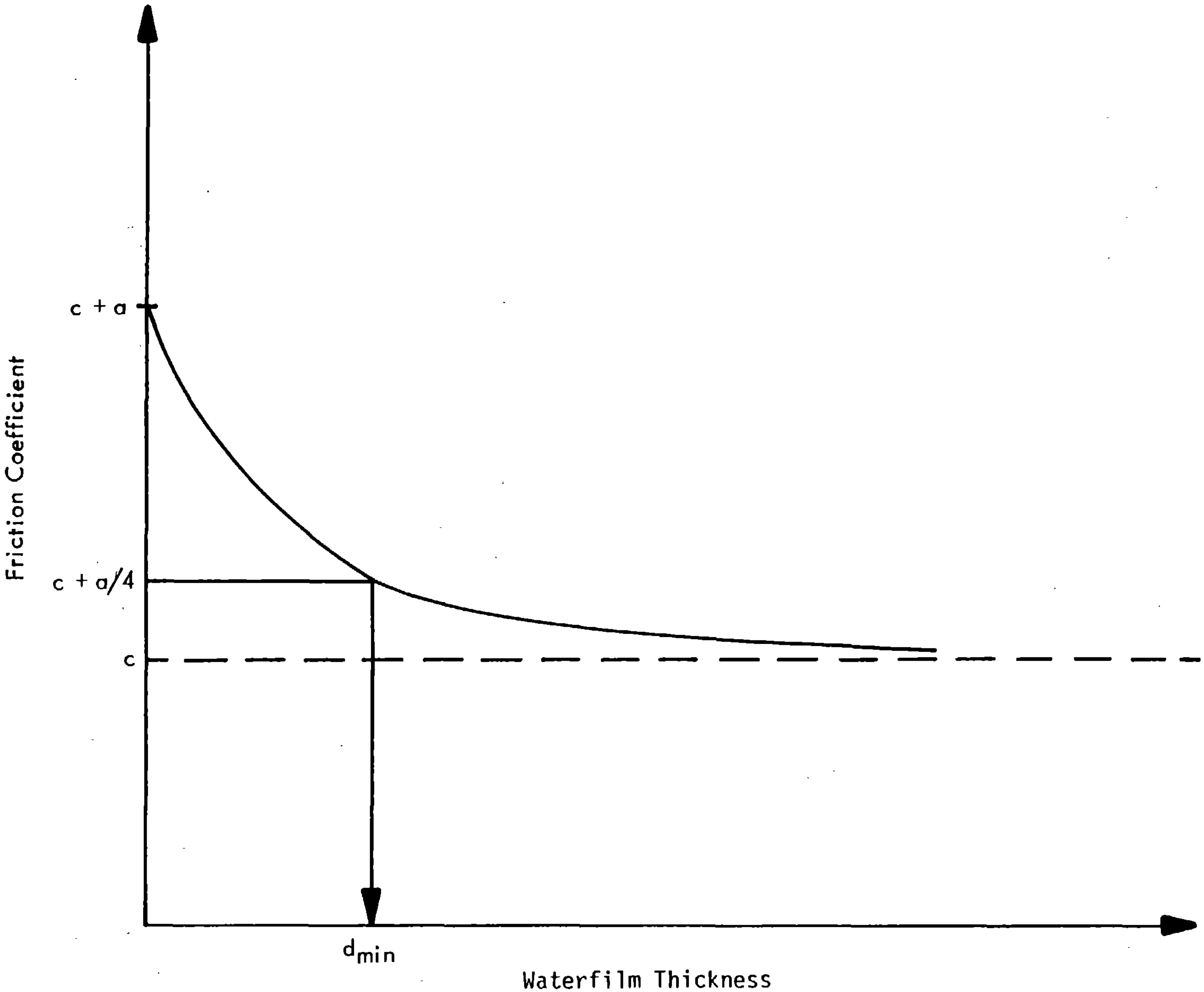


Figure 2 - General Form of Negative Experimental Relationship Between Friction Coefficient and Waterfilm Thickness

The position of the minimum level of wetness, d_{min}, is illustrated in Figure 2.

The recommended criterion for the minimum level of wetness is reasonable because it is a function only of the b coefficient, which sets the shape of the negative exponential curve. The choice of the 75 percent reduction criterion is conservative. It results in a greater minimum level of wetness than, say, a 50 percent reduction criterion and thus assures that when the minimum level of wetness is reached the pavement friction coefficient is approaching that of a thick waterfilm.

c. Laboratory friction tests: Laboratory tests were conducted in this study to further investigate the relationship between pavement surface friction and waterfilm thickness and to estimate the minimum level of wetness.

A new laboratory testing device, known as the PTI Friction Tester, was developed for this study. The device, which is illustrated in Appendix A, consists of a rubber slider mounted on a slider assembly with linear bearings pulled along horizontal rails by the force of a freely falling weight. The tester is positioned so that the rubber slider approaches the test surface while running freely and then is dragged along the test surface by the force of the falling weight. A parameter proportional to the coefficient of friction is calculated from the deceleration of the slider assembly produced by the frictional force between the rubber slider and the test surface. The PTI Friction Tester was generally operated at a speed of 5 to 7 mi/h (8 to 11 km/h). One set of higher speed tests was performed at 10 to 12 mi/h (16 to 19 km/h). Speeds higher than 12 mi/h (19 km/h) could not be achieved under laboratory conditions.

Laboratory friction tests were conducted for six surface types, four water types, and two testing speeds, as shown in Table 2. A total of 548 friction tests were conducted for 20 selected combinations of the factors in Table 2. The different surface types represented a range of pavement types and textures. The different water types represented ordinary distilled water, actual rain water, tap water that would normally be used in skid testing, and a salt solution (representing water contaminated by deicing chemicals).

The laboratory test results were not very conclusive with regard to the minimum level of wetness. Statistically significant negative exponential relationships between friction and waterfilm thickness were found for only six of the 20 combinations tested. The other 14 combinations displayed no apparent relationship between friction and waterfilm thickness. This result was not surprising, because the literature indicates the difficulty of establishing such relationships for low-speed tests. For the six combinations that did show a significant negative exponential relationship, the minimum level of wetness as defined in Equation (5), ranged from 0.0002 to 0.002 in. (0.005 to 0.05 mm).

TABLE 2

FACTORS EVALUATED IN LABORATORY FRICTION TESTS

Pavement Type

Smooth polished granite block
Artificial surface - limestone aggregate
Artificial surface - gravel aggregate
Real pavement surface - open-graded friction course
Real pavement surface - dense-graded asphalt
Artificial surface - sand aggregate

Water Type

Distilled water
Rain water
Tap water
Salt solution (NaCl)

Test Speed

Low (5 to 7 mph)
High (10 to 12 mph)

The laboratory friction data did not indicate any sensitivity of the minimum level of wetness to pavement type or to contaminants in the test water.

d. Field friction tests: Given the poor results of the laboratory tests, it was decided that the issue of the minimum level of wetness needed to be investigated at higher speeds under field conditions. Therefore, the minimum level of wetness was further investigated using a conventional skid tester at speeds of 5, 20, and 40 mi/h (8, 32, and 64 km/h) on selected pavement surfaces at the PTI Test Track. The field tests used three different types of full-scale tire including an ASTM-standard ribbed test tire, an ASTM-standard blank test tire, and a worn passenger car tire. The pavement surfaces evaluated included both asphalt and portland cement concrete (PCC) surfaces. The factors varied in the test are summarized in Table 3.

The data from the field friction tests were used to develop negative exponential regression relationships between pavement friction and waterfilm thickness similar to those developed in the laboratory experiment. No significant relationships were found for the field data collected at 5 and 20 mi/h (8 and 32 km/h). However, at 40 mi/h (64 km/h), statistically significant negative exponential relationships were found for 10 of the 11 combinations of variables tested. These relationships are illustrated in Figure 3 and the coefficients for these relationships are presented in Table 4. It was concluded from the data in Table 4 that the minimum level of wetness for the pavement surfaces tested lies in the range from 0.001 to 0.009 in. (0.025 to 0.23 mm). The results did not indicate any consistent trends in the minimum level of wetness for specific pavement surface types or tire types.

e. Interpretation of results: The results indicate that as little as 0.001 in. (0.025 mm) of water on a pavement surface can, in some cases, reduce friction 75 percent of the way from the dry to the wet value. This minimum level of wetness is likely to be exceeded whenever the hourly rainfall is 0.01 in. (0.25 mm) or greater. Thus, all measurable amounts of rainfall in the available NCDC Hourly Precipitation Data are likely to exceed the minimum level of wetness and should be considered as wet-pavement exposure in the WETTIME model.

On the other hand, the minimum level of wetness is so small that some trace amounts of rainfall could exceed that level. However, trace amounts of precipitation are not available explicitly in the input data, but can only be presumed when the Hourly Surface Observations indicate that rainfall was observed, but does not indicate a measurable amount. The uncertainty about trace amounts of rainfall is such that a decision was reached to exclude them from consideration in the WETTIME model.

2. Rainfall intensity and duration: Existing wet pavement exposure models make no distinction between hours of precipitation based on rainfall intensity or duration. These models assume that the pavement was wet for the entire hour during any hour in which the hourly rainfall is 0.01 in. (0.25 mm) or greater. This is unrealistic since one would expect that, on the average, the more rain that falls during an hour, the longer the rainfall would last; however, no data were available to quantify this phenomenon.

TABLE 3

FACTORS EVALUATED IN FIELD FRICTION TESTS

Pavement Type

- Smooth asphalt
- Medium-texture asphalt
- High-texture asphalt
- Smooth portland cement concrete (PCC)

Tire Type

- ASTM-standard ribbed tire
- ASTM-standard blank tire
- Worn passenger car tire

Test Speed

- 5 mph
- 20 mph
- 40 mph

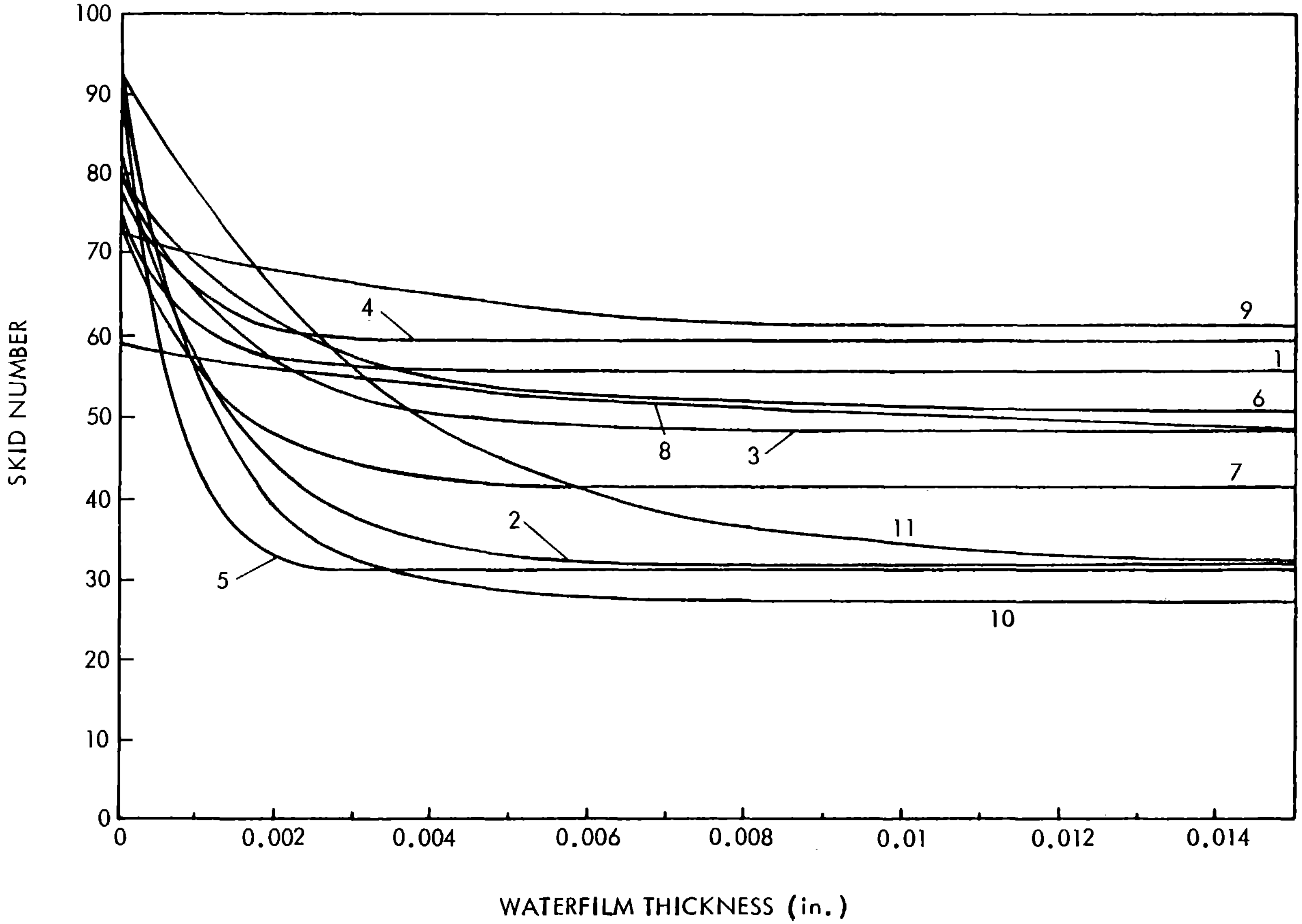


Figure 3 - Negative Experimental Relationships Between Pavement Friction and Waterfilm Thickness Developed from Field Test Data

TABLE 4

COEFFICIENTS OF NEGATIVE EXPONENTIAL RELATIONSHIPS BETWEEN PAVEMENT FRICTION AND WATERFILM THICKNESS FOR FIELD FRICTION TESTS AT 40 mi/h

Pavement Type	Tire Type	Curve Number[1]	Regression Coefficients[2]			Minimum Level[3] of Wetness (d_{min}) (in.)
			a	b	c	
Smooth asphalt	Ribbed	1	19.3	-1,343	55.8	0.0010
	Blank	2	51.1	-735	31.9	0.0020
	Worn passenger car	3	31.6	-675	48.3	0.0020
Medium texture asphalt	Ribbed	4	19.2	-1,121	59.0	0.0010
	Blank	5	57.6	-1,685	31.2	0.0008
	Worn passenger car[4]	-	-	-	-	-
High texture asphalt	Ribbed	6	29.1	-437	49.8	0.0030
	Blank	7	31.4	-786	41.3	0.0020
	Worn passenger car	8	11.5	-152	47.0	0.0090
Portland cement concrete	Ribbed	9	12.4	-263	60.3	0.0050
	Blank (Replicate 1)	10	63.3	-848	27.2	0.0020
	Blank (Replicate 2)	11	61.5	-315	32.0	0.0040
	Worn passenger car[5]	-	-	-	-	-

1 Curve number as shown in Figure 3.

2 Regression coefficients as defined in Equation (12).

3 Minimum level of wetness as defined in Equation (13).

4 Best represented by straight line with negative slope rather than by a negative exponential curve.

5 No data available.

The only data available to the WETTIME model as a basis for estimating differences in rainfall intensity and duration between rainstorms is the amount of rainfall during each hour. Therefore, to incorporate consideration of rainfall intensity and duration in the WETTIME model, MRI sought a source of data to indicate the distribution of rainfall during an hour for different total rainfall amounts. Such a data source was found in the United States Geological Survey (USGS) Urban Stormwater database.[16]

The USGS Urban Stormwater database contains detailed data on rainfall, runoff, and water quality for 717 selected periods of rainfall at 99 stations located in 22 metropolitan areas throughout the United States. The periods of rainfall ranged in duration from a few hours to several days. The data of greatest value to the development of the WETTIME model were rainfall amounts by 5-min periods throughout each rainfall period. These data allowed us to study the patterns of rainfall during an hour for a given total hourly precipitation amount. The USGS Urban Stormwater database is not necessarily a statistically representative sample of rainstorms; it is a unique resource because rainfall amounts by 5-min periods are not often available.

Four States representing a variety of climate regions in the United States were selected and used throughout the study for development and testing of the WETTIME model. These States were Missouri, Pennsylvania, Florida, and Washington. The USGS Urban Stormwater database included stations in each of these States except Pennsylvania; however, data from nearby Baltimore, Maryland, were included in the database. Thus, analysis of the USGS data were performed for rainstorms at the following stations: Kansas City, Missouri; Baltimore, Maryland; Miami, Florida; Tampa, Florida; and Bellevue, Washington.

Table 5 presents a summary of the duration of rainfall for different hourly rainfall amounts. The duration of rainfall was defined as the time from the first 5-min period in which rain fell during the hour to the last 5-min period in which it fell. This duration could include some 5-min periods in which there was no rainfall, but it is assumed that the time required for runoff and pavement drying (discussed in subsequent sections) would keep the pavement wet during this period.

Table 5 includes both the mean duration of rainfall (an average of the duration for all available hours for each rainfall amount) and the mode of the duration of rainfall (the most frequently occurring value of the duration of rainfall). For hours with rainfall amounts of 0.04 in. (1.0 mm) and less, the mean duration of rainfall provides a good estimate of the typical duration of rainfall during the hour. These mean durations were rounded to the nearest quarter hour for use in the WETTIME model. Thus, the typical duration of rainfall during an hour with 0.01 in. (0.25 mm) of rainfall is 15 min; the typical duration is 30 min for an hour with 0.02 in. (0.5 mm) of rainfall and 45 min for an hour with 0.03 or 0.04 in. (0.75 or 1.0 mm) of rainfall. For hours with 0.05 in. (1.25 mm) of rainfall or more, the most common duration of rainfall is 60 min, indicating that rain fell in both the first and last 5-min period of the hour. The mean duration is

TABLE 5

VARIATION OF DURATION OF RAINFALL DURING AN HOUR WITH HOURLY RAINFALL AMOUNT

Hourly Rainfall Amount (in.)	No. of Hours Available	Mean Duration of Rainfall (min)	Most Common Duration of Rainfall (min)	Duration of Rainfall in WETTIME Model (min)
0.01	262	13.0	5	15
0.02	72	33.0	40	30
0.03	60	42.0	55	45
0.04	59	43.0	55	45
0.05	47	45.9	60	60
0.06-0.07	26	49.6	60	60
0.08-0.09	65	53.5	60	60
0.10 and over	146	54.5	60	60

slightly less than 60 min, but typically the rainfall lasts for most or all of the 5-min periods during the hour. Therefore, when the hourly rainfall amount is 0.05 in. (1.25 mm) or more, the pavement is usually wet due to rainfall for the entire hour.

An analysis of variance was conducted which indicated that the effect of hourly rainfall amount on duration of wetness, described above, was statistically significant at the 95 percent confidence level. The same analysis found no statistically significant effect of region of the United States (represented by the four states identified above) on the duration of pavement wetness. This result was somewhat surprising, since we had assumed that some regions of the country might be more subject to cloudbursts (large amounts of rainfall in a short time period) or to drizzle (small amounts of rainfall over a long time period) than others. However, on the average, the variation of the duration of rainfall with rainfall amounts proved to be the same in the four states considered, and it was concluded that the estimates for typical duration of rainfall shown in Table 5 could be applied without respect to regional differences.

The analysis of variance also showed no statistically significant difference, for a given hourly rainfall amount, in the duration of pavement wetness related to whether an hour was an isolated hour of rainfall (with no rainfall in either the previous or the next hour) or a nonisolated hour. Thus, it was concluded that the estimates for typical duration of wetness shown in Table 5 could be used without respect to whether the hour was an isolated or a nonisolated hour of rainfall.

The rainfall in adjacent hours was used in the WETTIME model to determine when, during an hour, the wetness due to rainfall was likely to occur. In an isolated hour of rainfall, the period of rainfall was considered to be centered within the hour; i.e., a 30-min rainfall period of would begin at quarter past the hour and end at quarter of the next hour. The rainfall period was assumed to occur at the end of the first hour of a period of two or more consecutive hours of rainfall and at the beginning of the last hour of two or more consecutive hours of rainfall. The rainfall period was assumed to last for the entire hour of any middle hour of a multi-hour period of precipitation. This assumption followed from the assumption that the pavement would be wet at the beginning and the end of the hour and rainfall would occur during the hour to keep the pavement wet.

The estimates of the duration of rainfall presented above include periods of wetness due to active rainfall and short pauses between periods of active rainfall. Pavement wetness was also found to extend after the end of active rainfall, during the runoff and pavement drying periods. These factors are addressed in the following sections.

3. <u>Runoff period following rainfall</u>: There is a period following the end of active rainfall when the pavement remains wet while water is running off the pavement. For purposes of the WETTIME model, it was assumed that pavement drying does not begin until runoff is complete.

The time required for water to flow off of the pavement while rain is falling is a function of the rainfall intensity (in/hr), the pavement surface texture (represented by the Manning coefficient), the length of the drainage path, and the slope of the pavement surface. The runoff time can be calculated from these parameters using the kinematic wave method,[17] as follows:

$$TC = \frac{0.94 \times L^{0.6} \times n^{0.6}}{i^{0.4} \times S^{0.3}} \qquad (6)$$

where: TC = time of concentration or runoff time (min)

L = length of drainage path (ft)

n = Manning coefficient

i = rainfall intensity (in/hr)

S = average slope of drainage path (ft/ft)

Estimates of runoff time were calculated for typical ranges of values for the input parameters. For example, the Manning coefficient for pavement surfaces typically ranges from 0.01 to 0.05. For highway sections with zero longitudinal grade, the drainage path length would be the distance from the pavement crown to the pavement edge, typically 12 to 24 ft (3.7 to 7.3 m); the slope used would be the normal pavement cross-slope, typically 0.01 to 0.02 in/in., except on superelevated sections. With a nonzero longitudinal grade, the drainage path length would be longer, but the slope along the drainage path would also be steeper. Drainage path length, up to 100 ft (31 m) with slopes up to 0.05 in/in were considered.

Table 6 presents estimates of runoff time within the ranges of the input parameters described above. The table shows that runoff time is usually less than 10 min and is often 5 min or less. While the kinematic wave approach in Equation (6) is not directly applicable to a period after the rain has stopped (i=0), the runoff time at the end of rainfall would be similar to the runoff time for a very low rainfall intensity such as 0.10 in/hr (2.5 mm/hr).

Based on the available data, it was decided that typical runoff times following rainfall would range from 0 to 10 min. The differences in runoff times between sites would not be expected to have a major effect on the annual percentage of pavement wet time so, to keep the model simple, possible site-to-site variations in pavement runoff time were not considered. A uniform runoff time of 5 min following the end of rainfall was incorporated in the WETTIME model.

4. Pavement drying period following rainfall and runoff: Previous studies have estimated the typical pavement drying time following rainfall and runoff at 30 min;[1,2] however, these estimates were based on limited observation and did not account for the possible influence of environmental and pavement variables on pavement drying time. Therefore, further studies of pavement drying time were undertaken as part of the development of the WETTIME model.

a. Laboratory studies: The first stage in the investigation of pavement drying time was a laboratory study of the effect of environmental and pavement variables on drying time. The environmental variables considered were solar radiation, wind speed, air temperature, and relative humidity. The effect of pavement type (asphalt/PCC) on pavement drying time was considered explicitly. The effects of these 10 individual pavement surfaces on drying time were reviewed for patterns that could result from other pavement variables including texture and color. The laboratory study is discussed briefly in this section and is discussed in more detail in Appendix B.

The laboratory study of pavement drying time was conducted in an 8- by 8- by 8-ft (2.4- by 2.4- by 2.4-m) chamber constructed so that environmental conditions could be controlled. Air temperature was controlled by a heater and an air conditioner. Relative humidity was controlled by a humidifier. Solar radiation was simulated by an array of solar lamps, and wind was simulated by a large fan. Instruments, including a thermometer, hygrometer, and anemometer, were installed in the chamber to monitor the environmental conditions.

TABLE 6

TYPICAL PAVEMENT RUNOFF TIMES BASED ON KINEMATIC WAVE METHOD

Length (ft)	Rainfall Intensity (in/hr)	Manning Coefficient (n)	Slope (ft/ft)	Runoff Time (min)
10	0.10	0.01	0.01	2.36
10	0.10	0.02	0.01	3.58
10	0.10	0.03	0.01	4.56
10	0.10	0.04	0.01	5.42
10	0.10	0.05	0.01	6.20
20	0.10	0.01	0.01	3.58
20	0.10	0.02	0.01	5.42
20	0.10	0.03	0.01	6.92
20	0.10	0.04	0.01	8.22
20	0.10	0.05	0.01	9.40
40	0.10	0.01	0.02	4.41
40	0.10	0.02	0.02	6.68
40	0.10	0.03	0.02	8.52
40	0.10	0.04	0.02	10.12
40	0.10	0.05	0.02	11.57
60	0.10	0.01	0.03	4.98
60	0.10	0.02	0.03	7.54
60	0.10	0.03	0.03	9.62
60	0.10	0.04	0.03	11.43
60	0.10	0.05	0.03	13.07
80	0.10	0.01	0.04	5.42
80	0.10	0.02	0.04	8.22
80	0.10	0.03	0.04	10.49
80	0.10	0.04	0.04	12.46
80	0.10	0.05	0.04	14.25
100	0.10	0.01	0.05	5.80
100	0.10	0.02	0.05	8.79
100	0.10	0.03	0.05	11.21
100	0.10	0.04	0.05	13.33
100	0.10	0.05	0.05	15.23

A Class A evaporation pan filled with water was placed in the chamber. Various asphalt and PCC pavement samples were wetted and placed in the evaporation pan so that the pavement surface was above the water surface. The time required for the pavement surface to dry was monitored for selected combinations of environmental conditions. The waterfilm thickness on the pavement surface was monitored at 5-min intervals during the drying period using a micrometer depth gauge (described in Appendix A) and the water level in the evaporation pan was also monitored with a hook gauge.

The independent variables considered in the pavement drying tests and the levels considered for each variable are shown in Table 7.

The pavement drying tests were conducted in accordance with an experimental design based on a Graeco-Latin square which allowed assessment of the effects of the independent variables. To keep the required number of pavement drying tests to a minimum, the experimental design chosen could evaluate the main effects of each of the independent variables but could only evaluate selected interactions between pairs of independent variables. A total of 132 pavement drying tests were conducted, including the formal Graeco-Latin square design plus a few additional tests described in Appendix B.

The test data were analyzed and a predictive model for pavement drying time was developed. This model is presented in Table 8, which shows the deviation from the mean drying time of 31.6 min for each level of each factor. These deviations constitute parameter estimates for a pavement drying time model. For example, the expected drying time for an asphalt pavement on a partly cloudy day with a temperature of 75°F (24°C), a 75 percent relative humidity, and a wind speed of 5 mi/h (8 km/h) would be:

$$31.6 - 0.7 - 1.5 + 5.6 - 11.6 + 3.9 = 27.2 \text{ min.}$$

The model presented in Table 8 can be used in this fashion to estimate the pavement drying time for any combination of air temperature, relative humidity, solar radiation, wind speed, and pavement type. The model results indicate that pavement drying time can range from a minimum of about 5 min to a maximum of about 60 min, depending upon conditions.

The two variables with the strongest influence on pavement drying time were solar radiation and wind speed. Either solar radiation equivalent to a bright, cloudless day (1.15 langleys/min) or wind speeds of 1.5 mi/h (2.4 km/h) or more were sufficient to result in very fast drying times. In contrast, pavement drying times were relatively long under nighttime conditions with no wind. The effects of air temperature and relative humidity on pavement drying time were also statistically significant but were not as strong as the effects of solar radiation and wind speed. Pavement drying time was found to increase as relative humidity increased and to decrease as air temperature increased. Finally, pavement type was found to have a small, but statistically significant, effect on pavement drying time. Portland cement concrete pavements were found to dry, on the average, about 8 min faster than asphalt pavements.

TABLE 7

FACTORS EVALUATED IN PAVEMENT DRYING TESTS

Solar Radiation

Nighttime or overcast (0 langleys/min)
Partly cloudy day (0.75 langleys/min)
Bright, cloudless day (1.15 langleys/min)

Wind Speed

No wind (0 mph)
2 mph
8 mph
15 mph

Air Temperature

60°F
75°F
90°F

Relative Humidity

45%
60%
75%
90%

Pavement Type

Asphalt concrete
Portland cement concrete (PCC)

The only major drawback of the model was that it was found to predict pavement drying times less than zero in some cases for the highest level of solar radiation when wind was also present. The model results appear to indicate that either high solar radiation or the presence of wind is sufficient to produce relatively fast drying times, but that the model overcompensates for this effect when both conditions occur simultaneously. The experimental design used for this investigation was not capable of evaluating the solar radiation-wind speed interaction, so it was not possible to formally adjust for this effect. However, it was decided in applying the model presented in Table 8 that, when both high solar radiation and winds over 1.5 mi/h (2.4 km/h) are present simultaneously, only the larger of the two effects (i.e., solar radiation) would be considered. This results in a model that never provides unrealistic estimates of pavement drying time.

The laboratory experiment included pavement drying tests for three PCC surfaces and seven asphalt surfaces, with a range of textures and colors. An analysis was conducted to determine if there was any pattern to the drying time results that could be interpreted as an effect of pavement texture or color. No such patterns were found, so it was concluded that the only pavement variable whose effect on drying time could be quantified was pavement type (asphalt/PCC).

It was originally hoped that the evaporation of thin waterfilms from a pavement surface could be related to the evaporation of water from a standard Class A evaporation pan. Pan evaporation data are available for stations throughout the United States and these data might be used to predict regional variations in pavement drying times; however, all attempts to develop a statistical relationship between the pavement drying rates and the pan evaporation rates observed in the laboratory chamber proved unsuccessful. Therefore, this approach was abandoned.

b. <u>Field tests</u>: A series of field tests were conducted to validate the pavement drying model under actual field conditions and to determine whether the action of traffic passages under actual highway conditions would decrease drying times from those predicted by the model. These studies are described briefly below and are described in more detail in Appendix B.

Outdoor drying time tests were conducted without the action of traffic at the PTI Test Track in State College, Pennsylvania. These tests involved both pavements that were artificially wetted and pavements wetted by rain. Observational studies were also conducted at actual highway sites with traffic present near State College following rainfall. During each test, instrumentation was used to monitor air temperature, relative humidity, and wind speed. Solar radiation was estimated based on time of day and cloud cover. A traffic count during the drying period was made at the actual highway sites. Limited field observations of highway and parking lot pavements were also made in Kansas City, Missouri, without the environmental instrumentation.

TABLE 8

PARAMETER ESTIMATES FOR PAVEMENT DRYING TIME MODEL

Factor	Level	Mean Drying Time[a] (min)	Deviation From Overall Mean Drying Time (min)[b]
Temperature	Below 67.5°F	35.3	+3.7
	67.5°-82.5°F	30.9	-0.7
	Above 82.5°F	28.6	-3.0
Relative humidity	Below 50%	27.1	-4.5
	50-82.5%	30.0	-1.6
	Above 82.5%	37.7	+6.1
Solar radiation	Night or overcast	43.2	+11.6
	Partly cloudy day	37.2	+5.6
	Clear day	14.4	-17.2
Wind speed	No wind	43.2	+11.6[c]
	Wind present	20.0	-11.6[c]
Pavement type	Asphalt concrete	35.5	+3.9
	Portland cement concrete	27.7	-3.9

[a] The mean drying times represent the effects of each factor taken one at a time, independent of the values of the other factors.

[b] Deviation from overall mean drying time of 31.6 min.

[c] Use this parameter estimate only if the parameter estimate for the solar radiation factor has a positive value.

The results of the field studies indicated that the pavement drying model presented in Table 8 provides reasonable estimates of pavement drying time under a wide variety of conditions. A comparison of observed and predicted drying times from the test track and highway tests is presented in Figure 4. The closer a point lies to the diagonal line in the figure, the better the agreement between the observed and predicted values. Based on a review of Figure 3, it was decided that the pavement drying model in Table 8 should be incorporated in the WETTIME model.

It was anticipated that observed drying times might be substantially shorter than predicted drying time due to the effect of traffic passages. However, no tendency toward shorter drying times was observed. The field observations indicated that the normal wheelpaths tend to dry more quickly than the remainder of the pavement. While traffic normally operates within those well-defined wheelpaths, a vehicle in an emergency maneuver could require friction at any point on the pavement surface. The field observations indicated that the pavement drying model was a good predictor of the time required for the entire pavement surface to dry.

Rather than very short drying times, two of the field observations in Figure 3 indicate drying times substantially longer than those predicted by the model. The investigation concluded that such longer drying times occurred because the air was saturated with moisture and evaporation could not begin. This issue is addressed in the next section.

c. Pavement drying under nearly saturated conditions: Several field observations indicated pavement drying times substantially longer than predicted by the model in Table 8. It was noted that these results were for very high relative humidities (over 90 percent). Particularly long drying times after nighttime rainfalls during the summer were also observed. Under these conditions, the pavement typically remained wet for the remainder of the night and pavement drying began after dawn.

Because of these observations, a feature was added to delay the beginning of pavement drying in the WETTIME model when the ambient air is nearly saturated. Nearly saturated conditions were identified by a dewpoint temperature within 2°F (1°C) of the ambient air temperature. During the daytime, this delay in the start of pavement drying was assumed to last a maximum of 2 hr or until the air is no longer saturated. At night, the delay in the start of pavement drying was assumed to last until the air is no longer saturated or until drying due to solar radiation begins, shortly after dawn.

d. Input parameters to the pavement drying model: The input parameters to the pavement drying model are available directly from the NCDC hourly weather observation data or can be estimated from these data. The parameters that are available directly from the NCDC data are:

- Air temperature
- Dewpoint temperature
- Relative humidity
- Wind speed

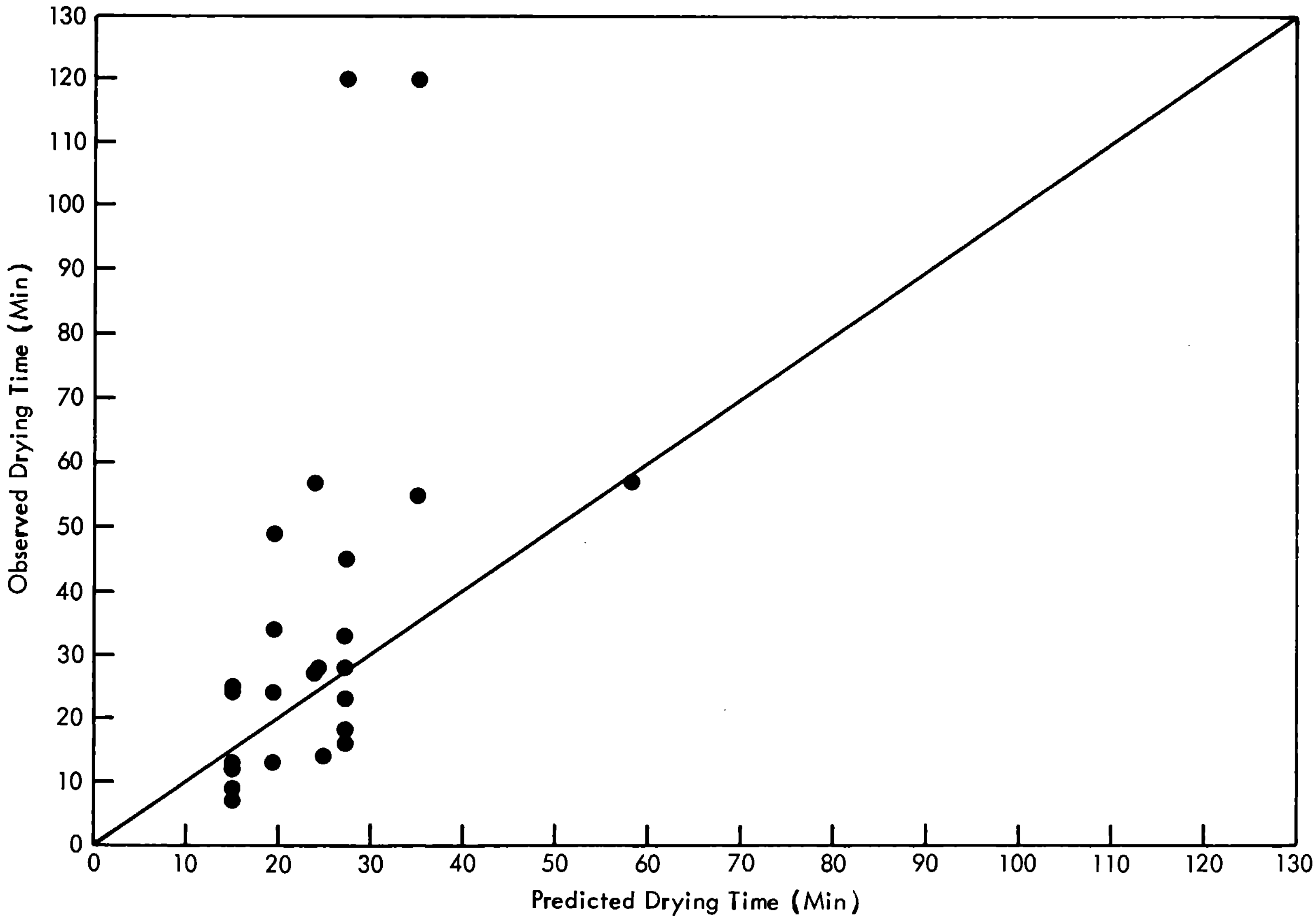


Figure 4 - Comparison of Pavement Drying Times Observed in Field Tests with Drying Times Predicted by Model

The only variable in the NCDC file related to solar radiation levels is the amount of cloud cover (in tenths of the sky covered by clouds). Therefore, it was necessary to incorporate another source of solar radiation intensity in the WETTIME program. The source used was a simple computerized solar ephemeris routine that estimates solar radiation intensity at ground level based on the month of the year, the time of day, and the latitude and longitude of a particular location. This routine, known as SOLRAD, was developed by students in the Mechanical Engineering Department at Penn State University.

Tests with the SOLRAD routine found that the total annual wet pavement exposure was not sensitive to the effect of latitude or longitude on solar radiation levels. Therefore, latitude and longitude were eliminated as input variables and set to default values. Longitude does not affect the solar radiation intensities, but only the times of day at which they occur. In the WETTIME model, longitude is set by default to the standard time meridian of each time zone (75°W, 90°W, 105°W, 120°W, etc.). In contrast, latitude has a definite effect on solar radiation intensity. At any given time of year, solar radiation is more intense in the U.S. over a longer period of the day in southern latitudes than in northern latitudes. However, when incorporated in the WETTIME model, the differences in solar radiation between latitudes 30°N and 50°N made a difference of less than 0.3 percent in annual wet-pavement exposure. Therefore, latitude was set in the WETTIME model to the default value of 40°N (near the center of the continental United States).

The solar radiation level predicted by the SOLRAD routine was reduced by the amount of cloud cover by the following relationship:

$$SR' = SR \times (1 - 0.65 * CC) \tag{7}$$

where:

SR' = solar radiation intensity adjusted for cloud cover (langleys/min)

SR = solar radiation intensity at ground level on a cloudless day (langleys/min)

CC = total sky cover (proportion of the sky obscured to the nearest tenth)

The three levels of solar radiation used in the pavement drying model were defined as follows:

Level	Range of Solar Radiation Intensity (langleys/min)
Nighttime or overcase	0.40 or less
Partly cloudy day	0.41-0.85
Bright cloudless day	0.86 or over

At some hours of the day and at some times of the year, the highest solar radiation level cannot be attained, even under cloudless skies, because the elevation of the sun is not sufficient to produce those levels. The SOLRAD routine also indicates that because of the low elevation of the sun, solar radiation levels are effectively zero for 1 to 2 hr after sunrise and for 1 to 2 hr before sunset. Pavement drying rates during this period should be similar to nighttime rates.

Procedures for estimating missing values of the input parameters by averaging the values available for adjacent hours were incorporated in the WETTIME model.

5. Pavement wetness due to fog: The WETTIME model includes consideration of pavement wetness due to fog. In some situations, a pavement can become wet due merely to the pavement condensation or misting conditions associated with fog. Existing wet-pavement exposure estimation models varied greatly in their consideration of pavement wetness due to fog. The California/NTSB approach does not consider the possibility of pavement wetness due to fog at all. The original MRI model classified all periods of fog as resulting in pavement wetness.

In the WETTIME model, pavement wetness due to fog is considered only when the ambient air is nearly saturated. Nearly saturated conditions are identified on the same basis for fog as for the delay in the beginning of pavement drying discussed above; i.e., pavement wetness due to fog occurs only when the NCDC hourly weather observation data indicate that fog was observed and that the dewpoint temperature is within 2°F (1°C) of the ambient air temperature.

Pavement wetness due to fog is most likely when the pavement temperature is colder than the ambient air temperature. Unfortunately, there is no way to determine pavement temperature from available weather data, so this aspect of pavement wetness due to fog is not considered in the WETTIME model.

6. Estimation of exposure to snow and ice conditions: The consideration of snow and ice conditions is important in the WETTIME model in two ways. First, it is important that snow and ice conditions be considered separately and not be included in wet time, as is done in the California/NTSB approach. Second, pavement wetness can result from ice and snow conditions, especially during periods when melting of ice or snow on the pavement may occur, or when meltwater might run onto the pavement.

Very little is known about predicting exposure to snow and ice conditions, but the NCDC hourly weather observation data can be used to classify precipitation as frozen or nonfrozen and to determine whether the air temperature is above or below the freezing point. Because of the lack of better information, ice and snow exposure due to frozen precipitation is estimated by the WETTIME model on the same basis that wet pavement exposure is estimated from nonfrozen precipitation, with the two exceptions described below.

The first exception is that trace amounts of frozen precipitation are considered adequate to keep a pavement ice and snow covered if these trace amounts follow immediately after a period of one or more hours of measurable snowfall, and if the temperature remains below 32°F (0°C). This aspect of the model was adopted because periods of trace amounts of snowfall, whose water equivalent is less than 0.01 in. (0.25 mm) per hour, were common in the wintertime data and, if these conditions were not considered, unexpectedly low estimates of ice and snow exposure resulted.

The second exception is that the pavement drying period following a period of ice and snow exposure is classified as wet-pavement time. This provision represents pavement wetness due to the melting of ice and snow. The melting period may not follow immediately after the snowfall period, as would be the case for pavement drying following rainfall, but it is likely that pavement wetness due to melting will occur sooner or later after each snowfall. The model provides an estimated minimum of pavement wetness resulting from ice and snow. However, pavement wetness could also be substantially longer due to runoff from snow accumulated on the roadside.

Pavement wetness due to melting ice and snow can be substantially prolonged by the presence of deicing chemicals on the pavement surface. Mortimer and Ludema[18] found that NaCl increased pavement drying time by about 30 min, and $CaCl_2$ can increase pavement drying time indefinitely. However, it cannot be assumed that deicing chemicals are always present during the winter months, so the WETTIME model uses the pavement drying model as it stands and assumes that there is no effect of deicing chemicals on the duration of pavement drying. Thus, the WETTIME model may under estimate wet-pavement time for conditions requiring the use of deicing chemicals.

C. Model Summary

This section presents a summary of the exact rules that are used in the WETTIME model to classify an entire month or year into DRY time, WET time, and ICE and SNOW time. The rationale for each of these rules was explained in the previous section.

1. An hour with no precipitation is counted as DRY, unless there is still pavement drying under way from the previous hour.

2. If nonfrozen precipitation of 0.01 in. (0.25 mm) or more occurs during an hour, then the time while the rain is falling and the subsequent drying time is counted as WET.

   a. For an isolated hour of precipitation (no precipitation in either the previous or the following hour), the duration of pavement wetness due to the rainfall is determined as follows:

Total Amount of Rainfall During the Hour (in.)	Duration of Wetness
0.01	15 min + runoff + drying time
0.02	30 min + runoff + drying time
0.03-0.04	45 min + runoff + drying time
0.05 or more	60 min + runoff + drying time

The rainfall period, whatever its duration, is assumed to be centered within the hour. For example, a 30-min rainfall period is assumed to start at quarter past the hour and end at quarter of the next hour.

b. For the first hour of two or more consecutive hours of precipitation, the duration of wetness is determined as described in the table. Whatever the duration of the rainfall period, it is assumed to occur at the end of the hour.

c. For the last hour of two or more consecutive hours of precipitation, the duration of wetness is also determined as described in the table. Whatever the duration of the rainfall period, it is assumed to occur at the beginning of the hour.

d. For a middle hour of a period of three or more consecutive hours of precipitation, the rainfall is assumed to last for the entire hour.

e. The runoff period following the end of rainfall is assumed to be 5 min.

f. Pavement drying usually begins at the end of rainfall and runoff, and continues until the pavement is dry or a new storm begins. If the pavement is still wet at the end of an hour, pavement drying continues into the next hour.

g. The start of pavement drying may be delayed if the ambient air is nearly saturated [as indicated by a dewpoint temperature within 2°F (1°C) of the ambient air temperature]. During the daytime, the delay in the start of pavement drying will last a maximum of 2 hr or until the air is no longer saturated. At night, the delay in the start of drying will last until the air is no longer saturated or until drying due to solar radiation begins shortly after dawn.

h. The duration of pavement drying is determined from a statistical model that predicts drying time (presented in Table 8). The factors that are used to predict pavement drying time are: solar radiation, wind speed, air temperature, relative humidity, and pavement type. The predicted pavement drying time is rounded to the nearest 5 min. The program user can specify the pavement type (asphalt or portland cement concrete). If no pavement type is specified by the user, asphalt concrete is assumed as the default.

i. The environmental factors in the pavement drying model are determined from weather data in the following manner:

Solar radiation	Determined from a solar ephemeris routine that predicts solar radiation levels considering month of year, time of day, and sky cover	
Wind speed	No wind present	0 or 1 mi/h
	Wind present	2 mi/h and over
Air temperature	Below 67.5°F	
	67.5°-82.5°F	
	Above 82.5°F	
Relative humidity	Below 50 percent	
	50-82.5 percent	
	Above 82.5 percent	

If sky cover data are missing during daytime hours, the value of 50 percent sky cover is used.

If wind speed is missing, wind is presumed to be present.

If air temperature is missing, the air temperature is presumed to be in the middle level of the three available levels (68° to 82°F or 20° to 28°C).

If relative humidity is missing, the relative humidity is presumed to be in the middle level of the three available levels (50 to 82 percent).

3. If fog occurs during an hour and the air is nearly saturated (dew point temperature within 2°F [1°C] of ambient air temperature) and the wind speed is 3 mi/h (5 km/h) or less, then the hour is counted as WET. Pavement drying following a period of fog follows the same rules as following a period of nonfrozen precipitation.

4. If frozen precipitation of 0.01 in. (0.25 mm) or more occurs during an hour, then the hour is counted as ICE and SNOW.

a. If a trace amount of frozen precipitation occurs during an hour and a measurable amount of frozen precipitation occurred during the previous hour and the temperature remains below 32°F, the hour is counted as ICE and SNOW. When these conditions apply continuously for several hours, subsequent hours may also be counted as ICE and SNOW.

b. The pavement drying time following a period of frozen precipitation is determined by the same rules as for nonfrozen precipitation and is counted as WET.

D. Model Input

To make a run with the WETTIME model, the user must specify the following input data:

- Station name
- Year to be analyzed
- Type of pavement (asphalt or PCC; asphalt is used as the default)
- Name of NCDC Hourly Precipitation File for the specified station and year
- Name of NCDC Hourly Surface Observation File for the specified station and year

A detailed discussion of the form of these data and required precipitation and weather data files is found in a companion volume, "Users Guide for the WETTIME Exposure Estimation Model."[3]

E. Model Output

The WETTIME model provides a simple one-page output for each station-year of data analyzed. A sample of this output is presented in Figure 5.

The output presents month-by-month totals of WET time, ICE and SNOW time, combined WET plus ICE and SNOW time, DRY time, TOTAL time, and MISSING time in hours. The MISSING time consists of hours for which the required precipitation and surface observation data are not available. There is usually very little MISSING time at first-order weather stations. The hourly exposure totals are also presented as percentages of the month; these percentages are corrected for any missing time during the month.

The last two lines of information in the output present the annual total hours of exposure and percentage of exposure for each exposure type. The single most important number on the printout, presented at the bottom of the WET time column, is the percentage of annual wet-pavement exposure. The sample output indicates, for example, that in 1984 in Kansas City, pavements were wet about 8.3 percent of the time.

The use of a percentage of time to represent wet-pavement exposure is the same form of exposure measure used in the NTSB study.[1] The accident study performed by NTSB was based on a wet fatal accident index (WFAI) defined as:

$$\text{WFAI} = \frac{\text{Percentage of fatal accidents on wet pavement}}{\text{Percentage of wet exposure}}$$

The results obtained with the WETTIME model provide a more accurage estimate of the denominator of the WFAI expression than the California/NTSB rule.

WET-PAVEMENT EXPOSURE ESTIMATE
REVISED MRI RULE
STATION: KANSAS CITY MO
YEAR: 1984

PAVEMENT TYPE: 1
ASPHALT CONCRETE

NUMBER OF HOURS BY EXPOSURE TYPE

	WET	ICE & SNOW	COMBINED	DRY	TOTAL	MISSING
JAN	8.1 1.1%	30.0 4.0%	38.1 5.1%	705.9 94.9%	744.0	0.0
FEB	59.6 8.6%	15.0 2.2%	74.6 10.7%	621.4 89.3%	696.0	0.0
MAR	103.0 13.8%	35.0 4.7%	138.0 18.5%	606.0 81.5%	744.0	0.0
APR	98.3 13.7%	0.0 0.0%	98.3 13.7%	621.7 86.3%	720.0	0.0
MAY	41.7 5.6%	0.0 0.0%	41.7 5.6%	702.2 94.4%	744.0	0.0
JUN	51.8 7.2%	0.0 0.0%	51.8 7.2%	668.2 92.8%	720.0	0.0
JUL	19.7 2.7%	0.0 0.0%	19.7 2.7%	724.2 97.3%	744.0	0.0
AUG	13.8 1.9%	0.0 0.0%	13.8 1.9%	730.2 98.1%	744.0	0.0
SEP	60.0 8.3%	0.0 0.0%	60.0 8.3%	660.0 91.7%	720.0	0.0
OCT	155.0 20.8%	0.0 0.0%	155.0 20.8%	589.0 79.2%	744.0	0.0
NOV	41.4 5.8%	8.0 1.1%	49.4 6.9%	670.6 93.1%	720.0	0.0
DEC	79.0 10.6%	19.0 2.6%	98.0 13.2%	646.0 86.8%	744.0	0.0
TOT	731.5 8.3%	107.0 1.2%	838.5 9.5%	7945.5 90.5%	8784.0	0.0 0.0%

Figure 5 - Sample Output from the WETTIME Model -- Wet-Pavement Exposure for Kansas City in Calendar Year 1984

IV. APPLICATION OF THE WETTIME MODEL

This section of the report describes the application of the WETTIME model. The following discussion addresses the computer requirements for use of the WETTIME model, the application of the model to several geographical regions, the application of the model to isoexposure contour mapping, and the advantages of the WETTIME model over current practice.

A. Computer Requirements

Two versions of the WETTIME model are available to suit the needs of different types of computer users. There are both mainframe computer and microcomputer versions of the model.

The mainframe version of the model is written in FORTRAN-77 and can be compiled by any FORTRAN-77 compatible compiler. Job control language to run the WETTIME model under an IBM operating system are presented in the companion volume, "Users Guide for the WETTIME Exposure Estimation Model."[3]

The microcomputer version of the model uses the same processing logic as the mainframe version, but differs slightly in the input data procedures. The program was developed to run on an IBM PC or compatible microcomputer under IBM Professional FORTRAN, which is FORTRAN-77 compatible. The microcomputer on which the model is run should have a hard-disk drive, because the NCDC Hourly Weather Observation File used as input for one station-year is too large to fit on a conventional floppy disk. The use of the microcomputer version of the WETTIME model is also documented in the users guide.[3]

B. Test Cases for Several Geographic Regions

A number of test cases have been run with the WETTIME model to illustrate its application to a variety of geographic and climatic regions. Four States were selected for these test cases: Florida, Missouri, Pennsylvania, and Washington. Missouri and Pennsylvania were selected because they are typical of the climates in the midwestern and northeastern regions of the United States. Florida was selected because of its pattern of short, frequent rainfalls, and Washington was selected because of its variety of climates, ranging from desert to rain forest.

Table 9 presents the annual distribution of wet-pavement exposure, ice and snow exposure, and dry-pavement exposure for 1984 for each first-order weather station in the four selected states and for a few stations in adjoining states. Data are presented in the table for a total of 33 weather stations. Table 9 shows the broad range of wet-pavement exposure in the selected states. Across these four states, wet-pavement exposure time for 1984 ranges from a low of 3.7 percent in Key West, Florida, to a high of 38.5 percent in the Washington rain forest. Ice and snow exposure time for 1984 ranges from a low of zero in Florida to a high of 11.3 percent in the Cascade Mountains of Washington State. The data in Table 9 apply to highway sections with asphalt pavements; wet-pavement exposure for PCC pavements would be slightly lower because they dry more quickly.

TABLE 9

EXPOSURE SUMMARY DETERMINED WITH THE WETTIME MODEL FOR CALENDAR YEAR 1984
AT SELECTED FIRST-ORDER WEATHER STATIONS

Station	Percentage of Annual Exposure		
	Wet	Ice & Snow	Dry
FLORIDA			
Apalachicola	5.5	0.0	94.5
Daytona Beach	5.9	0.0	94.1
Fort Myers	13.6	0.0	86.4
Gainesville	23.0	0.0	77.0
Jacksonville	21.6	0.0	78.4
Key West	3.7	0.0	96.3
Miami	6.9	0.0	93.1
Orlando	13.6	0.0	86.4
Tallahassee	19.6	0.0	80.4
Tampa	6.0	0.0	94.0
Vero Beach	7.8	0.0	92.2
West Palm Beach	9.2	0.0	90.8
MISSOURI			
Columbia	10.1	1.7	88.2
Des Moines IA	8.7	1.9	89.4
Kansas City	8.3	1.2	90.5
Memphis, TN	10.9	0.2	88.9
St. Louis	12.9	1.7	85.4
Springfield	6.6	1.1	92.3
PENNSYLVANIA			
Allentown	8.7	1.8	89.5
Erie	8.4	5.7	85.9
Harrisburg	10.9	1.5	87.6
Philadelphia	9.4	0.8	89.8
Pittsburgh	9.5	3.7	86.8
Wilkes-Barre	9.7	2.5	87.8
WASHINGTON			
Astoria OR	21.9	0.0	78.1
Lewiston ID	5.1	0.5	94.4
Olympia	23.5	0.3	76.2
Portland OR	15.2	0.1	84.7
Quillayute	38.5	0.2	61.3
Seattle	15.0	0.4	84.6
Spokane	9.9	2.7	87.4
Stampede Pass	20.9	11.3	67.8
Yakima	4.2	0.8	95.0

The data in Table 9 apply to highway sections with asphalt pavements; wet-pavement exposure for PCC pavements would be slightly lower because they dry more quickly.

C. Isoexposure Contour Maps

The data provided by the WETTIME model can be used to construct contour maps showing the variations in exposure over an entire State or region. The following discussion describes the process by which such maps can be developed and presents sample maps of three States.

1. Construction of contour maps: While exposure estimates for point locations (such as those presented in Table 9) are interesting, maps presenting isoexposure contour lines showing variations in exposure over an entire state are potentially more useful. However, Table 9 shows that the WETTIME model can provide exposure estimates for only 6 to 12 locations per State because of the limited availability of the required weather data. Therefore, in order to construct maps showing isoexposure contours, a method was needed to extend the wet-pavement exposure estimates to more numerous stations covering an entire State.

Two alternative methods for extending estimates to additional stations were considered:

- Estimate annual wet-pavement exposure at minor stations from annual exposure estimates for first-order stations by proportioning on annual number of hours with measurable precipitation.

- Estimate annual wet-pavement exposure at minor stations from annual exposure estimates for first-order stations by proportioning on total annual rainfall.

The first approach is equivalent to using exposure estimates for the California/NTSB method, which are available both for first-order stations and for many minor stations to establish the ratio between wet-pavement exposure at a minor station and at the closest first-order station. This approach was initially thought to be the most desirable. However, it was found that the quality of the NCDC Hourly Precipitation Data for many minor stations was too poor to produce accurate estimates. For example, the following table shows the percentage of hours with measurable precipitation during 1984 for the first-order weather station at Kansas City International Airport and for several nearby minor stations in Missouri:

Station	Type of Station	Percentage of Hours With Measurable Precipitation
Kansas City	First-order	6.0
Elm	Minor	6.3
Gladstone	Minor	3.1
Kearney	Minor	1.2
Unity Village	Minor	2.5
Warrensburg	Minor	2.8

The percentages of hours with measurable precipitation, shown above, have been adjusted for the hours of missing data identified in the NCDC file. These stations represent all Missouri stations within 80 miles (129 km) of Kansas City that have less than 25% missing data. The table shows most minor stations near Kansas City report less than half as many annual hours with measurable precipitation as the first-order Kansas City station. Since precipitation patterns in this relatively small region of Missouri do not vary widely, it is evident that the data from most of the minor stations are misleading. It is likely that some of these minor stations have rainfall gauges that are not, in fact, read each hour and that several hours of rainfall results are accumulated into a single hour without this being indicated in the NCDC file. This same pattern of underestimation of the number of hours with measurable precipitation in comparison to nearby first-order stations is also evident at minor stations in other regions of the United States. Thus, it was concluded that the hourly precipitation data from minor weather stations cannot be relied upon in applying the California/NTSB rule.

The second alternative method to establish the ratio between wet-pavement exposure at a minor station and wet-pavement exposure at the closest first-order station is the use of annual total precipitation. NCDC publishes long-term estimates of annual precipitation totals based on 30 years of records (1951-1980) for numerous weather stations in each State.[19] These data were used to provide a reliable basis for estimating wet-pavement exposure at minor stations, although to obtain consistent results, it was necessary to use an average of the wet-pavement exposure estimates for the two closest first-order weather stations, weighted inversely by their distance from the minor station. This weighting procedure avoids discontinuities on the contour map near the boundaries of the area of influence of different first-order weather stations and provides a smooth transition between their areas of influence. As an example of the amount of data available for developing isoexposure contour maps, Figure 6 illustrates the locations of the first-order stations and the minor stations for which long-term average annual precipitation totals are available in Missouri. Data from first-order stations in Des Moines, Iowa, and Memphis, Tennessee, were also used in construction of an isoexposure contour map for Missouri.

The procedure for constructing isoexposure contour maps was as follows:

a. Obtain wet-pavement exposure estimates for each first-order weather station in a State using the WETTIME model.

b. Select a minor weather station and determine its average annual precipitation. This is available in the State-by-State volumes of the NCDC publication, "Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree-Days 1951-1980."[19]

c. Determine the closest and second closest first-order weather stations to the selected minor weather stations.

d. Calculate a wet-pavement exposure estimate for the minor station as follows:

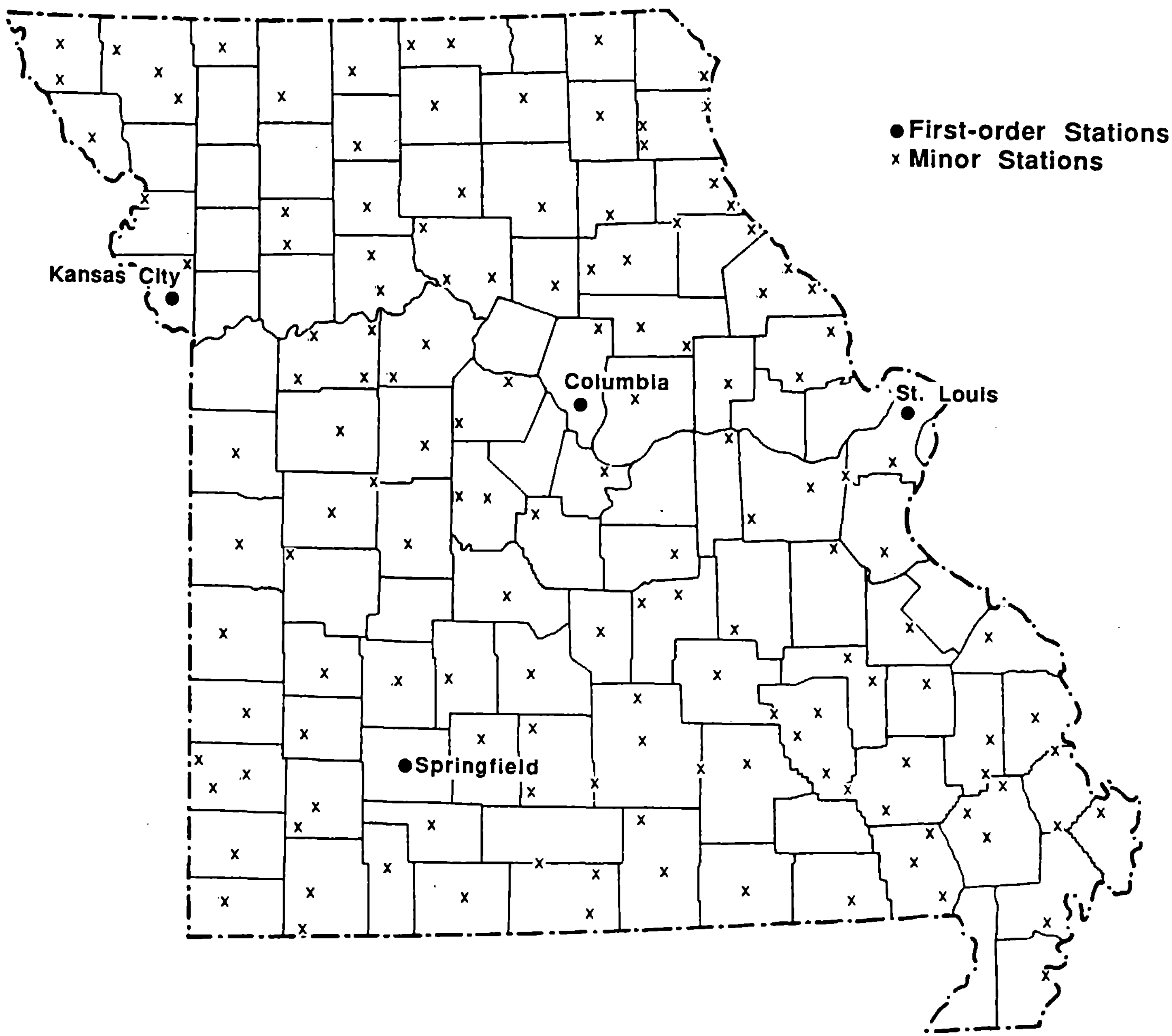


Figure 6 - Weather Stations in Missouri for Which Long-Term Estimates of Annual Total Precipitation are Available

$$E_A = \frac{(E_B)\left(\frac{P_A}{P_B}\right)(D_{AC}) + (E_C)\left(\frac{P_A}{P_C}\right)(D_{AB})}{D_{AB} + D_{AC}} \qquad (8)$$

where: E_X = wet-pavement exposure percentage for Station X

P_X = average annual total precipitation (in.) at Station X

D_{XY} = airline distance (miles) from Station X to Station Y

X,Y = station number as defined below:

Station A is a minor weather station
Station B is the closest first-order weather station
Station C is the second closest first-order weather station

e. Repeat steps b through d for each minor weather station in the State.

f. Plot the locations of each first-order and each minor weather station on a map of the State.

g. Write the annual wet-pavement exposure percentage for each station on the map next to the station location.

h. Choose an appropriate contour interval for the map, considering the range of wet-pavement exposure shown on the map and the level of detail desired on the map.

i. Plot isoexposure contour lines on the map considering the exposure values shown for particular stations. For example, if two minor stations have annual wet-pavement exposure of 8.5 and 9.5%, respectively, then a 9% exposure contour line should pass roughly halfway between them.

j. In States with distinctive topography or distinctive climatic regions, these regional patterns should be considered as well as the distance between stations in performing steps d and i. For example, the presence of a mountain range might make it desireable to use only the nearest first-order weather station on the same side of the range as the minor station being considered. A first-order station on the other side of the mountain range might not be representative of the same climate region as the minor station. This situation can be handled by setting D_{AC} equal to zero in Equation (8).

Several isoexposure contour maps plotted in accordance with these rules are illustrated in the next section.

2. Examples of isoexposure contour maps: Isoexposure contour maps of three states have been plotted to illustrate this application of the WETTIME model. These maps were constructed for asphalt pavements, but maps for PCC pavements would not appear noticeably different.

An isoexposure contour map of Missouri is presented in Figure 7. The map illustrates that annual wet-pavement exposure generally increases from west to east across the State, with the wettest area in the southeast part of the State.

A similar map of Washington is presented in Figure 8. The map illustrates the strong influence of topography on the Washington climate. The Pacific coastal area is the wettest part of the State, with the highest wet-pavement exposure in the rain forest area near the Quillayute station. The climate becomes progressively drier as one moves west into the Puget Sound basin, then becomes wet again on the west slope of the Cascade Mountains (immediately west of the Stampede Pass station shown on the map). East of the Cascades is a desert area with very little rainfall and very low wet-pavement exposure.

Figure 9 presents an isoexposure contour map of Florida. The map illustrates the influence of the unique weather patterns in Florida with relatively little wet-pavement exposure along the coast, but much higher wet-pavement exposure beginning a few miles inland. The construction of precise isoexposure contour maps is difficult in a climate of this type because of the extreme ranges of wet-pavement exposure over very short distances.

Isoexposure contour maps similar to Figures 7, 8, and 9 could be constructed from available data for any state in the United States.

D. Advantages of the WETTIME Model Over Current Practice

The contour maps presented in Figure 7, 8, and 9 illustrate the need for wet-pavement exposure estimation model in highway safety management. Even a State like Missouri, with a relatively homogeneous climate, has substantial geographic variations in wet-pavement exposure.

Table 10 presents a comparison of the differences between annual wet-pavement exposure estimates developed both with the California/NTSB rule and with the WETTIME model for first-order stations in Missouri. The table illustrates that the two sets of estimates agree in some regions of the State, but differ in others. In most cases, the WETTIME model results in higher wet-pavement exposure estimates than the California NTSB rule. When interpreting the data in Table 10 it should be kept in mind that the California/NTSB estimates of wet-pavement exposure include the ice- and snow- exposure time, while the estimates made with the WETTIME model do not.

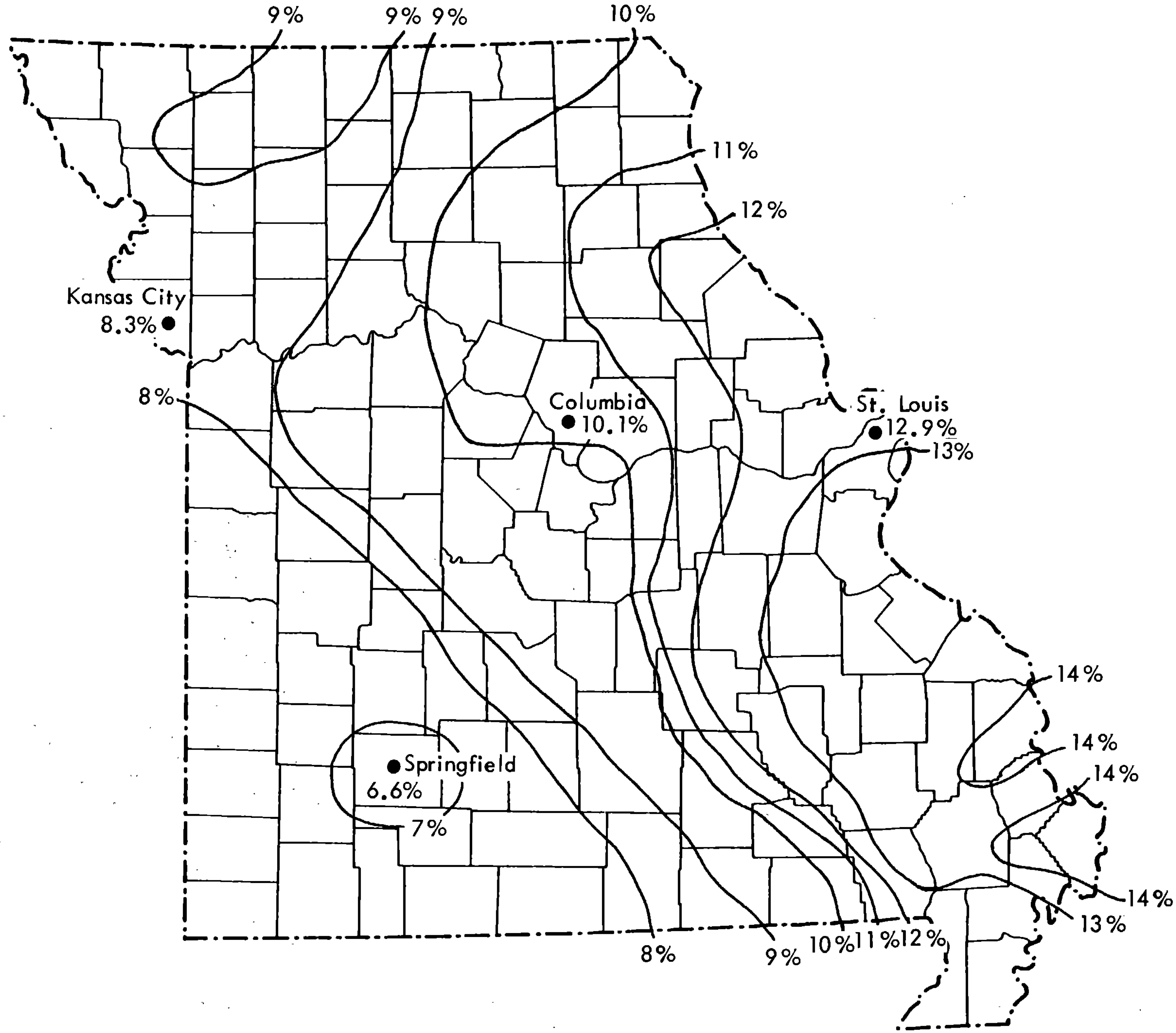


Figure 7 - Isoexposure Contour Map for Wet-Pavement Exposure in Missouri

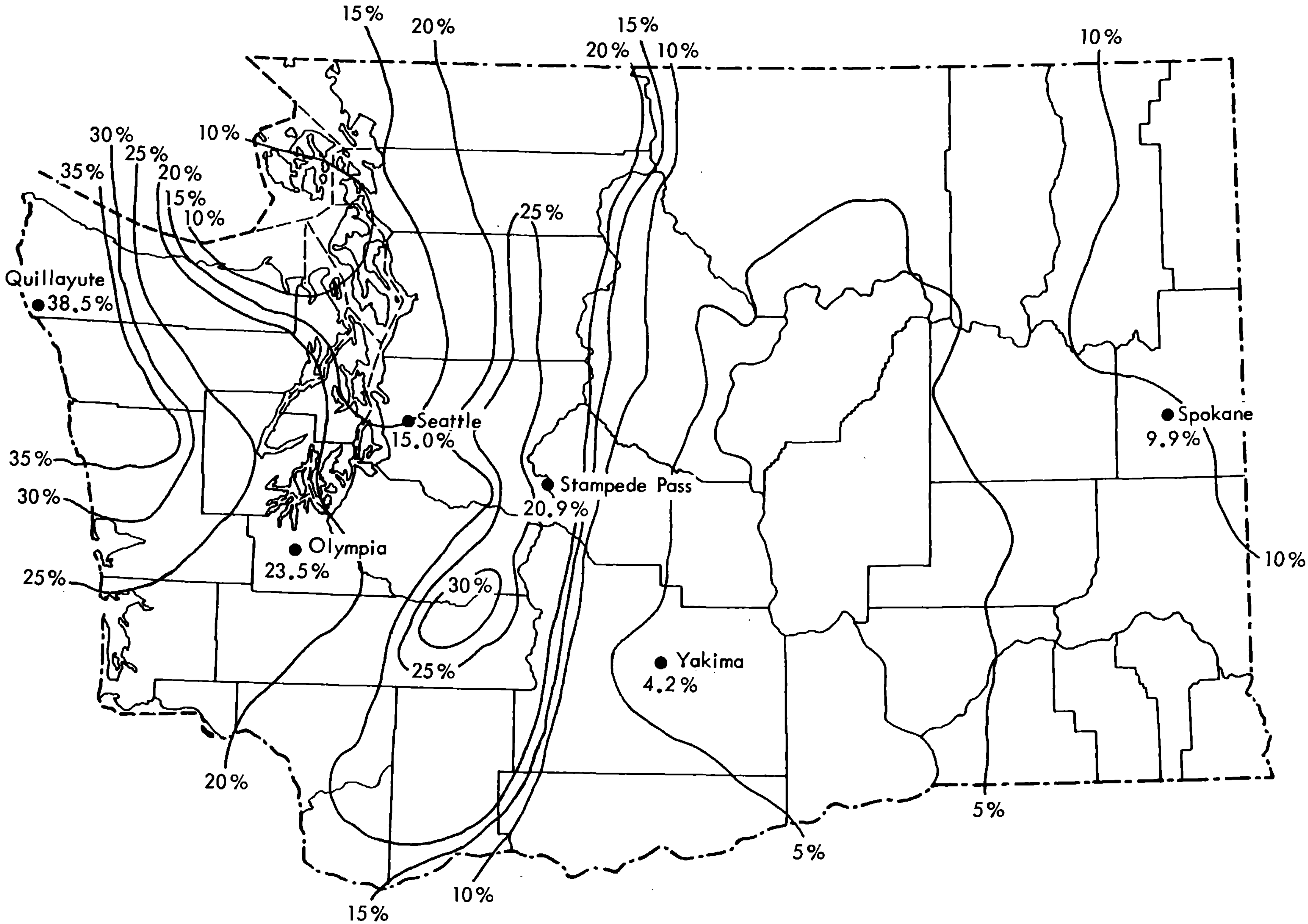


Figure 8 - Isoexposure Contour Map for Wet-Pavement Exposure in Washington

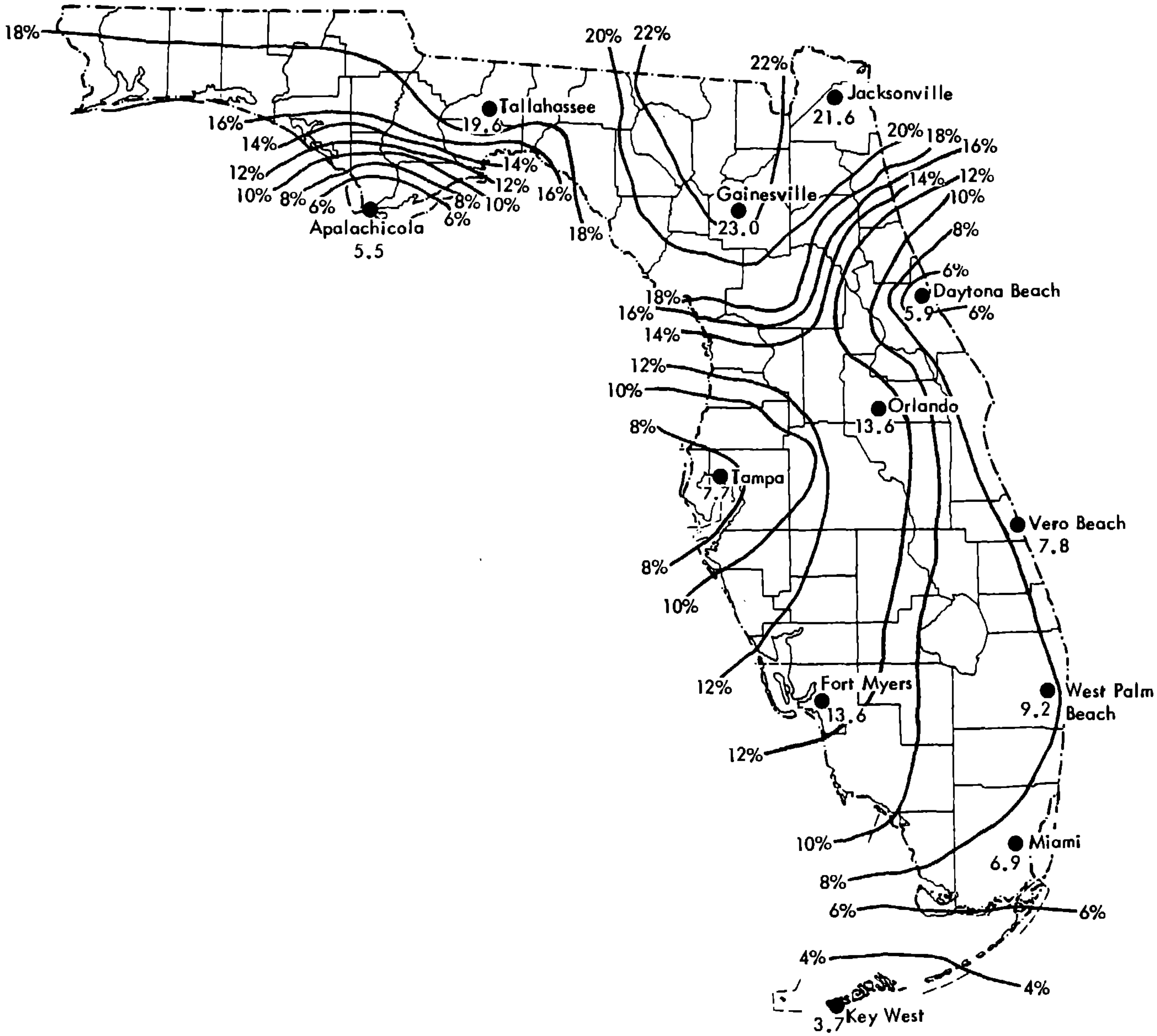


Figure 9 - Isoexposure Contour Map for Wet-Pavement Exposure in Florida

TABLE 10

COMPARISON OF WET-PAVEMENT EXPOSURE ESTIMATES FOR MISSOURI USING THE CALIFORNIA/NTSB RULE AND THE WETTIME MODEL

Region of State	Annual Wet-Pavement Exposure California/NTSB Rule	Annual Wet-Pavement Exposure WETTIME Model
Springfield	6.7%	6.6%
Kansas City	6.0%	8.3%
Columbia	7.0%	10.1%
St. Louis	7.8%	12.9%

Table 11 presents an example of three different methods of looking at the wet-pavement accident rates in different regions of a State. The table considers a hypothetical rural two-lane highway section, 8 miles (13 km) long, with a traffic volume of 5,000 veh/day and five wet-pavement accidents per year. The three accident rate measures illustrated in the table are:

- Accident rate with no wet-pavement exposure measure (calculated as a ratio between wet-pavement accidents and total exposure).
- Accident rate based on wet-pavement exposure determined with the California/NTSB rule.
- Accident rate based on wet-pavement exposure determined with the WETTIME model.

The first of these accident rates is computed using Equation (3), first presented in Section II.B. of this report. This equation is:

$$R'_w = \frac{A_w}{E}$$

where: R'_w = modified wet-pavement accident rate (accidents per million veh-mi)
A_w = number of wet-pavement accidents
E = total exposure under all pavement conditions

The second and third of these accident rates are computed with Equation (2), also first presented in Section II.B. This equation is:

$$R_w = \frac{A_w}{E_w}$$

where: R_w = wet-pavement accident rate (accidents per million veh-mi).
A_w = number of wet-pavement accidents.
E_w = wet-pavement exposure (veh-mi).

The second and third accident rates presented above differ only in the method used to determine E_w.

TABLE 11

EXAMPLES OF VARIOUS ACCIDENT RATE MEASURES FOR A HYPOTHETICAL ROAD SECTION IN MISSOURI

(Conditions: Rural two-lane highway, 8 miles long with 5,000 veh/day and 5 wet-pavement accidents per year)

Region of State	Wet-Pavement Accident Rate (per MVM): No Wet-Pavement Exposure Measure[a]	Wet-Pavement Exposure Based on California/NTSB Rule[b]	Wet-Pavement Exposure Based on WETTIME Model[b]
Springfield	0.34	5.11	5.19
Kansas City	0.34	5.71	4.13
Columbia	0.34	4.89	3.39
St. Louis	0.34	4.39	2.65

[a] Based on Equation (3).
[b] Based on Equation (2).

Table 11 shows that if no wet-pavement exposure estimate is available, the highway in question would have the same wet-pavement accident rate regardless of where it was located in the State. This unrealistic assumption is made implicitly by any highway agency that does not incorporate a measure of wet-pavement exposure in its wet-pavement accident surveillance program. Furthermore, the use of wet-pavement accidents in the numerator and total exposure in the denominator expresses the accident rate on an unconventional scale that cannot be directly compared to other types of accident rates.

The wet-pavement exposure estimates based on the California/NTSB rule show some variation between parts of the State. The accident rate for the hypothetical highway section with five wet-pavement accidents per year is 30.1 percent higher in the driest part of the State than in the wettest. However, the differences between the drier and wetter parts of the state are even more dramatic when the results of the WETTIME model are considered. The final column in Table 11 indicates that the accident rate for the hypothetical highway section is 95.8% higher in the driest part of the State than in the wettest. This example shows how easy it would be to miss a highway section with high wet-pavement accident experience that happens to be located in a dry part of the State or, vice versa, to identify a highway section as a problem location merely because it happens to be located in a relatively wet part of the State.

The contour maps and the previous example have dealt with wet-pavement exposure for entire calendar years, but the availability of month-by-month exposure estimates of the output of the WETTIME model has other important advantages. For example, the California Department of Transportation[5] has observed that their seasonal patterns of precipitation and traffic volume are opposite with more traffic, but less rainfall, during the summer months. The month-by-month output of the WETTIME model, as illustrated in Figure 5, can be used as a basis for adjusting the annual wet-pavement exposure estimate for monthly variations in travel, in the following manner:

$$E_W = \sum_{i=1}^{12} E_{Wi} \frac{VMT_i}{VMT} \qquad (9)$$

where: E_W = annual wet-pavement exposure percentage

E_{Wi} = monthly wet-pavement exposure percentage in month i

VMT_i = month veh-mi of travel in month i

VMT = annual veh-mi of travel

The need for use of Equation (9) in a particular State can be easily tested by estimating E_{Wi} with the WETTIME model and estimating VMT_i from traffic volumes data at continuous count stations and comparing the calculated value of E_W with the annual value indicated by the WETTIME model. The routine use of Equation (9) is recommended only for States with particularly large seasonal variations in precipitation patterns or in travel that are found to have a substantial impact on wet-pavement exposure.

V. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were reached in the research:

1. Estimation of wet-pavement exposure is an essential part of wet-pavement accident surveillance programs. Accident surveillance programs that do not incorporate a measure of wet-pavement exposure may unnecessarily identify highway sections in relatively wet regions as problem locations and may fail to identify highway sections that have high wet-pavement accident rates, but happen to be located in relatively dry regions. Year-to-year variations in rainfall that may explain observed increases or decreases in wet-pavement accident frequencies may also be missed.

2. A computer model, known as the WETTIME model, has been developed to estimate wet-pavement exposure from available weather records.

3. The minimum level of pavement wetness that substantially reduces pavement surface friction is between 0.001 and 0.009 in. (0.025 and 0.23 mm) of water on the pavement surface. This minimum level of wetness is likely to be exceeded during any hour in which there is at least 0.01 in. (0.25 mm) of rainfall.

4. The duration of pavement wetness during an hour increases with the amount of rainfall during the hour. When 0.05 in. (1.25 mm) of rain falls during an hour, the pavement is likely to be wet for the entire hour.

5. In addition to pavement wetness during rainfall, pavements are also wet during the runoff and drying periods following rainfall; during fog when atmospheric conditions are saturated or nearly saturated; and during the melting period following frozen precipitation.

6. The period following rainfall required for water to flow off the pavement ranges from 0 to 10 min, with 5 min representing a typical average value.

7. Pavement drying times following rainfall and runoff range from 0 to 60 min depending on the pavement type and environmental conditions. The environmental conditions found to influence the pavement drying time include solar radiation, wind speed, temperature, and relative humidity. A model for predicting pavement drying time was developed and is presented in Table 8. The start of pavement drying can be delayed if the atmospheric conditions are saturated or nearly saturated.

8. Portland cement concrete pavement dries, on the average, approximately 8 min faster than asphalt pavement following the end of rainfall. However, this difference does not have a substantial effect on annual wet-pavement exposure.

9. Published evaporation data cannot be used as a predictor of pavement drying times, because the evaporation rates of thin waterfilms from pavement surface are not similar to the rates observed for evaporation pans or larger bodies of water.

The following recommendations were developed as a result of the study:

1. Highway agencies should incorporate a measure of wet-pavement exposure in their accident surveillance programs.

2. The WETTIME computer model is available from the Federal Highway Administration to assist highway agencies in estimating wet-pavement exposure on an annual basis from available weather data.

3. The WETTIME model should be validated by comparison to actual wet-pavement exposure in several climatic regions. Actual wet-pavement exposure can be determined with a moisture sensor installed in a pavement or a bridge deck.

4. Isoexposure contour maps, similar to those illustrated in this report, should be prepared for use by highway agencies to investigate variations in wet-pavement exposure within their jurisdiction.

5. The Federal Highway Administration should consider the development of an atlas of 50 state wet-pavement exposure maps as an aid to highway agencies in managing their wet-pavement accident surveillance programs.

6. Automated plotting routines should be investigated as a means of increasing the efficiency with which isoexposure contour maps can be developed.

APPENDIX A

MINIMUM LEVEL OF WETNESS THAT REDUCES PAVEMENT SURFACE FRICTION

A laboratory and field investigation was undertaken as part of this study to determine the minimum level of pavement wetness that substantially reduces pavement surface friction. This investigation was undertaken to determine the amount of rainfall that would be required to result in slippery conditions on a pavement surface.

This appendix begins with a critical review of the published literature related to the effect of thin waterfilms on pavement surface friction. The methods used in the study to measure the waterfilm thickness on a pavement surface are then discussed, followed by a detailed presentation of the laboratory and field testing programs conducted in this study.

1. Literature review: An overview of the literature related to the effect of thin waterfilms on pavement surface friction is presented below, followed by an assessment of the literature.

a. Overview of published literature: The primary focus in assessing the literature was to determine the functional form of the relationship between waterfilm thickness and pavement surface friction, and to define the minimum level of wetness that substantially reduces pavement surface friction. A key element that has been missing from previous attempts to estimate wet-pavement exposure is a minimum level of wetness that results in slippery conditions. The existing estimation techniques[1,2,5,8] assume that 0.01 in. (0.25 mm) of rainfall during an hour, or in some cases a trace amount of rainfall during an hour, is enough to produce slippery conditions without explicitly considering the amount of water on the pavement that results from such rainfall and whether that amount, in fact, results in slipperiness. It is important to consider both the level of wetness that results in slippery conditions at the onset of rainfall and the level of wetness at which the pavement ceases to be slippery during the drying period, and to recognize that these levels of wetness may not be the same. Variations in the minimum level of wetness for different pavement types and textures also need to be considered.

Locked wheel skid tests conducted in accordance with ASTM E 274 at 40 mi/h use a flow rate of 3.6 gal/min/in. of wetted width (0.54 L/min/mm). This flow rate results in a nominal waterfilm thickness of 0.02 in. (0.5 mm) on the pavement during skid testing. Figure 10 illustrates that on most surfaces skid number is relatively insensitive to waterfilm thickness at thicknesses of 0.015 in. (0.38 mm) and above.[9] The 0.02 in. (0.5 mm) waterfilm thickness was selected as a convenient value for use in skid testing since it assures a film thickness greater than 0.015 in. (0.38 mm) despite variations in water application rates. Thus, it is likely that the minimum level of wetness that produces slippery conditions is a film less than 0.02 in. (0.5 mm) thick.

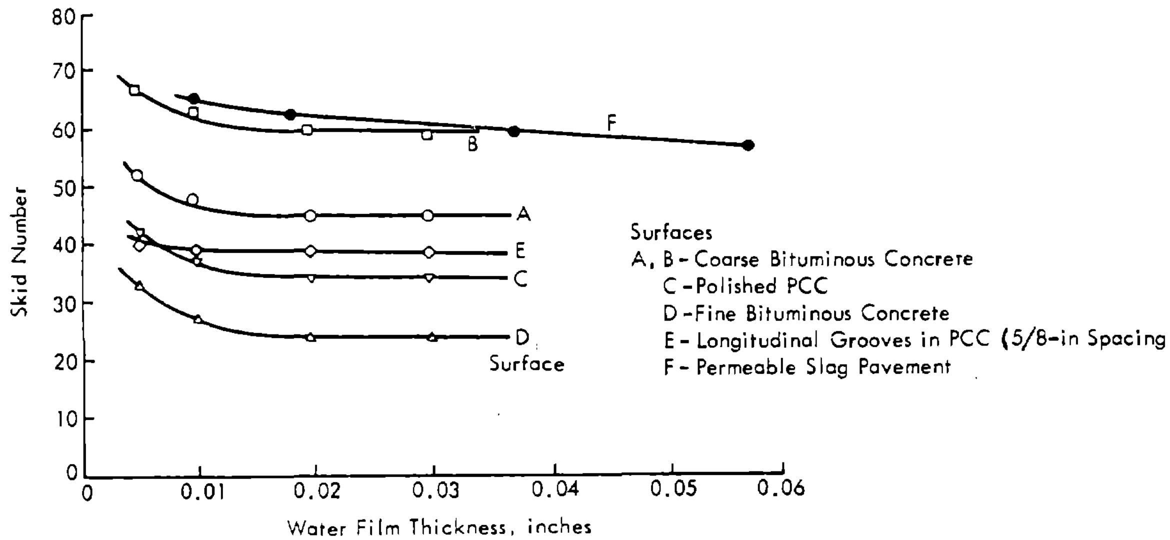


Figure 10 - Skid Resistance at 40 mi/h as Function of Waterfilm Thickness on Various Surfaces[9]

It is known that contaminants on the pavement, such as oil and grease and deicing chemicals, may influence skid number.[18,20] The influence of such contaminants may depend on the length of time since the last substantial rainfall. Such contaminants are often washed away by continued rainfall or by the forceful application of water during a skid test. Thus, the relationship between skid number and water depth illustrated in Figure 10, which was established through conventional skid testing, is probably indicative of conditions at the onset of rainfall on a relatively clean surface or during a rainstorm after the contaminants have been washed away.

Additional studies that have examined the variation of tire-pavement friction with waterfilm thickness include the work of Giles,[10] Gegenbach,[11] Veith,[12] Pelloli,[13] Williams and Evans,[14] and Rose and Gallaway.[15] Only those studies that have addressed relatively thin waterfilms are reviewed here; many studies that examined the influence of waterfilms only for thicknesses above 0.04 in. have not been addressed here. Table 12 identifies the range of waterfilm thicknesses and speeds considered in the studies that address the effects of thin waterfilms. These investigators are in general agreement that over the range of waterfilm thicknesses shown in Table 12 friction is largely independent of waterfilm thicknesses at low speeds (20 to 30 mi/h or 32 to 48 km/h), while there may be a stronger relationship between friction and waterfilm thickness for

TABLE 12

RANGE OF WATERFILM THICKNESSES AND SPEEDS EVALUATED IN VARIOUS STUDIES

Study	Range of Waterfilm Thickness, in	Range of Test Speed, mi/h
Besse[9]	0.010-0.060	40
Giles[10]	0.005-0.002	30
Gegenbach[11]	0.002-0.008	12-80
Veith[12]	0.005-0.300	20-60
Pelloli[13]	0.002-0.040	25-60
Williams and Evans[14]	0.0008-0.008	35-85
Rose and Gallaway[15]	0.005-0.200	20-60

higher speeds (40 to 60 mi/h or 64 to 97 km/h). However, the studies provide conflicting evidence about the nature of the relationship between friction and waterfilm thickness and the existence of a transition zone for very thin waterfilms, where friction decreases rapidly with increasing water depth.

Giles[10] suggests in the curves presented in Figure 11 that there is a transition zone where the friction coefficient at 30 mi/h (48 km/h) changes rapidly with water depth, but this occurs for very thin waterfilms. According to Giles, skid resistance at a given speed decreases initially with increasing waterfilm thickness but stabilizes on most pavements when the waterfilm thickness exceeds 0.01 in. (0.25 mm). The results shown in Figure 11 are somewhat unexpected because the friction coefficient decreases more rapidly with waterfilm thickness for coarse textured pavements than for fine textured pavements. Unfortunately, no information is available concerning the equipment used to obtain the data.

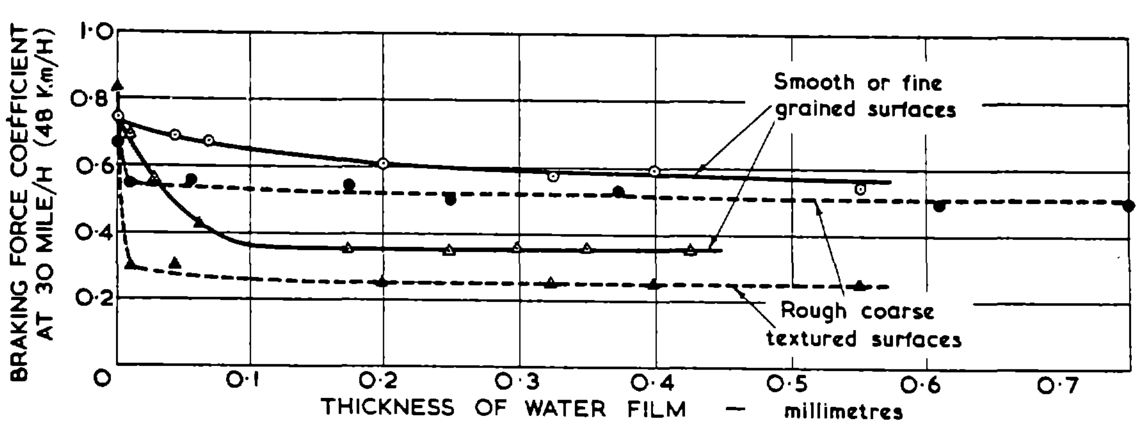


Figure 11 - Skid Number as a Function of Waterfilm Thickness[10]

Gegenbach[11] made two important observations in friction tests conducted in the laboratory with a rotating drum. First, only a slight moistening of the drum surface resulted in a decrease in the coefficient of friction. Second, as illustrated in Figure 12, waterfilm thickness is of small influence on the coefficient of friction for speeds below 30 mi/h (50 km/h).

Veith[12] found a logarithmic relationship between waterfilm thickness and cornering traction, as illustrated in Figure 13 for full and half skid depth tires. The figure illustrates the greater sensitivity of cornering traction to waterfilm thickness at high speed than at low speed.

Pelloli[13] found a linear relationship between the coefficient of friction and waterfilm thickness at low speed (25 mi/h or 40 km/h), and a logarithmic relationship similar to that found by Veith at higher speeds. The relationships developed by Pelloli have the form:

$$\mu_v = a_v + b_v \, d \qquad \text{for } v = 25 \text{ mi/h (40 km/h), and} \qquad (10)$$

$$\mu_v = a_v + b_v \ln d \qquad \text{for } v \geqq 37.5 \text{ mi/h (60 km/h).} \qquad (11)$$

where: μ_v = Coefficient of friction at speed v,

a_v = Coefficient determined from coefficient of friction at 25 mi/h (40 km/h),

b_v = Coefficient determined from pavement surface macrotexture (defined as t_m-S/2 and determined with a profile measuring device),

d = Waterfilm thickness (mm),

t_m = Median texture depth (mm), and

S = Standard deviation of texture depth.

Figure 14 illustrates relationships of this form for an asphalt pavement surface. Typical values of b_v range from 0.008 to 0.052 in. (0.2 to 1.3 mm).

An experimental investigation by Williams and Evans[14] found little effect of waterfilm thickness on friction in the range from 0.2-2.0 mm for speeds below 40 mi/h (25 km/h).

Finally, the results obtained by Rose and Gallaway,[15] presented in Table 13, also indicate very little sensitivity of skid number to waterfilm thickness, even for thicknesses below 0.01 in. (0.25 mm).

TABLE 13

RELATIVE EFFECT OF WATERFILM THICKNESS ON SKID NUMBERS AT DIFFERENT SPEEDS[19]

Test Conditions	Waterfilm Thickness (in.)	ASTM Tire, 32 psi Skid Number	ASTM Tire, 32 psi Percentage Decrease	Commercial Tire, 32 psi Skid Number	Commercial Tire, 32 psi Percentage Decrease	ASTM Tire, 24 psi Skid Number	ASTM Tire, 24 psi Percentage Decrease	Commercial Tire, 24 psi Skid Number	Commercial Tire, 24 psi Percentage Decrease
Tread,	0.005	65	-	50	-	63	-	48	-
0.25 in.	0.010	65	0	50	0	62	1.6	48	0
Texture,	0.020	64	1.5	50	0	62	1.6	48	0
0.03 in.	0.040	64	1.5	50	0	61	3.2	48	0
Speed,	0.100	62	4.6	49	2.0	60	4.8	47	2.1
20 mph	0.200	61	6.2	48	4.0	58	7.9	47	2.1
Tread,	0.005	40	-	28	-	37	-	27	-
0.25 in.	0.010	39	2.5	28	0	37	0	27	0
Texture,	0.020	39	2.5	28	0	36	2.7	26	3.7
0.03 in.	0.040	39	2.5	28	0	36	2.7	26	3.7
Speed,	0.100	38	5.0	28	0	35	5.4	26	3.7
40 mph	0.200	37	7.5	27	3.6	34	8.1	26	3.7
Tread,	0.005	30	-	20	-	27	-	19	-
0.25 in.	0.010	29	3.3	20	0	27	0	19	0
Texture,	0.020	29	3.3	20	0	27	0	19	0
0.03 in.	0.040	29	3.3	20	0	26	3.7	19	0
Speed,	0.100	28	6.7	20	0	26	3.7	18	5.3
60 mph	0.200	28	6.7	19	5.0	25	7.4	18	5.3

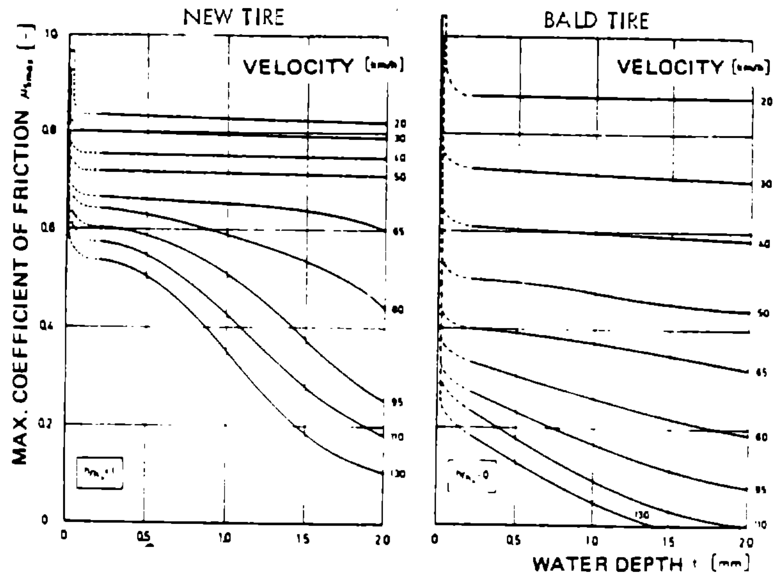


Figure 12 - Coefficient of Friction as a Function of Waterfilm Thickness and Velocity[11]

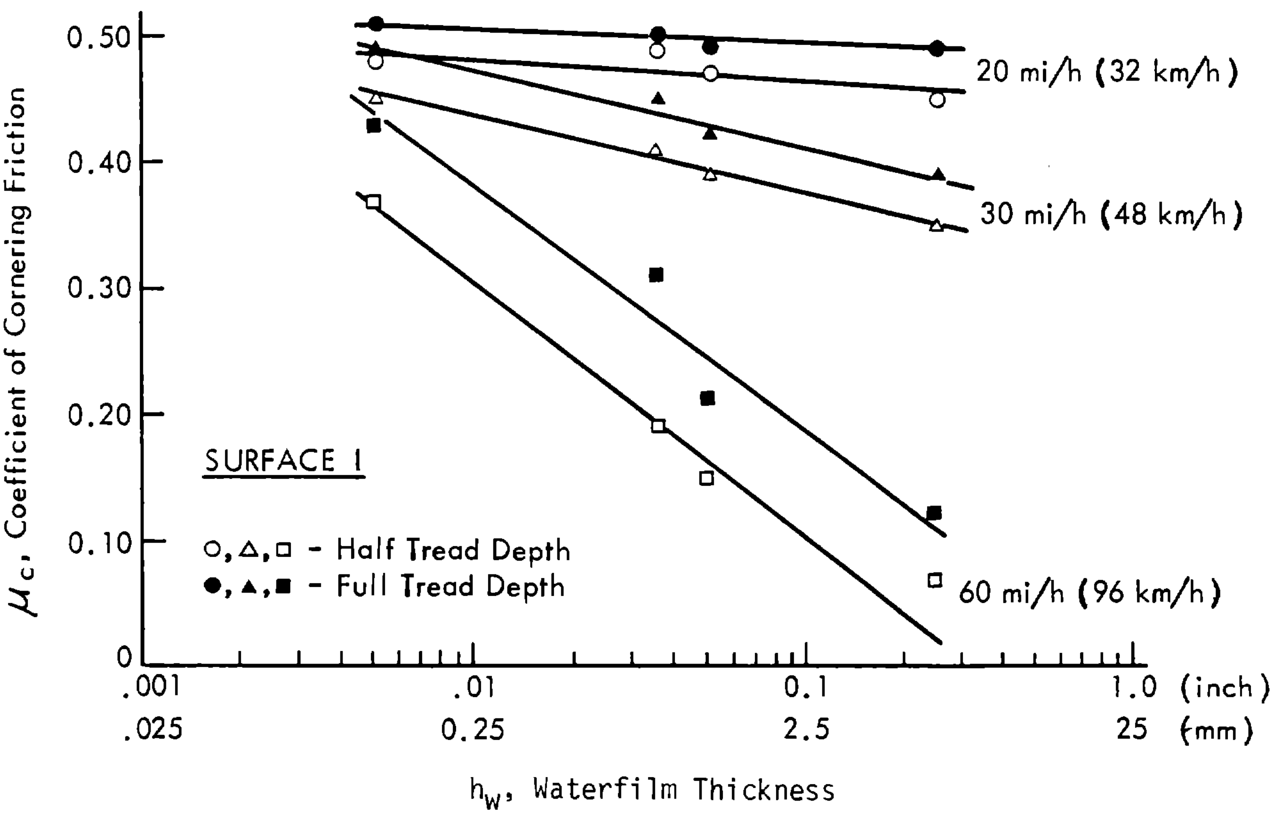


Figure 13 - Cornering Traction Versus Waterfilm Thickness for Full and Half Skid Depth Tires[12]

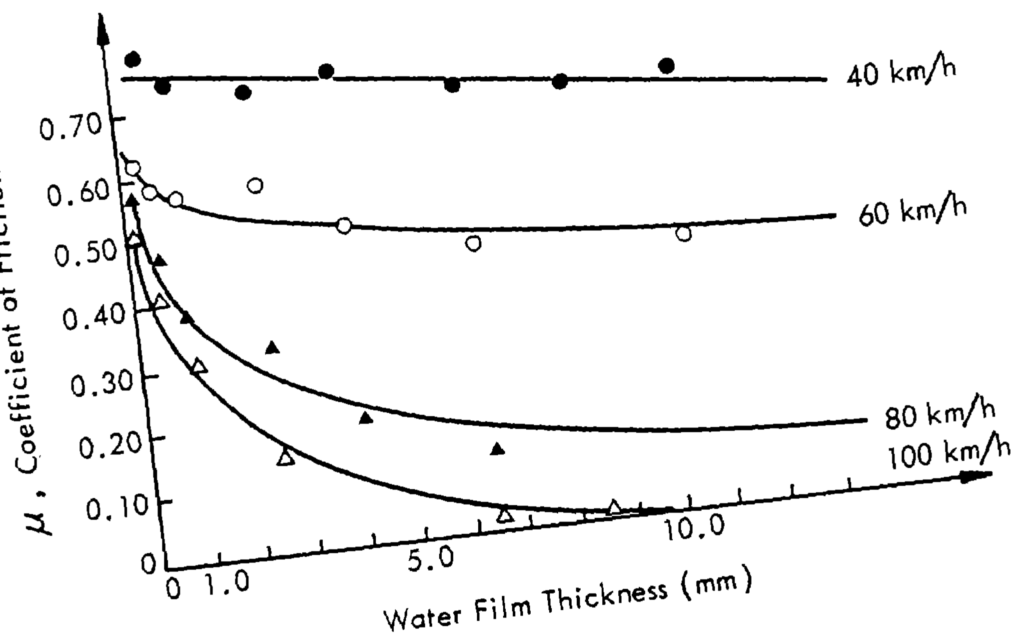


Figure 14 - Friction Coefficient as a Function of Waterfilm Thickness and Speed for an Asphalt Pavement[13]

b. Assessment of literature: The literature reviewed above provided a basis for selection of an approach to determine the relationship between pavement friction and waterfilm thickness in the laboratory. The constraints on a laboratory testing program should be recognized in the assessment of the literature and selection of a laboratory testing approach. The need for a reliable laboratory method for determining pavement friction that is equivalent to pavement friction tests performed in the field is a classic problem. The primary constraint on laboratory testing for realistic pavement specimens is that it must be performed at relatively low speeds which can be achieved in a laboratory setting. Laboratory testing methods for determining pavement friction also typically use a rubber wheel or slider pad that is smaller and differently shaped than a full-scale tire.

The literature indicates that the relationship between tire-pavement friction and waterfilm thickness is elusive, especially for tests at low speeds. Both Gegenbach[11] and Veith[12] found almost no sensitivity of pavement friction to waterfilm thickness for speeds below 30 mi/h (48 km/h), while Williams and Evans[14] found no sensitivity for speeds below 40 mi/h (64 km/h). Speeds of 30 to 40 mi/h (48 to 64 km/h) cannot be obtained in laboratory friction tests for realistic pavement specimens by any existing testing apparatus. Thus, the laboratory testing is necessarily limited to a speed range where previous investigators have been unable to determine a relationship between pavement friction and waterfilm thickness.

The functional form for this relationship most commonly used in the literature is a negative exponential or logarithmic relationship. Veith[12] and Pelloli[13] made explicit use of a negative exponential form for the pavement friction-waterfilm thickness relationship and Besse,[9] Giles,[10] and Gegenbach[11] obtained relationships that appear to be negative exponential, at least for some pavement types and speed ranges. These results suggest the most likely representation of the relationship between tire-pavement friction and waterfilm thickness is a negative exponential model of the general form:

$$\mu = ae^{-bd} + c \tag{12}$$

where: μ = coefficient of friction,

d = waterfilm thickness, and

a,b,c = regression coefficients to be determined.

Figure 15 illustrates this general form. It should be noted that the c coefficient represents a constant friction level that the relationship approaches asymptotically at large water depths, the b coefficient determines the shape of the curve, and the sum of the a and c coefficients represents the intercept of friction coefficient at zero waterfilm thickness (i.e., dry pavement friction).

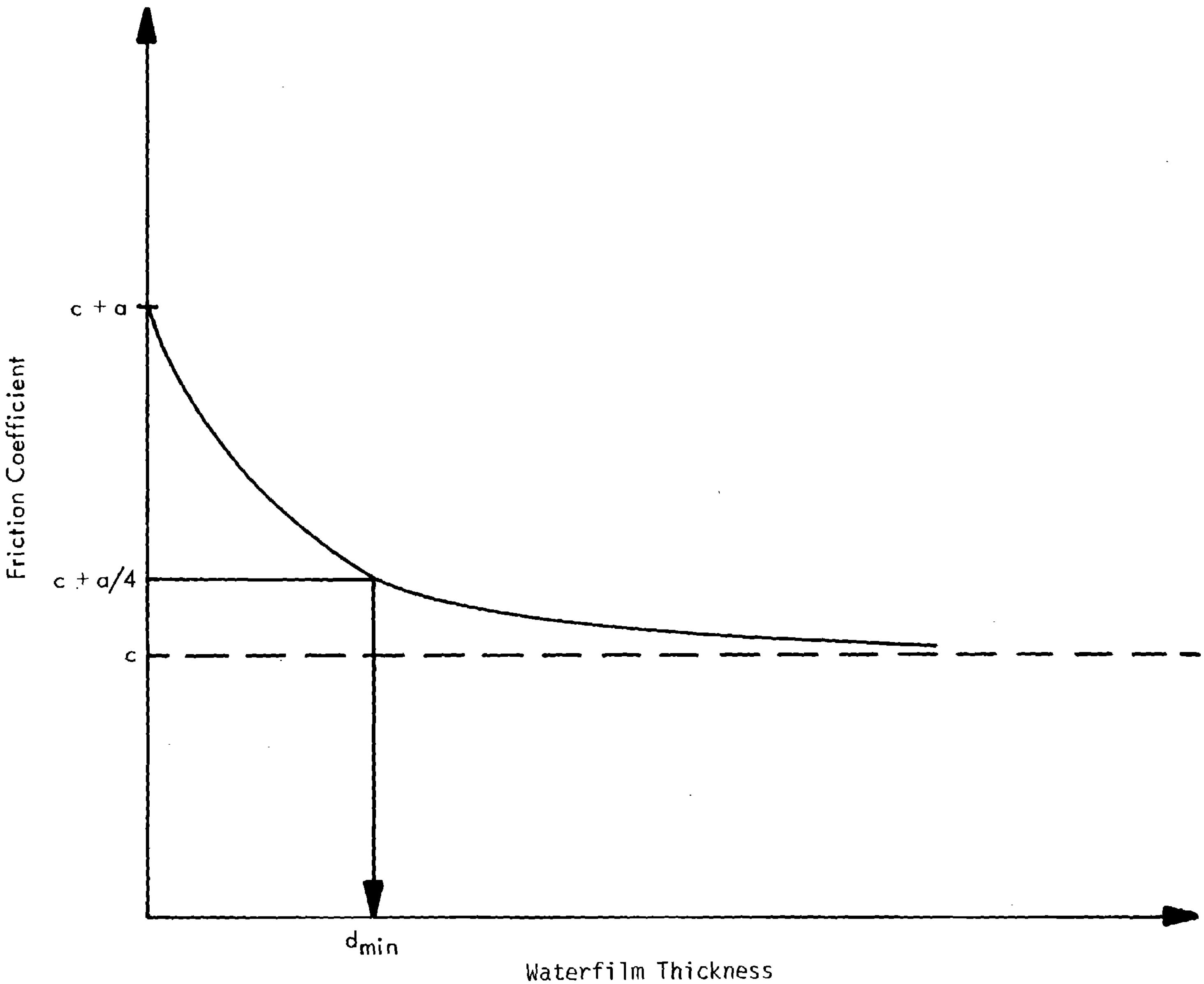


Figure 15 - General Form of Negative Experimental Relationship Between Friction Coefficient and Water Depth

While the negative exponential relationship is considered to be the most likely form for the relationship between pavement friction and waterfilm thickness, the literature is not unanimous on this point. Pelloli[13] suggests that the relationship is linear with negative slope, rather than negative exponential, for speeds below 25 mi/h (40 km/h), while Williams and Evans[14] and Rose and Gallaway[15] found too little sensitivity to suggest any particular functional form. Nevertheless, the available data in the literature support the choice of a negative exponential relationship of the type shown in Equation (4) as the best functional form for modeling of the pavement friction-waterfilm thickness relationship.

The purpose of determining the relationship between pavement friction and water depth is to establish the minimum level of wetness at which pavement friction is substantially reduced. This determination requires a definition of what constitutes a significant reduction in tire-pavement friction. Several possible criteria of the minimum level of wetness were hypothesized, including:

- The waterfilm thickness at which pavement surface friction drops to a specified level;
- The waterfilm thickness at which pavement surface friction has been reduced by a specified percentage from the dry friction level; and,
- The waterfilm thickness at which pavement surface friction has been reduced by a specified percentage of the difference between dry-pavement and wet-pavement friction.

After comparison of these alternative definitions, it was decided that the first two criteria were not appropriate. Although appealing, these two criteria are simplistic, since there is no agreement on a rational basis for defining acceptable and nonacceptable levels of skid resistance. Instead, the criterion for minimum level of wetness should be based on the shape of the friction vs. waterfilm thickness curve. The third criterion identified above meets this definition.

For a negative exponential curve, such as that shown in Figure 15, there is a need to define the waterfilm thickness at which the pavement friction coefficient has decreased substantially from the dry friction value, such that it is approaching the relatively insensitive relationship to pavement friction found for thick waterfilms. In Figure 15, the pavement friction coefficient under dry conditions is represented by c+a, while the pavement friction coefficient for thick waterfilms asymptotically approaches the value of c. Several candidate methods for estimating the minimum level of wetness were considered. A decision was reached to define the minimum level of wetness at which friction is substantially reduced as the waterfilm thickness at which the pavement friction coefficient has fallen 75 percent of the way from the dry friction coefficient to the friction coefficient for thick waterfilms (i.e., the waterfilm thickness at which the pavement friction coefficient equals $c + \frac{a}{4}$. Using this criterion, the minimum level of wetness is defined as:

$$d_{min} = -\frac{1}{b}\ \ell n\ \frac{1}{4} \tag{13}$$

where: d_{min} = minimum level of wetness at which friction is substantially reduced

b = regression coefficient from Equation (12).

The waterfilm thickness considered to be the minimum level of wetness, d_{min}, is illustrated in Figure 15.

The form of this definition of the minimum level of wetness is reasonable because it is a function only of the b coefficient, which sets the shape of the negative exponential curve. The choice of the 75 percent reduction criterion is conservative in that it results in a greater minimum level of wetness than other candidate criteria, such as a 50 percent reduction. Thus, when the minimum level of wetness is reached, there is good assurance that the pavement friction coefficient is approaching, but has not yet reached, the friction coefficient for a thick waterfilm. The definition of the minimum level of wetness based on a 75 percent reduction was used throughout the research.

2. Measurement of waterfilm thickness: One of the major challenges in both the laboratory and field testing programs was to develop a rapid and accurate method for measuring the waterfilm thickness on a pavement surface. The review of published literature indicates that the minimum level of wetness that substantially reduces tire-pavement friction is likely to be between 0 and 0.03 in. (0 and 0.75 mm), so the waterfilm thickness measurement method must be accurate for relatively thin waterfilms. This section documents the definition of the waterfilm thickness on a pavement surface used in this study and the thickness measurement devices that were developed.

a. Definition of waterfilm thickness: The primary definition of waterfilm thickness used in this research was the depth of the water on a pavement surface above the tops of the pavement surface asperities. Figure 16 illustrates that the waterfilm thickness (d) based on this definition is the vertical distance from the water surface to an imaginary plane defined by the tops of the asperities.

It was also recognized that a pavement can be wet even when the water surface is at or below the tops of the pavement asperities. For such cases, water is present in the pavement voids to reduce friction. A

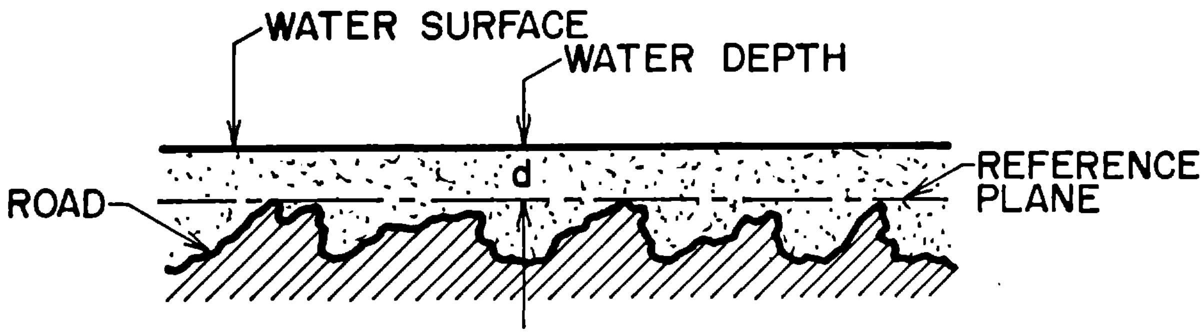


Figure 16 - Definition of Water Depth on a Textured Pavement Surface

pavement can appear wet with just a thin film of water clinging to the pavement surface asperities. Waterfilm thickness less deep than the asperities were referred to a trace amount of water. While the waterfilm thickness for trace amounts of water could not be measured directly, they could be estimated in controlled laboratory and field studies from the volume of water applied over a known area of the pavement surface.

b. Waterfilm thickness measurement device: The devices used to measure waterfilm thickness in previous studies were reviewed in the literature, but none of these devices were found to be satisfactory. Therefore, a device for measuring waterfilm thickness, as defined in Figure 14, was developed as part of the research.

After testing of several approaches, the most workable concept for measurement of waterfilm thickness proved to be a micrometer depth gauge. This device is illustrated by the schematic drawing in Figure 17 and the photographs in Figure 18.

In the application of this device, a plastic cylindrical element 2.5 in. (63 mm) in diameter and 3 in. (76 mm) in height is placed on the tested surface. A gauge block of known thickness, d_g, is put on the surface inside the cylinder. The depth gauge is first used to measure the reference distance between the top of the cylinder and the gauge block, d_{ref}. The gauge block is then removed, and after a waterfilm is applied on the pavement surface, the distance d^1 is measured. To measure this distance, an operator manually turns the micrometer handle, lowering the tip of the micrometer rod toward the water surface. An ohm meter is used to detect when the tip of the micrometer rod touches the water surface. The waterfilm thickness, dw, is then obtained as:

$$d_w = d_g + d_{ref} - d_1 \qquad (14)$$

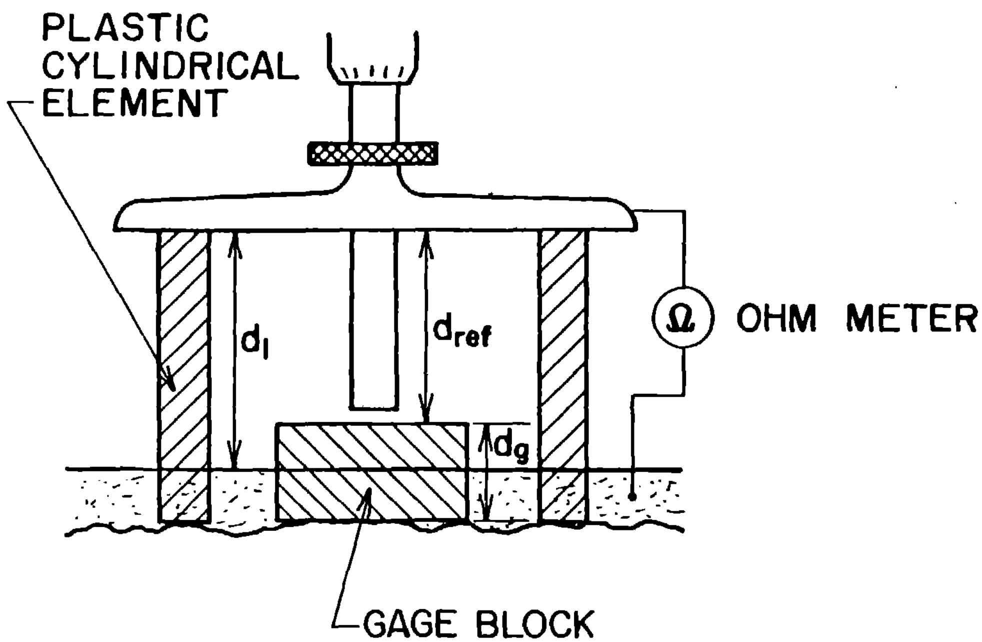


Figure 17 - Schematic Diagram of Micrometer Depth Gauge Used for Waterfilm Thickness Measurement

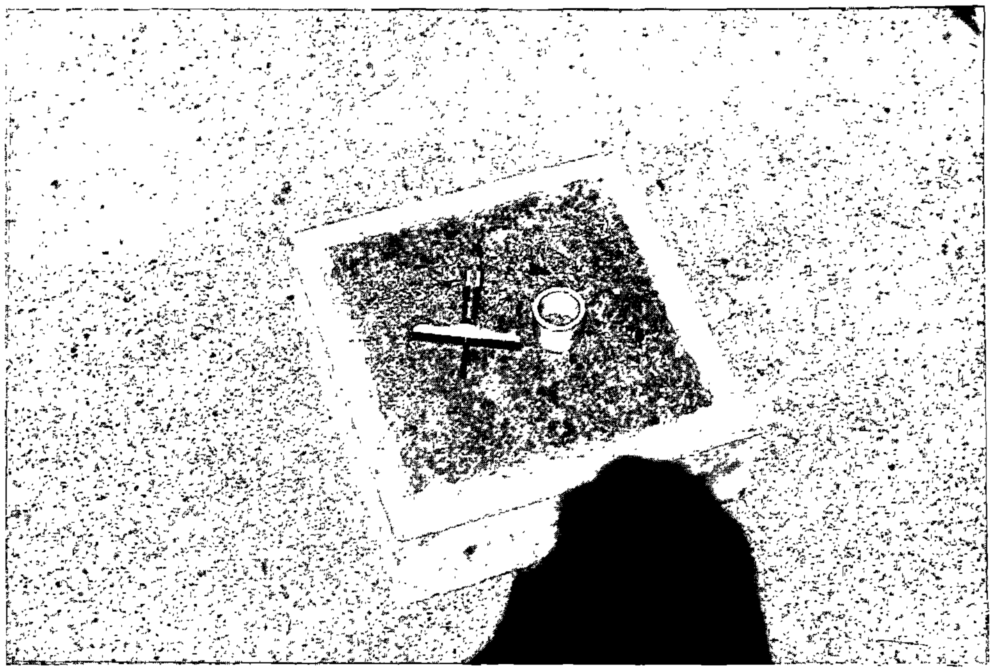


Figure 18 - Photographs of Micrometer Depth Gauge Used to Measure Waterfilm Thickness on a Pavement Surface

The accuracy of this method theoretically approaches the accuracy of the micrometer gauge which is 0.0005 in. (0.01 mm).

The micrometer depth gauge was used throughout the laboratory testing portion of the research in both the pavement friction and pavement drying time experiments. However, a concern remained about one potential cause of error in use of the micrometer depth gauge. It was difficult to determine the position where the micrometer rod first touched the water surface. An operator may tend to "overturn," or lower the rod too far, especially after several hours of testing. An automated system using a D.C. stepping motor to lower the rod of the micrometer depth gauge was developed and eliminated this problem. The automated micrometer depth gauge is illustrated in Figure 19.

An electric multiprobe tester, with an array of probes of different lengths to contact the water surface, was also developed in the research. This device proved difficult to keep level on a textured pavement surface and was only used for water depth measurement on one laboratory test surface, a smooth granite block.

c. Experimental design: The experiment design for the minimum level of wetness investigation involved the development of regression relationships between pavement friction and waterfilm thickness for six test pavement surfaces and four types of water.

The six test surfaces included a smooth granite block, three artificial surfaces, and two samples of real pavement surfaces obtained in the field. The artificial surfaces were made in the laboratory to be impermeable so that water placed on the test surface would be prevented from seeping into the interstices of the pavement. Table 14 presents a summary of the six pavement surfaces used in the friction tests.

Four types of water were used in friction tests: distilled water; rain water; tap water; and salt solution. Both rain water and tap water were used in tests to investigate the differences, if any, between pavement friction using actual rain water and tap water that is typically applied to the pavement surface in skid tests. The rain water used in the tests was naturally occurring rain water obtained in Pennsylvania. The salt solution was used to represent the effects of deicing chemicals dissolved in rain water on the surface of a highway. Eighteen of the 24 possible combinations of water type and pavement surface were tested to enable evaluation of the possible effects on pavement friction of chemical reactions between the water and the paving materials.

For each combination of water type and test surface, approximately 20 friction tests were performed to define the pavement friction vs. waterfilm thickness relationship. The intended range of waterfilm thicknesses for these tests was 0 (dry) to 0.030 in. (0.8 mm), although it was not always possible to obtain the full range of thicknesses desired on each test surface.

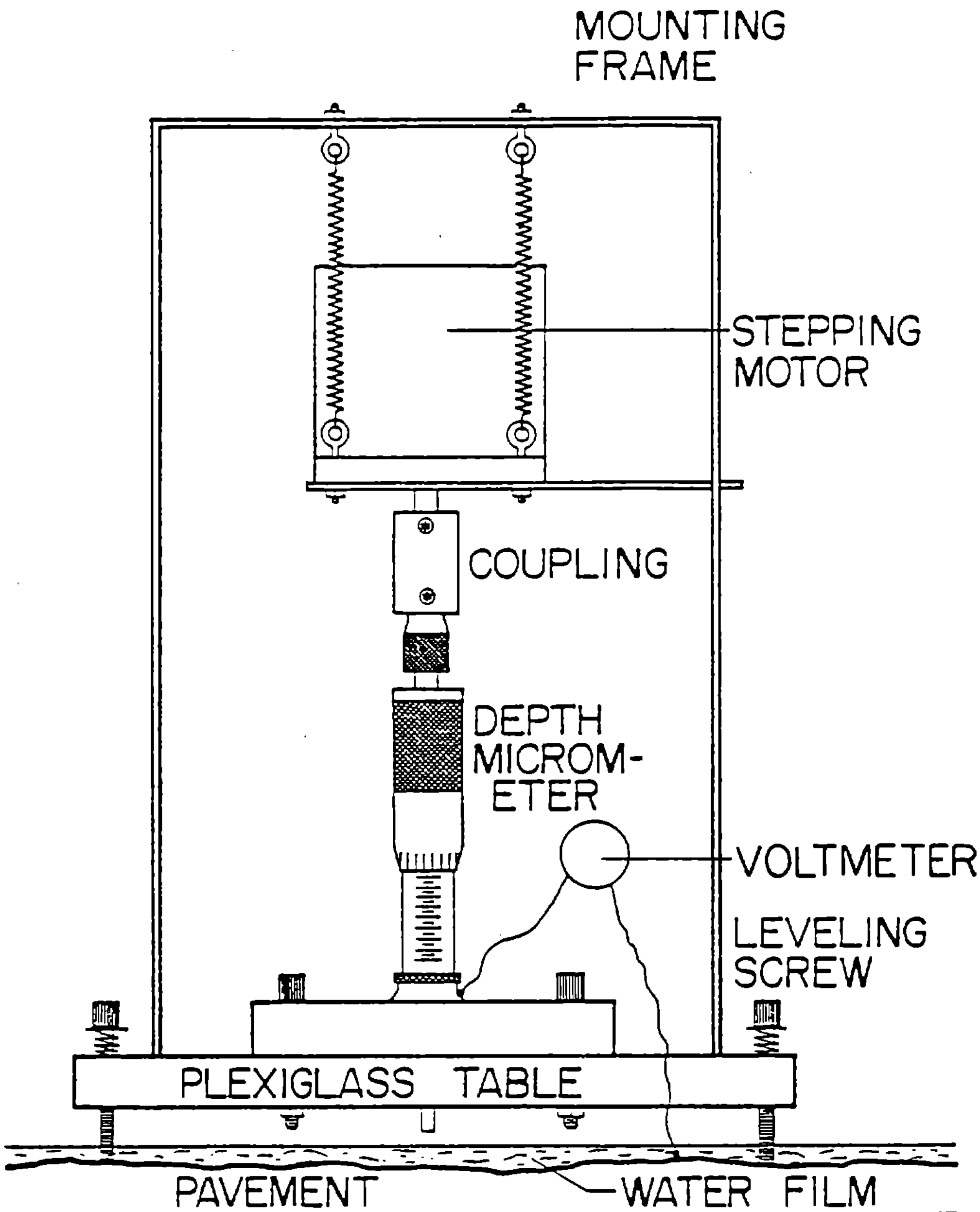


Figure 19 - Automated Micrometer Depth Gauge for Measuring Waterfilm Thickness

TABLE 14

SUMMARY OF PAVEMENT SURFACE SAMPLES USED IN FRICTION TESTING

Test Surface Number	Description	Sand Patch Texture Depth (in.)	Mean British Portable Number (BPN)
1	Smooth polished granite block	-	-
2	Artificial surface - limestone aggregate	-	-
3	Artificial surface - gravel aggregate	-	-
4	Real pavement surface - open-graded friction course	0.048	81
5	Real pavement surface - dense-graded asphalt	0.022	76
6	Artificial surface-sand aggregate	-	-

For one selected combination of water type and test surface -- tap water on an artificial surface with gravel aggregate -- comparable sets of tests were performed for both low speed (5 to 7 mi/h or 8 to 11 km/h) and high speed (10 to 12 mi/h or 16 to 19 km/h) conditions.

A total of 584 friction tests were performed in the conduct of the laboratory studies. Table 15 illustrates the distribution of these tests by test surface and water type. The results obtained from the analysis of these test data are presented in the next section.

3. Laboratory friction tests: The first stage in the determination of the minimum level of wetness was a laboratory testing program to investigate the pavement friction-waterfilm thickness relationship. This effort involved the development of a new friction tester suitable for laboratory use and the investigation of friction levels for different waterfilm thickness on various pavement surfaces with the new tester.

a. Friction testing equipment: A review of existing equipment for conducting laboratory friction measurements found that no existing device was suitable for this research. Candidate devices considered included the Penn State Drag Tester, the British Portable Tester, and the North Carolina State University Variable Speed Friction Tester. A decision was reached to construct a new testing device. This new device, known as the PTI Friction Tester, is described below.

The PTI Friction tester consists of a slider assembly mounted on linear bearings and driven along a rail or track by a freely falling weight. The friction tester is illustrated by the photograph in Figures 20 and by the schematic diagram in Figure 21. Top and side views of the slider assembly are shown in the schematic drawings in Figure 22. The normal force exerted by the slider on the test surface can be adjusted by raising or lowering the frame of the tester with the three power screws located at the ends of the frame.

The friction coefficient is determined by estimating the amount of kinetic energy lost by the slider assembly as it travels over the tested surface. The loss of kinetic energy is determined from the reduction in velocity of the slider that results from the frictional force generated as it travels across the test surface. Average velocities are determined over a distance of 5 in. (127 mm) immediately before striking the test surface and over the first 5 in. (127 mm) for which the rubber slider is in contact with the test surface. Since the measurement distances are fixed at 5 in. (127 mm), the average velocities are directly proportional to the time intervals, known respectively as t_{12} and t_{23}, during which the slider travels the two 5-in. (127-mm) distances.

Timing is accomplished by three small coils, acting as proximity sensors, installed above the track, 5 in. (127 mm) apart. A small magnet mounted on the slider assembly induces voltage in each of the three coils as the slider assembly passes its location. An oscilloscope is used to determine the duration of the time intervals, t_{12} and t_{23}. The resolution of the digital time read-out provided by the oscilloscope is 0.2 milliseconds.

TABLE 15

NUMBER OF FRICTION TESTS PERFORMED BY PAVEMENT SURFACE AND WATER TYPE

Test Surface Number	Water Type				Total
	Distilled Water	Rain Water	Tap Water	Salt Solution	
1	43[a]	22	-	22	87
2	24	-	32	27	83
3	33	19	94[b]	28	163
4	35	-	24	20	79
5	42[a]	-	24	25	91
6	-	31	21	29	81
	166	72	195	151	584

[a] Two replicate sets of tests run on different days.

[b] Thirty-nine tests run at low speed (5-7 mph) and 55 tests run at high speed (10-12 mph).

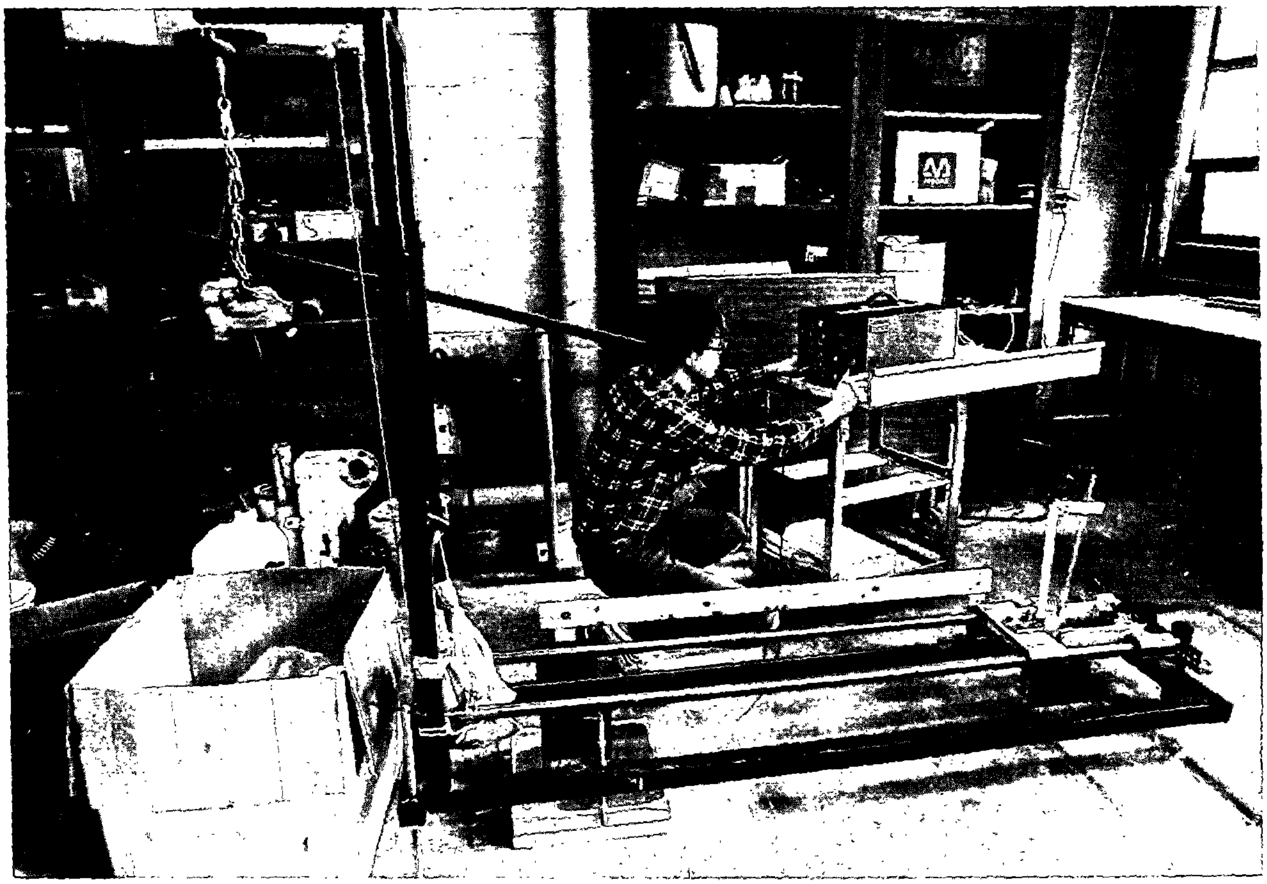


Figure 20 - Photograph of PTI Friction Tester Showing Oscilloscope
Used to Measure Slider Speed

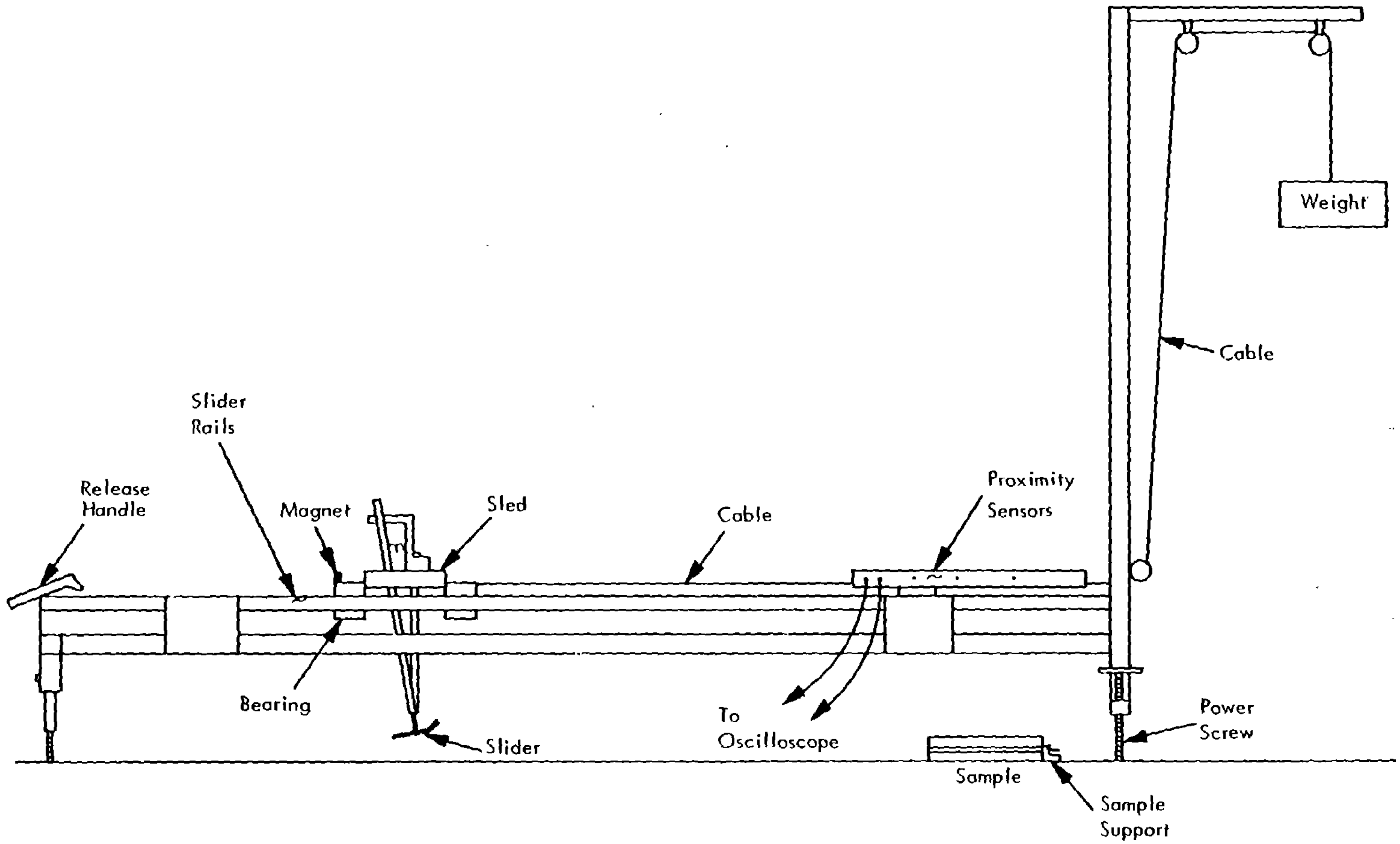
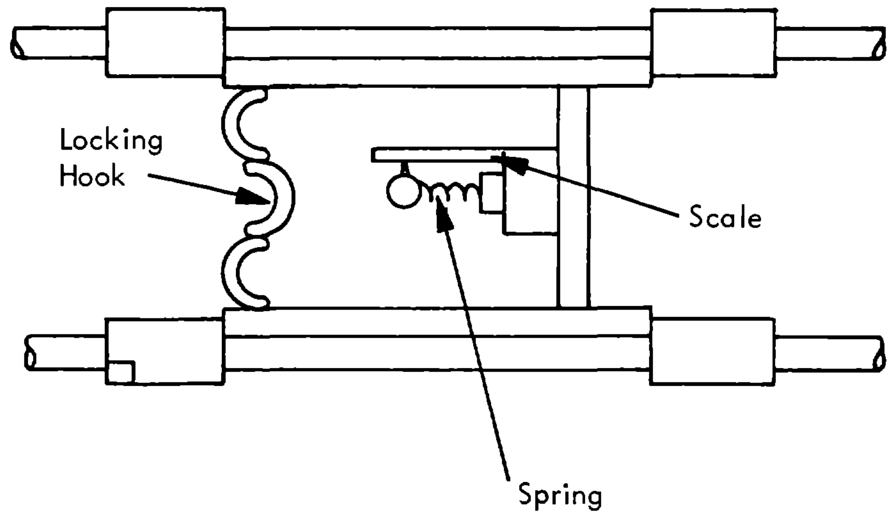
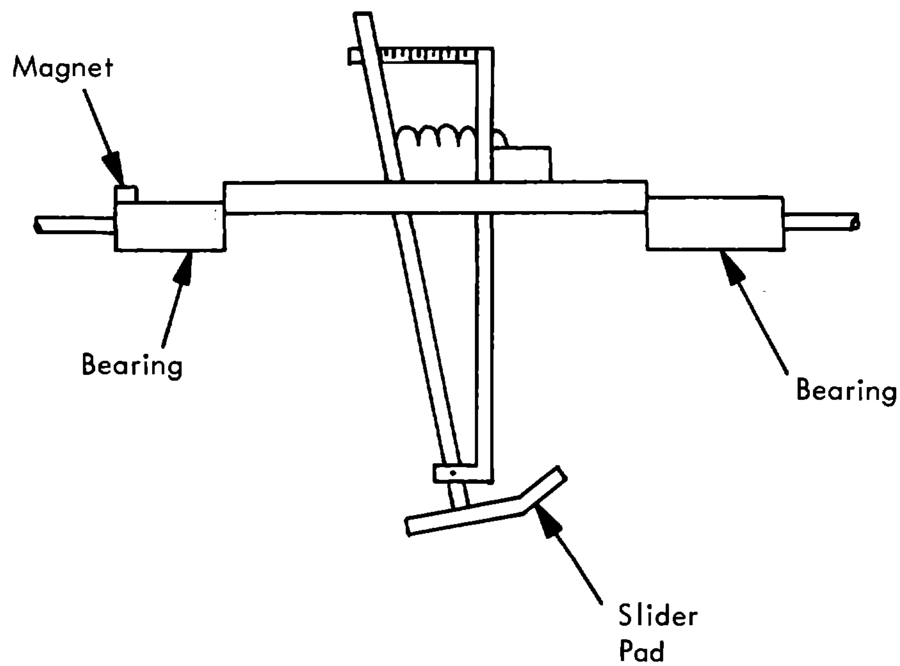


Figure 21 - Schematic Diagram of PTI Friction Tester



TOP VIEW



SIDE VIEW

Figure 22 - Schematic Diagram of Slider Assembly for PTI Friction Tester

The falling weight propels the slider over the test surface at a speed of approximately 5 to 7 mph (8 to 11 kph), equivalent to the speed of the British Portable Tester. Higher speeds, up to 10 to 12 mph (16 to 19 kph), were achieved in a few tests by manually pulling on the cable attached to the slider rather than relying upon falling weight.

The test results obtained from use of the PTI Friction Tester include the travel times over the two 5-in. (127-mm) paths, t_{12} and t_{23}, and a relative measure of normal force, Δ. These data were used in the following manner to compute a relative coefficient of friction:

$$\phi = \left(\frac{1}{t_{12}^2} - \frac{1}{t_{23}^2}\right) \frac{c_n}{\Delta} \qquad (15)$$

where: ϕ = relative coefficient of friction

t_{12} = time required for slider to traverse 5 in. (127 mm) just prior to striking test surface (msec)

t_{23} = time required for slider to traverse 5 in. (127 mm) in contact with test surface (msec)

Δ = parameter proportional to static normal load applied by slider to the test surface

c_n = constant used to normalize ϕ to a specific value of static normal load, Δ (= 2.5, in this case)

The quantity ϕ represents a relative friction coefficient because it is proportional to the kinetic energy lost by the slider assembly as it traverses 5 in. (127 mm) of the test surface.

Various calibration methods were considered to obtain an absolute friction coefficient (μ), rather than a relative coefficient (ϕ), from the test data. However, these calibration methods did not produce consistent results, and it was determined that use of the device to obtain the absolute friction coefficients (μ) would require further development. All analyses of laboratory friction data in this report are based on the relative friction coefficient (ϕ), as defined in Equation (15).

b. Data analysis: This section presents the estimation of the minimum level of wetness resulting in a significant reduction in pavement friction through analysis of the friction testing data obtained in the laboratory. The data analysis is presented in three parts. The first part of the section presents the analysis procedure used. The analysis results are presented in the second part of the section. The third part of the section interprets the analysis results and discusses their limitations in light of the poor repeatability of the friction testing device.

Analysis procedure: Each data set for a specific combination of test surface and water type was analyzed separately in a regression analysis to develop a negative exponential relationship of the form shown in Figure 15. The dependent variable used to represent tire-pavement friction in these analyses was the relative friction coefficient (ϕ), defined in Equation (15). Thus, the regression relationships developed in the analysis have the form:

$$\phi = ae^{-bd} + c \tag{16}$$

where: ϕ = relative friction coefficient

d = water depth (in.)

a,b,c = regression coefficients

Equation (16) has three regression coefficients to be determined in the analysis. This relationship is fundamentally nonlinear since it has three coefficients and cannot be linearized by a simple transformation, such as taking the logarithm of both sides of the equation. Because the relationship is not linear, simple linear regression is not applicable, and a nonlinear regression technique was employed. Nonlinear regression involves the use of an iterative mathematical approach to make successively closer approximations to the values of the three regression coefficients a, b, and c. The nonlinear regression techniques selected for use in this analysis were the Gauss-Newton Method and the Marquardt Method, which were applied using the NLIN procedure of the Statistical Analysis System (SAS) computer package.[21]

The nonlinear regression approach requires the user to specify suggested starting values for the regression coefficients a, b, and c. The starting values of the a, b, and c coefficients are simply the best available estimates of the true values of these coefficients; the closer the starting estimates are to the true values of the coefficient, the fewer iterations will be required to reach convergence (i.e., acceptable approximations of the regression coefficients). For each data set, the starting value of the coefficient c was estimated to be a value just below the minimum observed value of ϕ. Starting values of the a and b coefficients were then determined from a simple linear regression of the form:

$$\ell n\ \phi' = a' - b'd \tag{17}$$

where: ϕ' = $\phi - c'$

d = waterfilm thickness (in.)

c' = assumed starting value of coefficient c

a', b' = regression coefficients

The NLIN computer procedure takes these starting values of the a, b, and c coefficients uses the Gauss-Newton Method to produce successively closer approximations to the values of the coefficients. At each iteration, the residual sum of squares (representing the deviation of the actual data from the values predicted by the regression) is evaluated. An acceptable set of values of the regression coefficients, or convergence, is said to be reached when an iteration produces only a very small improvement in the error sum of squares in comparison to the previous iteration. Where convergence was not reached with 50 iterations of the Gauss-Newton Method, the final values obtained for the a, b, and c coefficients were used as the starting point for another nonlinear approximation technique, the Marquardt Method. If convergence was not obtained for a particular data set in 50 iterations of the Gauss-Newton Method and 50 iterations of the Marquardt Method, it was concluded no valid negative exponential relationship of the form shown in Equation (16) could be derived.

When convergence was obtained from either the Gauss-Newton Method or the Marquardt Method, the values of the a, b, and c coefficients at convergence are the best available estimates of the true values of these coefficients. Convergence, however, does not necessarily imply that the nonlinear regression obtained is statistically significant. For a nonlinear regression, there is no correlation measure directly equivalent to the correlation coefficient (R^2) that is used to evaluate the statistical significance of a simple linear regression. As a substitute for the use of R^2, an F-test for lack of fit was employed. This F-test is an exact test when applied to simple linear regression, but is only approximate for nonlinear regression. The null hypothesis tested was that the nonlinear regression fits the data well, as opposed to the alternative hypothesis that there is not a good fit. The F-test for lack of fit requires that the residual sum of squares from the regression be partitioned into two components: "lack of fit" and "pure error." The F-ratio used to test for lack of fit is the quotient of two mean squares:

$$F = \frac{\text{MS Lack-of-fit}}{\text{MS Pure-error}} \tag{18}$$

A value of F large enough to be statistically significant implies that the nonlinear regression <u>does</u> <u>not</u> provide a good fit to the friction test data.

For each nonlinear regression relationship obtained, the minimum level of wetness that substantially reduces pavement friction (d_{min}) was determined by the definition presented in Equation (13). According to this definition, the minimum level of wetness is estimated to be at the point where the pavement friction is reduced by 75 percent of the difference between the dry friction level and the friction level for thick waterfilms.

<u>Analysis results</u>: Table 16 summarizes the results obtained from the nonlinear regression analysis of the laboratory friction test data.

TABLE 16

SUMMARY OF NONLINEAR REGRESSION RESULTS FOR PAVEMENT FRICTION VERSUS WATER DEPTH

Surface No.	Water Type	Speed (mph)	Range of Waterfilm Thickness (in.)	Regression Coefficients for Equation 16: a	b	c	Lack of Fit Test: F-Ratio	Sig. ?	Minimum Level of Wetness (d_{min}) (in.)
1	Distilled	5-7	0-0.008	33.5	1,163.9	34.3	0.77	No	0.0012
	Rain	5-7	0-0.008	66.3	1,534.2	29.2	0.51	No	0.0009
	Salt	5-7	0-0.006	26.7	1,329.7	24.6	0.44	No	0.0010
2	Distilled	5-7	0-0.028	18.7	2,305.1	104.5	5.55	Yes	0.0006
	Tap	5-7	0-0.036	10.1	6,430.5	58.3	0.84	No	0.0002
	Salt	5-7	0-0.0004		No relationship found				
3	Distilled	5-7	0-0.015		No relationship found				
	Rain	5-7	0-0.007		No relationship found				
	Tap	5-7	0-0.040		No relationship found				
		10-12	0-0.011		No relationship found				
	Salt	5-7	0-0.012		No relationship found				
4	Distilled	5-7	0-0.040		No relationship found				
	Tap	5-7	0-0.002		No relationship found				
	Salt	5-7	0-0.005		No relationship found				
5	Distilled	5-7	0-0.028	17.1	305.3	86.9	4.05	Yes	0.0045
	Tap	5-7	0-0.017	3.3	829.3	37.7	1.05	No	0.0017
	Salt	5-7	0-0.001		No relationship found				
6	Rain	5-7	0-0.022		No relationship found				
	Tap	5-7	0-0.010		No relationship found				
	Salt	5-7	0-0.011	34.4	6,447.6	58.6	0.52	No	0.0020

The first four columns of the table identify the test surface, water type, testing speed, and range of water depths for each set of data that was analyzed. The next three columns of the table give the values of the a, b, and c coefficients for the nonlinear (negative exponential) regression, if convergence was found and acceptable values for these coefficients were determined. The next two columns present the value of the F-ratio used to test the nonlinear regression for lack of fit and whether or not that F-ratio is statistically significant. If the F-ratio is statistically significant ("Yes"), then the nonlinear regression relationship does not fit the data well. If the F-ratio is not statistically significant ("No"), then the nonlinear regression provides a good fit to the data. The final column of the table presents the minimum level of wetness (d_{min}), as defined in Equation (13).

The results reported in Table 16 show that nonlinear regression relationships were obtained for eight of the 19 data sets that were analyzed. Six of these eight nonlinear regression relationships were found to fit the data well (lack of fit not statistically significant), while two of the regressions did not produce relationships with a good fit. Figure 23 presents an example of one of the six data sets for which statistically significant regression relationships were obtained. The figure illustrates the data points obtained from the friction tests and the negative exponential regression relationship.

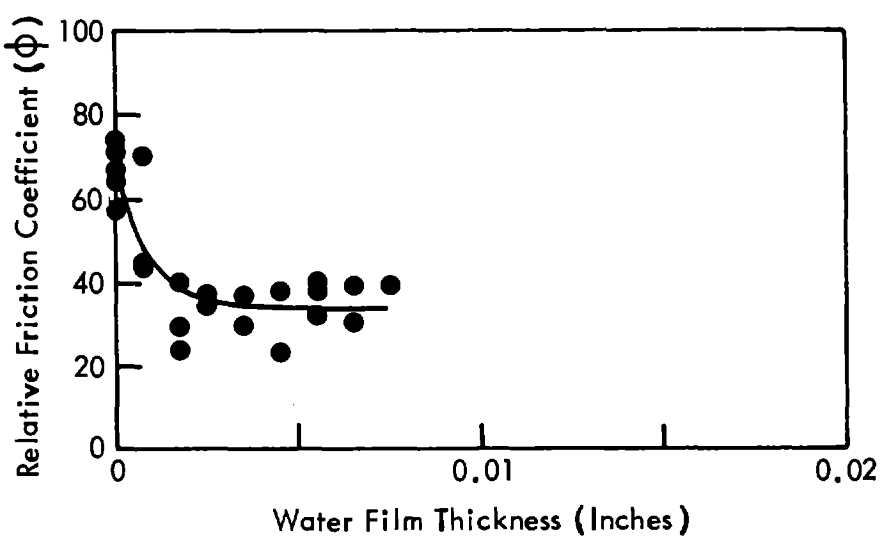


Figure 23 - Example of Pavement Friction Versus Waterfilm Thickness Curve Developed from Laboraotry Test Data

The minimum level of wetness found for these eight data sets ranges from 0.0002 to 0.002 in. (0.005 to 0.05 mm). A higher minimum level of wetness, 0.0045 in. (0.11 mm), was found, in one case, where estimates of the regression coefficients were obtained but the regression relationship was not found to be statistically significant.

Interpretation of results: The analysis found statistically significant regression relationships between pavement friction and waterfilm thickness were obtained for only 6 of the 19 sets of conditions tested. The difficulty in obtaining valid relationships between pavement friction and waterfilm thickness at low speeds, which is also typical of previous studies reported in the literature, may mean that there is little sensitivity of friction to water depth at low speeds. However, it may also result in part from the lack of repeatability of measurements with the friction testing device and the difficulty of making water depth measurements on a textured pavement surface.

The greatest success in developing regression relationships was found for the polished granite block (Test Surface 1), which resulted in statistically significant regression relationships for all three conditions tested. It should be noted that the measurement of waterfilm thickness is much easier and more repeatable on a smooth polished surface than on a textured pavement surface.

Despite the lack of success in obtaining significant regression relationships for some test conditions, the relationships obtained in this study indicate that the minimum level of wetness that substantially reduces pavement friction is probably less than 0.002 in. (0.05 mm) and is possibly as low as 0.0002 in. (0.005 mm). Thus, it appears that the minimum level of wetness could be one or two orders of magnitude less than the range of 0.015 to 0.02 in. (0.4 to 0.5 mm) suggested by some previous research. However, this conclusion needs to be verified in field tests at highway speeds with a full-scale tire.

Test Surface 5, a field sample of a dense-graded asphalt wearing course, was the only one of the two real pavement surfaces for which a statistically significant relationship between pavement friction and waterfilm thickness was obtained. The minimum level of wetness for this surface was found to be 0.0017 in. (0.04 mm), which is close to the largest value of the minimum level of wetness found for any of the test surfaces. The value of the minimum level of wetness found for this surface -- 0.0017 in. (0.04 mm) -- is the best single estimate of the minimum level of wetness obtained in the laboratory study.

c. Summary of conclusions: The findings of the laboratory investigation of tire-pavement friction indicate that the relationship between pavement surface friction and waterfilm thickness is difficult to quantify, as suggested by the literature review. Statistically significant nonlinear regression relationships were obtained for only 6 of the 19 sets of friction data collected. Nevertheless, the six nonlinear regression relationships obtained suggest that the minimum level of wetness that substantially reduces the friction available on a pavement surface may be lower than previously suspected. The minimum level of wetness appears to be less than 0.002 in. (0.05 mm) based on the laboratory tests, and could be as low as 0.0002 in. (0.005 mm). By comparison, the range of 0.015 to 0.02 in. (0.4 to 0.5 mm) for the minimum level of wetness was suggested in previous research.

These findings must be qualifed in two important ways. First, the tests on which the reported results are based represent rubber surface friction at relatively low speeds -- 5 to 7 mi/h (8 to 11 km/h) -- as opposed to much higher speed commonly found on the open highway and in full-scale skid testing. Previous research indicates that valid relationships between pavement surface friction and waterfilm thickness can be most reliably established for speeds above 30 mi/h (48 km/h). It seems likely that the sensitivity of pavement friction to waterfilm thickness should increase with speed. Second, the friction test results were obtained with a testing device that must be considered to be still in the developmental process. The repeatability and calibration of the device is poor and further development work is needed if the device is to be used for further testing. The need for friction data of higher reliability and friction tests at higher speeds were addressed in the field studies described below.

4. Field friction tests: A field testing program for pavement friction followed the laboratory testing program. The purpose of the field testing program was to extend the laboratory results to higher speeds and to employ a full-scale tire for more realistic test results. As in the laboratory testing program, the objective of the field tests was to establish the minimum level of wetness that substantially reduces pavement friction. The friction testing equipment, experimental design, data analysis, and conclusions of the field testing program are discussed below.

a. Friction testing equipment: Tire-pavement friction was measured in the field testing program using the Penn State Road Friction Tester, a locked-wheel skid tester. The tester satisfies the requirements of the ASTM Method E 274 for measurement of pavement skid resistance.

Three types of tires were used in the testing program: a standard ASTM ribbed test tire; a standard ASTM standard blank test tire; and, to represent "real world" conditions, a worn Goodyear G78-15 passenger car tire. The average tread depth of the passenger car tire was measured as 5/32 in. (3.97 mm).

b. Experimental design and testing plan: The experimental design for the field testing program involved comparisons between the friction levels of wet and dry pavements and the development of nonlinear regression relationships between pavement friction and waterfilm thickness, similar to those developed in the laboratory testing program. Four pavement surfaces, three types of tires, and three testing speeds were used in the field tests.

The field tests were conducted on four different pavement surfaces at the PTI Skid Resistance Research Facility, representing both PCC and asphalt pavements and a wide range of texture. The test surfaces included: a smooth asphalt surface; a medium-texture asphalt surface; a high-asphalt surface; and a portland cement concrete surface. Each test surface is 6 ft (1.83 m) wide by 200 ft (60.96 m) long. The results of sand patch texture depth measurements and British Portable Tester measurements are given in Table 17.

As stated above, tests were conducted with standard ASTM ribbed and blank tires and with a worn passenger car tire.

Friction tests were conducted with the Penn State Road Friction Tester operating at three speeds: 5, 20, and 40 mi/h (8, 32, and 64 km/h). The following procedure was employed in the tests.

(1) A 10-ft (3-m) target section to be tested was marked with cones.

(2) The test area was swept with a broom, including at least 50 ft (15 m) before and after the test section, to prevent the tire from picking up pebbles and debris during the test.

(3) Three skid tests on a dry surface were performed, with no water applied by the friction tester.

(4) A standard skid test was performed in accordance with ASTM E 274 with water applied at the normal rate. This results in the test surface being covered with a waterfilm at least 0.02 in. (0.5 mm) thick.

(5) The wetted area was then swept to ensure that a waterfilm as uniform as possible covers the entire test section.

(6) Three measurements of waterfilm thickness were made with the motorized micrometer depth gauge in selected locations over which the wheel of the friction tester will pass in subsequent tests. Obvious peaks and depressions were avoided in selecting the locations for waterfilm thickness measurements. If the water surface was below the voids of the pavement surface and no waterfilm thickness could be measured with the micrometer depth gauge, the waterfilm thickness was recorded as a trace amount.

(7) Five or six additional friction tests were made without any additional water application. Through normal evaporation, these tests included thin waterfilms less than 0.02 in. (0.5 mm) thick. The waterfilm thickness was measured with the micrometer depth gauge prior to each test.

TABLE 17

SAND PATCH TEXTURE DEPTH AND BPN DATA FOR THE PAVEMENT SURFACES USED IN THE FIELD TESTING PROGRAM

Surface Location	Description	Mean Texture Depth,[a] (in.)	BPN[b]
Skid Pad No. 6	Smooth asphalt	0.013	95.2
Skid Pad No. 2	Medium texture asphalt	0.029	94.0
Skid Pad No. 4	High texture asphalt	0.045	86.6
Skid Pad No. 5	Smooth portland cement concrete	0.018	98.8

[a] From sand patch tests.

[b] From British Portable Tester.

(8) Finally, two additional standard skid tests, with normal water application, were made.

This testing sequence resulted in a total of three friction tests on dry pavements, five or six friction tests for thin waterfilms, and three friction tests for thick waterfilm. A total of 162 friction tests were performed in the testing program, including 11 of the 12 possible combinations of pavement type and tire type. The distribution of these tests over the various experimental variables is summarized in Table 18. The waterfilm thickness for the thin waterfilms varied from a trace amount to nearly 0.015 in. (0.38 mm). The range of waterfilm thicknesses for the thin waterfilms tested is summarized in Table 19.

c. Data analysis: A preliminary set of tests, primarily with the ribbed tire, were performed at the beginning of the field testing program. These tests were performed at all three speeds: 5, 20, and 40 mi/h (8, 32, and 64 km/h). Also, in these preliminary tests, the portland cement concrete surface was tested with the blank tire. A statistical analysis of the preliminary data concluded that:

- No effect of waterfilm thickness on pavement friction was observed with the ribbed tire at 5 mi/h (8 km/h).
- The effect of waterfilm thickness on pavement friction at 20 mi/h (32 km/h) is very small except on high-texture asphalt tested with the ribbed tire and on portland cement concrete tested with the blank tire.
- The blank tire is more sensitive to thin waterfilms than the ribbed tire.

Based on these results, it was decided that the 40 mi/h (64 km/h) tests showed the greatest promise for determining a relationship between waterfilm thickness and pavement friction. Therefore, a more extensive set of tests were conducted at 40 mi/h (64 km/h). These tests employed the blank tire on all of the pavement surfaces, and also employed the more realistic worn passenger car tire.

The initial analysis approach employed for the full set of field test results at 40 mi/h (64 km/h) was an analysis of variance to examine differences in friction for tests on dry pavements, thin waterfilms and thick waterfilms. These tests showed that the coefficients of friction for

TABLE 18

SUMMARY OF NUMBER OF TESTS IN FIELD FRICTION TESTING PROGRAM

Pavement Type	Tire Type	Test Speed 5 mph	20 mph	40 mph
Smooth asphalt	Ribbed	6	5	5
	Blank	-	-	12
	Worn passenger car	-	-	16
Medium texture asphalt	Ribbed	5	5	5
	Blank	-	-	12
	Worn passenger car	-	-	12
High texture asphalt	Ribbed	4	4	5
	Blank	-	-	12
	Worn passenger car	-	-	12
Smooth portland cement concrete	Ribbed	5	5	4
	Blank	5	5	18
	Worn passenger car	-	-	-

TABLE 19

RANGE OF WATERFILM THICKNESS TESTED FOR THIN WATERFILMS

Pavement Type	Tire Type	Range of Waterfilm Thickness (in.) for Thin Waterfilms
Smooth asphalt	Ribbed	0.0012-0.0040
	Blank	0.0007-0.0020
	Worn passenger car	0.0013-0.0027
Medium texture asphalt	Ribbed	0.0018-0.0055
	Blank	0.0006-0.0012
	Worn passenger car	0.0014-0.0123
High texture asphalt	Ribbed	0.0005-0.0022
	Blank	0.0010-0.0013
	Worn passenger car	0.0008-0.0039
Smooth portland cement concrete	Ribbed	0.0015-0.0018
	Blank	0.0007-0.0038
	Worn passenger car	-

pavements under thin waterfilms were between the coefficients for dry pavement surfaces and for thick waterfilms. However, thin waterfilm coefficient was at times relatively close to the dry pavement coefficient and at times close to the thick waterfilm coefficient. It was decided that, because of the variation in waterfilm thickness for thin waterfilms (illustrated in Table 19), this simple analysis of variance approach was not productive. Therefore, it was decided to develop nonlinear regression relationships between waterfilm thickness and pavement friction, similar to the relationships developed in the laboratory testing program.

A careful examination of the data were conducted to identify outliers. Three data points were obviously outliers and were eliminated prior to the analysis. Quantitative estimates of the waterfilm thickness were made for a few data points for which a trace amount of water was reported. There was a fair amount of scatter in the friction readings, both for dry pavements and for thick waterfilms, so these values were averaged prior to the analysis.

The nonlinear regression analysis approach for the 40 mi/h (64 km/h) field friction test data was much more successful than for the laboratory testing program. The SAS NLIN procedure (described above in Section 3 of Appendix A) found regression coefficients for negative exponential relationships for 10 of the 11 combinations of pavement type and tire type that were tested. The eleventh combination was found to be best represented by a straight line with negative slope rather than by a negative exponential curve.

Each of the 11 nonlinear regression analyses using the Marquart method converged to a set of regression coefficients for the negative exponential relationship within nine iterations. It will be recalled that many of the nonlinear regression analyses for the laboratory test data did not converge to a solution even after 100 iterations.

Table 20 presents the results of the nonlinear regression analyses performed for the 40 mi/h (64 km/h) field friction data. The a, b, and c coefficients whose values are shown in the table are those for the negative exponential relationship in Equation (16). The minimum level of wetness in the table is the value of d_{min}, as defined in Equation (18). The 11 regression relationships presented in Table 20 are illustrated in the graph in Figure 24. All of the negative exponential regression relationships in Table 20 and Figure 24 provide a good fit for the friction test data.

d. Interpretation of results: The results from the field friction tests indicate that the minimum level of wetness that substantially reduces pavement friction, as defined in Equation (18), lies between 0.001 and 0.009 in. (0.025 and 0.23 mm). This range for the minimum level of wetness is generally higher than, but overlaps, the range of 0.0002 to 0.002 in. (0.0005 to 0.05 mm) found in the laboratory tests.

TABLE 20

COEFFICIENTS OF NEGATIVE EXPONENTIAL RELATIONSHIPS BETWEEN PAVEMENT FRICTION AND WATERFILM THICKNESS FOR FIELD FRICTION TESTS AT 40 mi/h

Pavement Type	Tire Type	Curve Number[1]	Regression Coefficients[2] a	b	c	Minimum Level[3] of Wetness (d_{min}) (in.)
Smooth asphalt	Ribbed	1	19.3	-1,343	55.8	0.0010
	Blank	2	51.1	-735	31.9	0.0020
	Worn passenger car	3	31.6	-675	48.3	0.0020
Medium texture asphalt	Ribbed	4	19.2	-1,121	59.0	0.0010
	Blank	5	57.6	-1,685	31.2	0.0008
	Worn passenger car[4]	-	-	-	-	-
High texture asphalt	Ribbed	6	29.1	-437	49.8	0.0030
	Blank	7	31.4	-786	41.3	0.0020
	Worn passenger car	8	11.5	-152	47.0	0.0090
Portland cement concrete	Ribbed	9	12.4	-263	60.3	0.0050
	Blank (Replicate 1)	10	63.3	-848	27.2	0.0020
	Blank (Replicate 2)	11	61.5	-315	32.0	0.0040
	Worn passenger car[5]	-	-	-	-	-

[1] Curve number as shown in Figure 23.

[2] Regression coefficients as defined in Equation (12).

[3] Minimum level of wetness as defined in Equation (13).

[4] Best represented by straight line with negative slope rather than by a negative exponential curve.

[5] No data available.

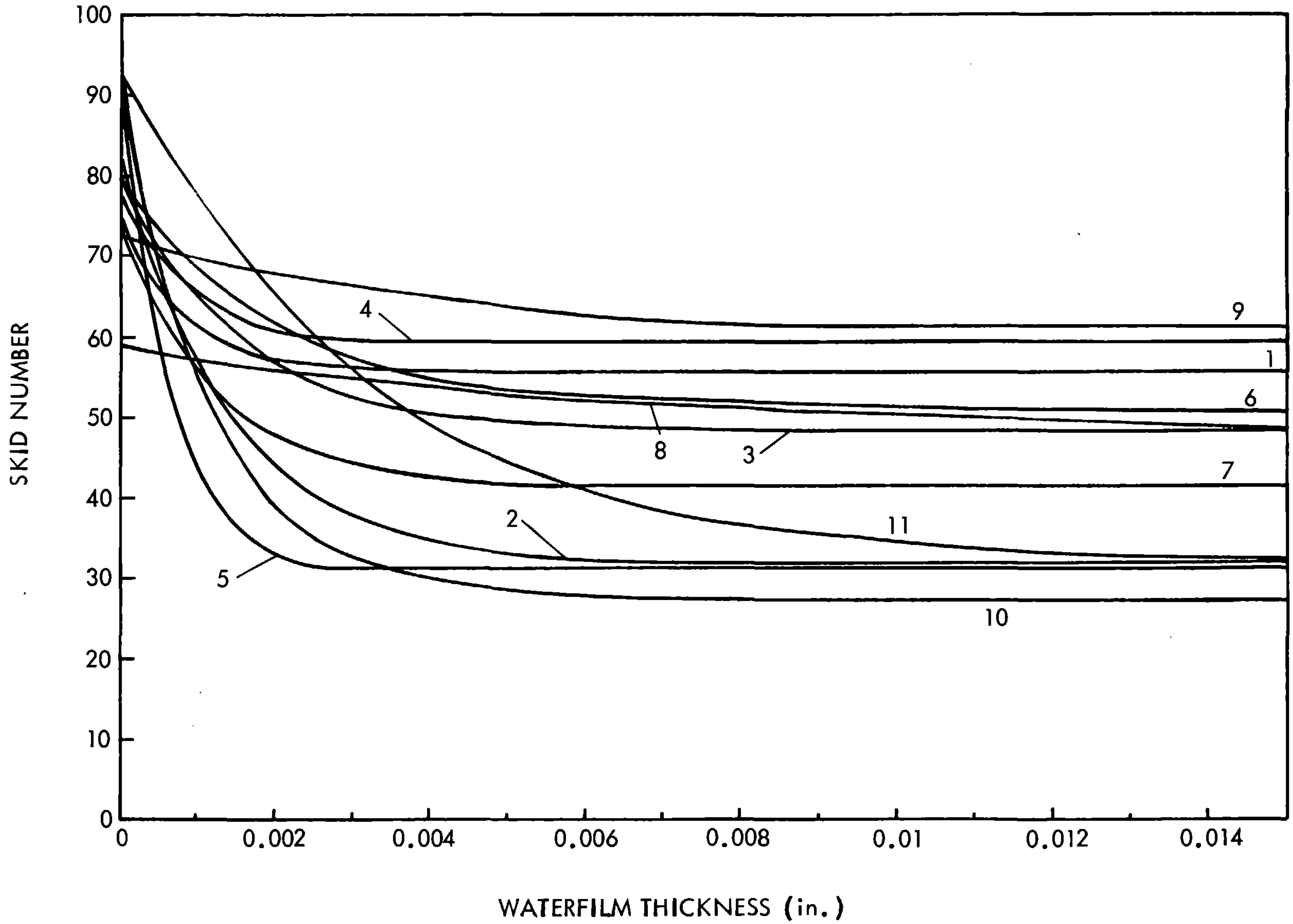


Figure 24 - Negative Experimental Relationships Between Pavement Friction and Waterfilm Thickness Developed from Field Test Data

The results of the field tests are considered more reliable than the results of the laboratory tests for several reasons, including: (1) the field tests were conducted at highway speeds; (2) the field tests were conducted with a full-scale tire rather than a rubber slider; (3) the field tests were conducted with an accepted testing device rather than a newly developed tester; (4) the field results were more consistent and repeatable than the laboratory results; and (5) the statistical analysis of the field data found an acceptable regression relationship in nearly every case.

The field test results indicate that as little as 0.001 in. (0.025 mm) of water on a pavement surface can, in some cases, reduce friction 75 percent of the way from the dry to the wet value. This minimum level of wetness is likely to be exceeded during any hour in which there is at least 0.01 in. (0.25 mm) of rainfall. Thus, all measurable amounts of rainfall in the NCDC Hourly Precipitation Data are likely to exceed the minimum level of wetness and should be considered as wet-pavement exposure in the WETTIME model.

APPENDIX B

PAVEMENT DRYING TIME FOLLOWING RAINFALL

This appendix addresses the measurement of pavement drying time and the prediction of its variations with environmental conditions and pavement types. The first part of the appendix reviews the literature related to pavement drying time as background to the laboratory and field investigation. Subsequent sections describe the measurement of pavement drying time in the laboratory, the development of a predictive model based on the laboratory drying time data, and the verification of the model through field drying time tests.

1. Background

A review of published literature indicates that two contrasting methods have been used to estimate annual wet-pavement exposure from environmental data. The California/NTSB approach[1,4] does not explicitly account for pavement drying time. However, pavement drying time may be implicitly accounted for, at least partially, in this technique because each hour with at least 0.01 in. (0.25 mm) of rainfall is classified as wet-pavement exposure, even though the duration of the rainfall may be less than a full hour. The MRI technique includes an explicit 30-min estimate for pavement drying time following each rainfall.[2] The 30-min estimate was based on field observations of pavement drying time in Ohio and Louisiana and on calibration of the wet-pavement exposure estimation techniques against data from a moisture sensor implanted in an interstate highway bridge near Iowa City, Iowa.

The development of a valid wet weather exposure estimation technique requires refined estimates of pavement drying time from either empirical measurements or from an evaporation model. Evaporation rate is the primary environmental factor that affects the drying time to return a given pavement to a nonslippery condition following a rainfall. Evaporation rates have been modeled in previous research based on data from Class A evaporation pans which are intended to simulate the evaporation rates from lakes and reservoirs. Evaporation data from Class A pans are available for numerous locations throughout the United States. However, evaporation of thin waterfilms on a textured pavement has not been investigated in any systematic way under controlled conditions. Thus, it is not known whether evaporation rates from pavement surfaces are similar enough to evaporation rates from Class A pans for the existing nationwide evaporation records to be useful in predicting pavement drying time.

Evaporation formulas applicable to the pavement drying problem have evolved from two main ideas: (1) an energy budget technique, wherein all long and short-wave radiation sources and sinks are measured and the energy removed by evaporation is obtained by back solution; and, (2) a turbulent transfer or diffusion technique, wherein the evaporation rate is equal to a sensible heat transfer coefficient times vapor pressure gradient above the evaporating water surface.

Both approaches (1) and (2) above have been summarized by Eagleson.[22] Basically, the energy budget method is intractable for the pavement evaporation problem because of the need for elaborate radiometer measurements which are generally unavailable. Also, because of difficulties in estimating changes in stored energy control of the evaporating body, the energy budget is not accurate for periods shorter than 7 days.[22]

The diffusion or turbulent transfer method for evaporation rate is normally expressed as:

$$E = -K \frac{de}{dz} \tag{19}$$

where,

K = sensible heat transfer coefficient, based on wind speed, eddy diffusivity and eddy viscosity terms

e = vapor pressure

z = vertical distance above evaporating surface

Because of difficulties in estimating the sensible heat transfer coefficient, Equation (19) is usually expressed in the semi-empirical Dalton form as:

$$E = (A + B \cdot u)\,(e_s - e) \tag{20}$$

where A and B are coefficients representing the sensible heat transfer by turbulent exchange based on mean wind speed, u; e_s is saturation vapor pressure of air at temperatures of the waterfilm; and e is vapor pressure of overlying air at elevation at which u is measured. Coefficients A and B must be obtained by controlled experiment. A special form of Equation (20), known as the Meyer equation, has been applied to lake surfaces as well as evaporation pans in the form:

$$E = C(e_o - e_a)\,(a + \frac{W}{10}) \tag{21}$$

where,

E = evaporation (in.day),

e_o = saturation vapor pressure at ponded water temperature (millibars) or mb),

e_a = actual vapor pressure of air (mb),

W = wind speed (mi/h) measured at 25 ft (7.6 m) above surface, and

C = coefficient which is normally set at 0.36 for lakes and 0.50 for shallow pans.

The meteorologic data required in normal application of equation (21) include: daily average wind speed in mi/h at 25 ft (7.6 m) elevation; temperature (°F) of ponded water; average air temperature (°F); and relative humidity.

An alternative to either the energy budget or turbulent transfer methods is called the "combination" method because it combines elements of turbulent diffusion with energy balance. It was first applied in very crude form by Thornthwaite,[23] refined by Penman[24,25] and subsequently modified by Van Bavel[26] and by Tanner and Pelton[27] for estimating potential evapotranspiration losses from agricultural watersheds. The combined equation is expressed in simplified form as:

$$E = \frac{(\Delta \cdot H + E_a \gamma)}{(\Delta + \gamma)} \qquad (22)$$

where,

E = evaporation (mm/day),

Δ = slope of saturation vapor pressure versus temperature curve at average air temperature

γ = psychrometric constant (0.27 for degrees Fahrenheit and vapor pressure in mm Hg).

E_a is determined by the expression:

$$E_a = C(e_o - e_a)\,(1 + \frac{W}{100}) \qquad (23)$$

where,

W = wind speed (mi/h) at elevation 6 ft,

C, e_o, e_a = terms defined previously in Equation (21), and

H = net short-wave and long-wave radiation term which can be estimated from air temperature, cloud cover and extraterrestrial radiation.

Equation (23) is quite similar to Equation (21) in that the wind-vapor pressure terms are nearly identical. The advantage of Equation (23) is that it has the capability to represent net radiation differences that occur both temporally and geographically. The only additional data requirements needed to apply Equation (23) are radiation and cloud cover. These data are available from NCDC at many first-order weather stations across the country.

Thus, the assessment of the published literature indicates that the Meyer and Van Bavel equations (Equations 21 and 23) are the most appropriate evaporation equations for laboratory evaluation.

2. Laboratory Testing Program

This section of Appendix B presents the laboratory testing program used to evaluate pavement drying time. The following discussion presents the testing apparatus and procedure, the experimental design, the data analysis, and the interpretation of results.

a. Pavement drying time testing apparatus and procedure: This section describes the testing apparatus and the testing procedure used in the laboratory drying time experiment.

(1) Testing apparatus: The laboratory evaluation of pavement drying time required the construction of an insulated, enclosed chamber in which key environmental variables, including temperature, relative humidity, wind speed, and solar radiation levels, can be controlled. The chamber was built in the laboratory as an 8- by 8- by 8-ft (2.4- by 2.4- by 2.4-m) framed structure with insulation on all sides and on the ceiling. A hinged access door was located on the front of the chamber. This door was kept closed after constant conditions were reached in the chamber and it remained closed during the data collection period. The ambient conditions in the room outside the chamber had almost no effect on conditions inside the chamber.

A variety of equipment was needed to measure and manipulate the environmental conditions inside the chamber including:

- Space heater;
- Room air conditioner;
- Humidifier;
- Solar lamp array;
- Variable speed fan for simulating wind;
- Class A evaporation pan (4 ft or 1.2 m in diameter);
- Hook gauge for depth measurement to determine evaporation losses from the Class A pan;

- Micrometer depth gauge for measurement of waterfilm thickness on pavement sample;

- Thermometers for measurement of air temperature and water temperature (in evaporation pan);

- Thermistors for measurement of pavement temperature;

- Relative humidity gauge; and

- Anemometer for wind speed measurement.

Figure 25 presents photographs of the outside of the environmental chamber and of the inside of the chamber illustrating the evaporation pan, pavement sample, solar lamp array, variable speed fan, and other equipment.

(2) Testing procedure: The drying time apparatus was used to measure the time required for the surface of a 12- by 12-in. (305- by 305-mm) pavement sample to dry under environmental conditions that were systematically varied. Each sample was encased in a 1-in. mortar mounting, so the overall surface dimensions of the sample were 14 by 14 in. (356 by 356 mm). The ten pavement samples used in the drying time experiment are identified in the discussion of the experiment design in the next section.

The drying time experiment was intended to identify the effects of two types of variables on drying time as follows:

1. Primary variables
   - Air temperature: 60°, 75°, and 90°F
   - Relative humidity: 45, 60, 75, and 90 percent
   - Solar radiation (short-wave): nighttime or overcast; partly cloudy, overcast day; and bright, cloudless day
   - Wind speed: 0, 2, 8, and 15 mi/h
   - Pavement type

2. Secondary variables
   - Acid rainfall
   - Roadway deicing materials (NaCl)
   - Oil films

The primary variables focus on climate and pavement characteristics, while the secondary variables focus on common contaminants found in rainfall and highway runoff.

Air temperature was maintained at 60°, 75°, or 90°F (16°, 24°, or 32°C) levels by a combination of solar lamps, space heater, and air conditioner. Because of the heat generated by the solar lamps, the space heater was required only intermittently except in one test which simulated 90°F conditions at night. The tests at 60°F, on the other hand, required the use of an air conditioner which was installed in the chamber for this purpose.

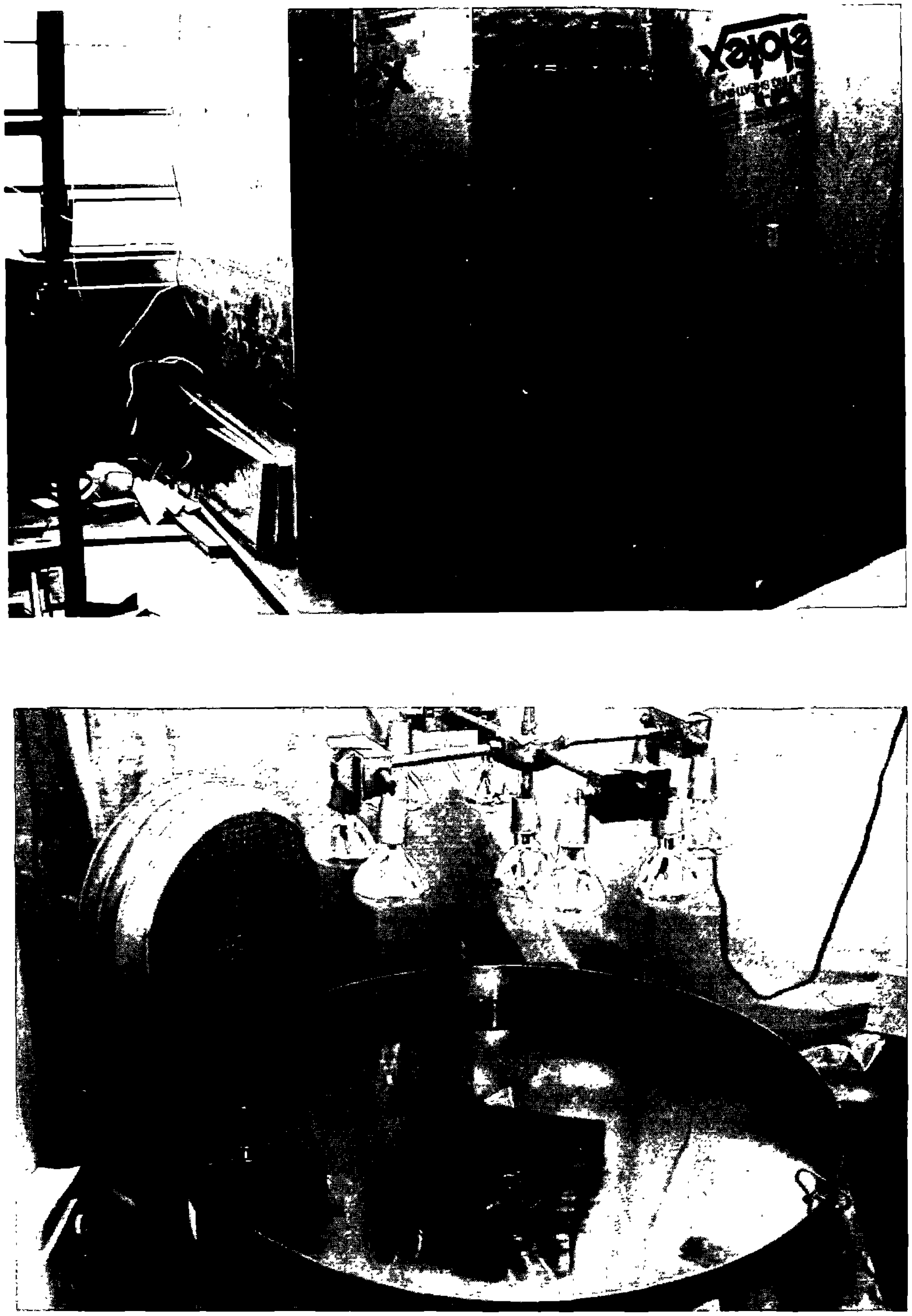


Figure 25 - Photographs of Exterior of Drying Time Chamber and Drying Time Measurement Apparatus Within Chamber

Relative humidity was maintained at 45, 60, 75, or 90 percent levels by means of an industrial humidifier with an automatic sensor. The humidifier emitted a fine mist which was circulated by a built-in blower and by the large variable-speed fan used to simulate wind speeds over the test surface. Air temperature and relative humidity were measured by a precision temperature and humidity indicator which was calibrated periodically against local weather station records.

Short-wave solar radiation levels were held at three levels corresponding to nighttime or overcast; partly cloudy day; and a bright, cloudless day at noon. These conditions were simulated inside the drying time chamber by a total of eight infrared (short-wave) lamps located in four paired clusters on the circumference of a 48-in. (1.2-m) diameter test area containing the pavement sample. The short-wave output of all lamps was controlled by a variable voltage regulator (variac) which was preset to produce desired radiation levels at the surface of the pavement sample.

Calibration of the lamp configuration and the variac was achieved with a mechanical pyranograph. This meteorologic instrument consists of a 6-in. (150-mm) glass hemisphere, a pen-arm recorder, and four metallic strips -- two white and two black. The deflection of the bimetallic strips under sunlight or artificial light provides a recorded measurement of incoming short-wave radiation. The instrument senses radiation having wavelengths in the range 0.36 to 2.0 μ and thus is designed specifically for short-wave solar radiation measurement. This is an important factor, since the incident short-wave radiation is a driving force in the evaporative process.

The mechanical pyranograph first had to be calibrated against known solar radiation intensities so that unit deflections could be translated into langleys/minute as a measure of radiation intensity. The calibration was established through local weather station observations on different days and at different times of day. The calibrated pyranograph was then used inside the chamber to determine an optimal arrangement of the infrared lamps over the test area. It was also used to identify desired radiation settings on the variac device. Accordingly, variac settings of 0, 40, and 100 percent correspond with 0, 0.75, and 1.15 langleys/min of short-wave or infrared radiation. These levels in turn correspond with night-time, partly cloudy, and bright mid-day conditions, respectively, as determined by direct measurement with the calibrated pyranograph.

Wind speed over the test area was controlled by a two-speed industrial fan. The low setting generated 8 mi/h (13 km/h) airflows, while the high setting gave approximately 15 mi/h (25 km/h). These velocities were measured by cup anemometer at an elevation in the chamber corresponding to the position of the top of the pavement specimen under test conditions. The fan was later adapted to produce wind speeds of approximately 2 mi/h (3 km/h), as well.

A stainless steel Class A NWS evaporation pan was installed in the chamber and used for two purposes in all the testing work. First, it was used as a bath to submerge and saturate each pavement sample prior to testing. The pan itself then served as a mounting platform and test area for the pavement samples. Second, water depth measurements in the pan were made simultaneously with those on the pavement surface to establish a basis for correlation studies. A separate set of measurements was made initially to determine the possible impact on pan evaporation of the pavement sample. No significant effect of the presence of the sample in the center of the pan could be found. Pan evaporation was measured by means of a hook gauge installed in a small stilling well inside the pan. Water temperature in the pan, as well as on the pavement surface, was measured by thermocouple with a digital display.

Several preliminary steps had to be completed before actual measurement of drying times was begun. The following sequence describes the preparation steps:

1. The sample was placed in evaporation pan and submerged overnight to ensure saturation;

2. The sample was raised on wooden blocks such that only the top inch was exposed; it was also leveled with metal shims so that drainage would be uniform after application of the waterfilm;

3. A 2-in. (51-mm) test circle was marked on sample so that micrometer depth gauge would be returned to same spot for each waterfilm thickness measurement on the pavement surface;

4. A reference depth or datum was established for dry sample by averaging five readings on the micrometer depth gauge at the test spot; film thickness would be calculated later by subtracting test readings from this reference depth; and

5. The hook gauge inside the evaporation pan was leveled and the reference water depth measured.

Once the above preparation steps were completed, nine tests on each pavement surface under varying environmental conditions were conducted according to an experimental plan described in the next section. In general, the full battery of nine tests for a particular pavement sample was run sequentially before going to the next pavement sample. Prescribed air temperature and relative humidity were maintained for a minimum of 10 min before test water was applied to the pavement surface. The test water was applied by means of a spray bottle after the lamps and fan were turned on at the required levels. Excess surface water was then allowed to drain from the sample over a 30-sec period and the drying time tests were started. The test surface was saturated with water at the beginning of the test period and the starting waterfilm thickness on the pavement surface was as close as possible to 0.02 in. (0.5 mm) at the point of water depth measurement. The water used in the drying time experiment was ordinary tap water.

Instrument readings were taken in the following order for each of the nine tests on each sample:

- Air temperature;
- Relative humidity;
- Pavement temperature;
- Water temperature in the pan at the top and bottom;
- Water depth on the pavement sample; and
- Water depth in the pan.

The time required to complete all readings was approximately 2 min, and these measurements were repeated periodically throughout the drying interval for each test (typically, at 5-min intervals). The pavement was considered dry when it returned to its original color. The color change upon drying was quite visible and marked the end point of each test.

The testing procedure for secondary variables was similar to that described above except for the composition of the test water. The deicing chemical tests used an NaCl solution in 10,000-ppm concentration in place of tap water. Similarly, acid rainwater was made up using a USEPA standard which was applied by spray bottle to the pavement surface. An oil film was applied by spraying WD-40 onto the wetted pavement. In each test of secondary factors, measurements of water depth were taken on the pavement and in the pan as described previously for the primary factors.

b. Experiment design: The pavement drying time experiment consisted of two components -- a primary experiment that evaluated the influence of environmental factors and pavement type and a secondary experiment that evaluated the effect of pavement surface contaminants.

(1) Primary drying time experiment: Table 21 identifies the independent variables included in the primary drying time experiment and the levels of each variable that were evaluated. The 10 pavement surfaces evaluated in the primary drying time experiment included both field samples of actual asphalt pavement surfaces and portland cement concrete surfaces made in the laboratory. The characteristics of these 10 pavement surfaces are summarized in Table 22. Pavement Surfaces 9 and 10 in Table 22 are the same as Pavement Surfaces 5 and 4, respectively, that were used in the laboratory friction testing program (see Appendix A).

TABLE 21

INDEPENDENT VARIABLES AND LEVELS INCLUDED IN PRIMARY DRYING TIME EXPERIMENT

Variable	No. of Levels	Description of Levels
Temperature	3	60, 75, and 90°F
Relative humidity	3	60, 75, and 90 percent
Solar radiation	3	Night or overcast, partly cloudy day, bright day (0, 0.75, and 1.15 ly/min)
Wind speed	3	0, 8, and 15 mi/h
Pavement type	10	See Table 22

Each of the primary environmental variables identified in Table 21 -- temperature, relative humidity, wind speed, and solar radiation -- has three levels that were investigated in the primary experiment. If all possible combinations of these variables were evaluated, 3 by 3 by 3 by 3 = 81 tests would be required for each pavement surface. To reduce the number of tests required to evaluate the environmental variables without sacrificing the ability to draw statistical conclusions concerning their effects, a fractional factorial experiment design was used. Figure 26 illustrates the fractional factorial design, known as a Graeco-Latin Square, that was selected for the primary drying time experiment. This design requires nine specific combinations of test conditions to be evaluated for each pavement surface, or a total of 90 drying time tests. Two or three of the nine test conditions were replicated for each pavement surface, so the total number of tests performed was approximately 115.

The Graeco-Latin Square design is capable of evaluating the main effects of all five design variables (temperature, relative humidity, wind speed, solar radiation, and pavement type). None of the two-way or higher-order interactions of the environmental variables can be evaluated in this primary experiment, but this disadvantage is offset by the reduction in the required sample size.

The dependent variable in the primary experiment is the pavement drying time, defined as the time required for the pavement condition to change from thoroughly wet (saturated) to completely dry. Drying of the pavement surface involves a highly visible color change which was easily observed.

TABLE 22

CHARACTERISTICS OF PAVEMENT SURFACES USED IN DRYING TIME EXPERIMENTS

Pavement Surface No.	Description	Sand Patch Texture Depth (in.)	Mean British Portable No.
1	Artificial PCC surface with Iowa sand aggregate approximately 16- to 30-mesh size	0.010	70
2	Artificial PCC surface with light brooming	0.027	84
3	Real coarse-graded bituminous mix with 1-in. maximum aggregate size	0.034	79
4	Real AC wearing course with 1/2-in. maximum aggregate size	0.037	84
5	Artificial PCC surface with heavy broom finish	0.080	91
6	Real AC wearing course -- well worn	0.025	74
7	Real AC wearing course with 3/8-in. maximum aggregate size	0.031	75
8	Real AC surface similar to Pavement Surface No. 3 with white paint stripe	0.041	78
9	Real AC wearing course with 3/8-in. maximum aggregate size -- more worn than Sample No. 7	0.022	76
10	Real open-graded AC friction course with 3/8-in. maximum aggregate size	0.048	81

Note: Pavement Nos. 9 and 10 were also used in friction testing.

	Temperature Level	Relative Humidity Level	Solar Radiation Level	Wind Speed Level
1	60 ° F	60 %	Night	0 mph
2	75 ° F	60 %	Cloudy Day	8 mph
3	90 ° F	60 %	Clear Day	15 mph
4	60 ° F	75 %	Cloudy Day	15 mph
5	75 ° F	75 %	Clear Day	0 mph
6	90 ° F	75 %	Night	8 mph
7	60 ° F	90 %	Clear Day	8 mph
8	75 ° F	90 %	Night	15 mph
9	90 ° F	90 %	Cloudy Day	0 mph

Note: Each factor shown has 3 levels. Entire set of 9 tests is repeated for each of 10 pavement types.

Figure 26 - Graeco-Latin Square Design for Primary Pavement Drying Time Experiment

The initial results obtained from the primary drying time experiment suggested the need for additional drying time data including relative humidities as low as 40 percent, wind speeds as low as 1.5 mi/h (2.4 km/h), and increased sample sizes for each temperature level considered. Therefore, 15 additional pavement drying tests were conducted and added to the results of the 115 drying tests already conducted. The analysis of the primary drying time experiment was repeated with this augmented data set.

(2) Secondary drying time experiment: The secondary experiment involved an evaluation of the effect of three pavement surface contaminants -- deicing salt, acid rain, and oil -- on pavement drying. The secondary experiment involved paired comparisons between the results of selected tests from the primary experiment and tests under identical conditions with pavement surface contaminants present. Two sets of paired tests were performed; the conditions selected for these tests were those labeled as Test No. 5 in Figure 26 -- 75°F, 75 percent relative humidity, clear day, and no wind -- and these tests were conducted for Pavement Surfaces 2 and 3.

c. Data analysis: This section describes the data analysis for the primary and secondary drying time experiments.

(1) Primary drying time experiment: Three types of analysis were performed with the data for the primary drying time experiment. These included: (1) analysis of variance based on the Graeco-Latin Square experiment design; (2) analysis of correlations between evaporation rates from the pavement surface and from the evaporation pan in the environmental chamber; and (3) fitting the data to an established evaporation model, such as the Meyer and Van Bavel equations. The analysis of variance approach proved to be most successful and is emphasized in the following discussion.

Analysis of variance: An initial analysis of variance was performed to evaluate the effect on pavement drying time of pavement type and four environmental factors: temperature (three levels); relative humidity (three levels; solar radiation (three levels); and wind speed (three levels). The results of this initial analysis indicated that:

- Solar radiation and wind speed have the strongest effects on pavement drying time. Higher levels of solar radiation and wind speed both produce faster pavement drying times.

- There was no difference in the effects of 8-mi/h (13-km/h) and 15-mi/h (24-km/h) wind speeds on pavement drying time. Both speeds produced much faster pavement drying times than the no wind condition.

- The influence on pavement drying time of relative humidity and air temperature are statistically significant but are not as strong as the solar radiation and wind speed effects. Pavement drying time increases with increasing relative humidity. However, surprisingly, pavement drying time was also found to increase with increasing air temperature (this concern was resolved through additional testing described in the next page).

- There was no difference in the effects of 60 and 75 percent relative humidities on pavement drying time. Both of these levels of relative humidity produced faster pavement drying times than the 90 percent relative humidity level.

- Portland cement concrete pavements dried faster, on the average, than asphalt pavements. However, there was no discernible influence of pavement color or texture on the pavement drying results.

Several decisions concerning the direction of the analysis were reached on the basis of these results. First, the 8-mi/h (13-km/h) and 15-mi/h (24-km/h) levels of wind speed were combined into a single level. Second, the only pavement effect considered was the difference between PCC and asphalt pavements. Table 23 presents an analysis of variance that illustrates the contribution of each of the factors to variations in pavement drying time with the two changes described above.

TABLE 23

ANALYSIS OF VARIANCE OF PAVEMENT DRYING TIME FOR FOUR ENVIRONMENTAL FACTORS

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	Significant at 95 percent Confidence Level
Temperature	2	2,821.5	1,411	17.94	YES
Relative humidity	2	2,971.9	1,486	18.90	YES
Solar radiation	2	13,864.0	6,932	86.16	YES
Wind speed	1	10,749.3	10,749	136.70	YES
Pavement type	1	1,134.0	1,134	14.42	YES
MODEL	8	31,540.8	3,942	50.14	YES
RESIDUAL	81	6,369.3	78.6		$R^2 = 0.83$
TOTAL	89	37,910.1			

Next, it was decided to perform additional drying time tests at very low (2 mi/h or 3 km/h) wind speeds to determine if the primary influence of wind on pavement drying time was the difference between the presence or absence of wind. Additional data were also collected for relative humidity levels from 40 to 50 percent to determine if the pavement drying times for very low relative humidity would be even faster than at the 60 to 75 percent level. Finally, there was concern that the observed increase of pavement drying time with increasing air temperature was counterintuitive. Therefore, additional laboratory pavement drying time data were collected for air temperatures of 60, 75, and 90°F (16°, 24°, and 32°C).

The results of these additional tests were much as expected. For example, there was a statistically significant difference in pavement drying time between wind speeds of 0 and 2 mi/h (0 and 3 km/h). Thus, pavement drying times are relatively long under completely still (no wind) conditions but decrease markedly with even with wind speeds as low as 2 mi/h (3 km/h). It is clear that even the smallest wind movement has a dramatic impact in reducing pavement drying times. Therefore, the wind speed factor was formulated with only two levels:

- No wind (1 mi/h or less)
- Wind present (2 mi/h or more)

Relative humidities in the 40 to 50 percent range resulted in faster pavement drying times than relative humidities in the 60 to 75 percent range which were, in turn, faster than pavement drying times for 90 percent relative humidity. The relative humidity factor was, therefore, formulated with three levels.

The additional data showed that pavement drying time did, in fact, decrease with increasing air temperature. All three temperature levels (60°, 75°, and 90°F) were found to have distinct effects on pavement drying time.

The results of the analysis of variance presented in Table 23 were adjusted based on the results of the additional drying time tests described above. Table 24 presents estimates of mean pavement drying time, based on these adjustments, for the levels of each statistically significant factor in the model. The table also shows the deviation of the mean drying time for each level from the overall mean drying time of 31.6 min. These deviations constitute parameter estimates for a pavement drying time model. For example, the expected drying time for an asphalt pavement on a cloudy day with a temperature of 75°F (24°C), a 75 percent relative humidity, and a wind speed of 5 mi/h (8 km/h) would be:

$$31.6 - 0.7 - 1.5 + 5.6 - 11.6 + 3.9 = 27.2 \text{ min}$$

The model presented in Table 24 can be used in this fashion to estimate the pavement drying time for any combination of air temperature, relative humidity, solar radiation, wind speed, and pavement type.

The only problem evident with the pavement drying model presented in Table 24 is that some cases for a clear day with wind speeds of 2 mi/h (3 km/h) or more can result in pavement drying times less than zero. The model appears to overcompensate for the combined effects of these two factors either of which alone is enough to substantially reduce pavement drying time. Unfortunately, the Graeco-Latin Square design used for this experiment does not have the capability to evaluate the solar radiation-wind speed interaction explicitly. Therefore, it was decided to consider only the solar radiation effect (-17.2 min) and not the wind speed effect (-11.6 min) when both of these effects are at their largest negative values. With this modification, the minimum pavement drying time predicted by the model is 3 min, which compares reasonably well with the minimum pavement drying time of 7 min observed in the laboratory data.

TABLE 24

PARAMETER ESTIMATES FOR PAVEMENT DRYING TIME MODEL

Factor	Level	Mean Drying Time[a] (min)	Deviation From Overall Mean Drying Time[b] (min)
Temperature	Below 67.5°F	35.3	+3.7
	67.5°-82.5°F	30.9	-0.7
	Above 82.5°F	28.6	-3.0
Relative humidity	Below 50%	27.1	-4.5
	50-82.5%	30.0	-1.6
	Above 82.5%	37.7	+6.1
Solar radiation	Night or overcast	43.2	+11.6
	Partly cloudy day	37.2	+5.6
	Clear day	14.4	-17.2
Wind speed	No wind	43.2	+11.6[c]
	Wind present	20.0	-11.6[c]
Pavement type	Asphalt concrete	35.5	+3.9
	Portland cement concrete	27.7	-3.9

[a] The mean drying times represent the effects of each factor taken one at a time, independent of the values of the other factors.
[b] Deviation from overall mean drying time of 31.6 min.
[c] Use this parameter estimate only if the parameter estimate for the solar radiation factor has a positive value.

Table 25 presents the pavement drying times predicted by the model for each combination of the five reactors: air temperature, relative humidity, solar radiation, wind speed, and pavement type.

Correlations between pavement and pan evaporation rates: Another approach to the prediction of pavement drying time was to develop a relationship between the observed evaporation rates from pavement surfaces and evaporation rates from a standard Class A evaporation pan. Such a relationship would be of value in the prediction of pavement drying time, because pan evaporation rates have been measured and tabulated for many locations throughout the United States.

Figure 27 illustrates an actual evaporation curve from the laboratory for a thin waterfilm on a pavement surface. The evaporation curve displays a characteristic negative exponential shape as the thickness of the waterfilm remaining on the pavement surface decreases with time. Although the pavement sample in question required 46 min to dry, nearly 90 percent of the water evaporated from the pavement surface within the first 25 min. If minimum level of wetness that results in a substantial reduction of pavement friction is as large as 0.002 in. (0.05 mm), evaporation curves such as that shown in Figure 27, could be used to adjust the pavement drying time accordingly.

The evaporation curve for the pavement surface in Figure 27 represents a total evaporation of 0.0184 in. (0.467 mm) of water in 46 min or 0.024 in/hr (0.61 mm/hr). A correlation analysis was conducted to examine the relationship between such pavement evaporation rates and the pan evaporation rates observed during the same period. Virtually no correlation was found. The correlation coefficient for the entire data set was very small ($r = 0.001$) and was not statistically significant. The lack of similarity between the pavement and pan evaporation rates was found throughout the data set. Evaporation rates from paved surfaces were much greater than from the evaporation pan. The ratio of pavement and pan evaporation rates varied considerably, although, on the average, the evaporation rate from a pavement surface was three times the pan evaporation rate. This finding is important to the research because it indicates that evaporation of a thin waterfilm from a pavement surface is a different phenomenon from evaporation from the free water surface of an evaporation pan and that pavement surface evaporation rates cannot be predicted from pan evaporation rates.

Evaporation models: Repeated attempts were made to fit one of the theoretical evaporation models, such as the Meyer and Van Bavel equations (Equations 21 and 23) to the evaporation of water from a pavement surface. No satisfactory model was obtained, which is a further indication that modeling approaches suitable for evaporation from the free water surfaces of evaporation pans or larger bodies of water are not suitable for modeling evaporation of thin waterfilms from pavement surfaces.

(2) Secondary drying time experiment: The secondary drying time experiment considered the effects of pavement surface contaminants -- deicing salt (NaCl), acid rainfall, and oil -- on pavement drying time. The results of the secondary drying time experiment are tabulated in Table 26 in comparison to the expected values for uncontaminated water from the primary drying time experiment.

TABLE 25

PREDICTED VALUES OF PAVEMENT DRYING TIME

Pavement Type/ Solar Radiation/ Wind Speed	Temperature (°F)	Relative Humidity (%) Below 50	50-82.5	Above 82.5
Asphalt pavement/ nighttime/ no wind	Below 67.5	57.9	60.8	68.5
	67.5-82.5	53.5	56.4	64.1
	Above 82.5	51.2	54.1	61.8
Asphalt pavement/ nighttime/ wind present	Below 67.5	34.7	37.6	45.3
	67.5-82.5	30.3	33.2	40.9
	Above 82.5	28.0	30.9	38.6
Asphalt pavement/ cloudy day/ no wind	Below 67.5	51.9	54.8	62.5
	67.5-82.5	47.5	50.4	58.1
	Above 82.5	45.2	48.1	55.8
Asphalt pavement/ cloudy day/ wind present	Below 67.5	28.7	31.6	39.3
	67.5-82.5	24.3	27.2	34.9
	Above 82.5	22.0	24.9	32.6
Asphalt pavement/ bright day/ no wind	Below 67.5	29.1	32.0	39.7
	67.5-82.5	24.7	27.6	35.3
	Above 82.5	22.4	25.3	33.0
Asphalt pavement/ bright day/ wind present	Below 67.5	17.5	20.4	28.1
	67.5-82.5	13.1	16.0	23.7
	Above 82.5	10.8	13.7	21.4
PCC pavement/ nighttime/ no wind	Below 67.5	50.1	53.0	60.7
	67.5-82.5	45.7	48.6	56.3
	Above 82.5	43.4	46.3	54.0
PCC pavement/ nighttime/ wind present	Below 67.5	26.9	29.8	37.5
	67.5-82.5	22.5	25.4	33.1
	Above 82.5	20.2	23.1	30.8
PCC pavement/ cloudy day/ no wind	Below 67.5	44.1	47.0	54.7
	67.5-82.5	39.7	42.6	50.3
	Above 82.5	37.4	40.3	48.0
PCC pavement/ cloudy day/ wind present	Below 67.5	20.9	23.8	31.5
	67.5-82.5	16.5	19.4	27.1
	Above 82.5	14.2	17.1	24.8
PCC pavement/ bright day/ no wind	Below 67.5	21.3	24.2	31.9
	67.5-82.5	16.9	19.8	27.5
	Above 82.5	14.6	17.5	25.2
PCC pavement/ bright day/ wind present	Below 67.5	9.7	12.6	20.3
	67.5-82.5	5.3	8.2	15.9
	Above 82.5	3.0	5.9	13.6

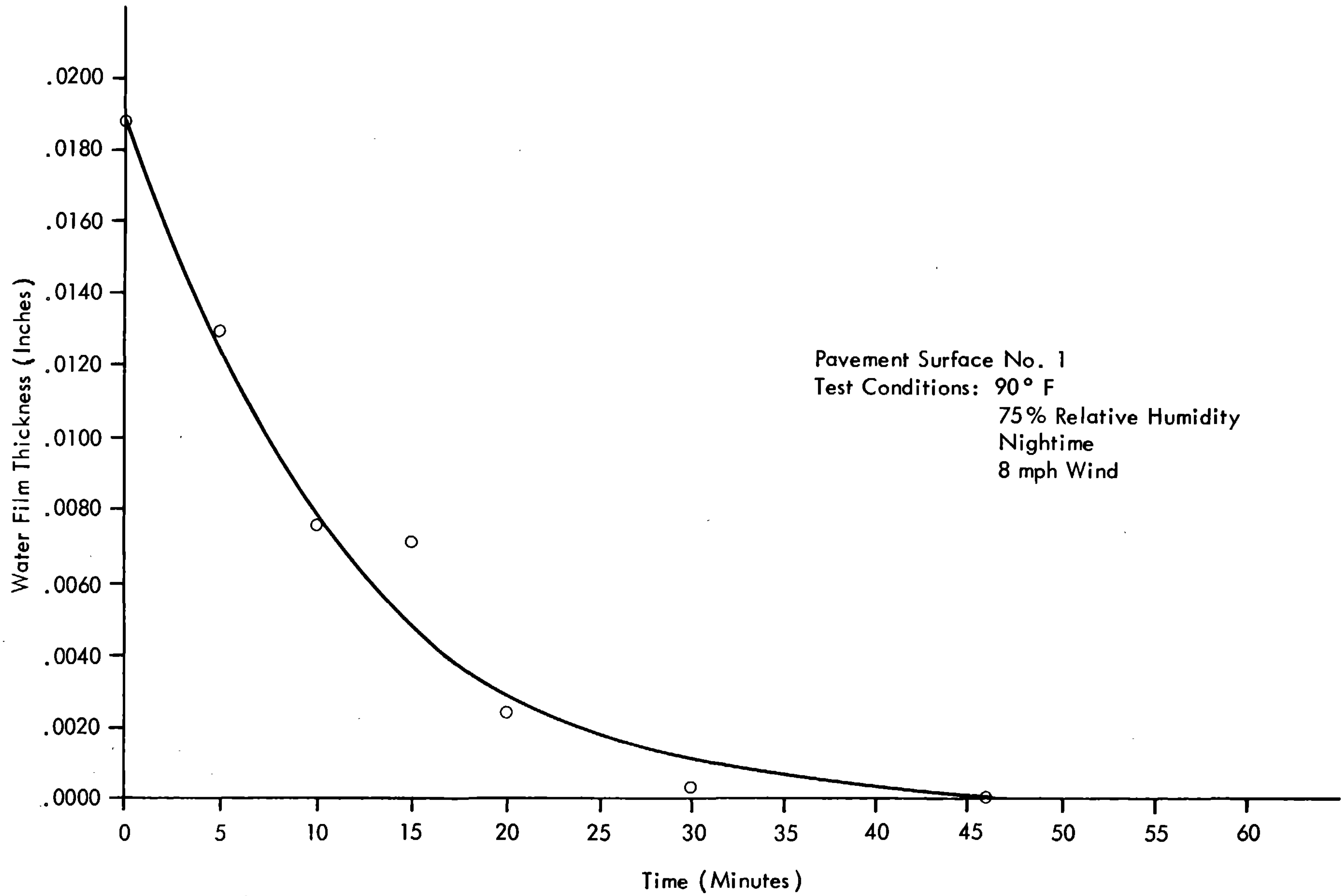


Figure 27 - Typical Laboratory Results Showing Reduction of Waterfilm Thickness Over Time Due to Evaporation from a Pavement Surface

TABLE 26

PAVEMENT DRYING TIME DATA WITH PAVEMENT SURFACE CONTAMINANTS PRESENT

Test Conditions: 75°F
75 percent relative humidity
Clear day (solar radiation = 1.15 langleys/min)

Pavement Surface No.	Contaminant Present	Pavement Drying Time (min)
2	None	14.6
	Salt	15
	Acid rain	15
	Oil	25
3	None	32
	Salt	35
	Acid rain	35
	Oil	30

The two pavement surfaces used in the test draw an interesting contrast, because Pavement Surface 2 was the surface which dried most quickly in the primary experiment and Pavement Surface 3 was the surface that dried most slowly. The data in Table 26 do not indicate a large effect of pavement surface contaminants on pavement drying time, except for the possible effect of oil which lengthened the drying time from 14.6 to 25 min on Pavement Surface 2, a surface which would otherwise dry very quickly. No comparable effect of oil on Pavement Surface 3 was observed. The observed effects of deicing salt and acid rain were negligible.

3. Field Testing Program

A series of field tests was conducted to validate the pavement drying model under actual field conditions and to determine whether the action of traffic passages under actual highway conditions would decrease drying times from those predicted by the model.

a. Experimental plan: Outdoor drying time tests were conducted without the action of traffic at the PTI Test Track in State College, Pennsylvania. These tests involved both pavements that were artificially wetted and pavements wetted by rain. Observational studies were also conducted at actual highway sites with traffic present near State College following rainfall.

During each test, instrumentation was used to monitor air temperature, relative humidity, and wind speed. Solar radiation was estimated based on time of day and cloud cover. A traffic count during the drying period was made at the actual highway sites. Limited field observations of highway and parking lot pavements were also made in Kansas City, Missouri, without the environmental instrumentation.

The data collection effort for the outdoor drying time tests was organized in three stages. The first stage was a series of 15 dry weather tests conducted at four sites: PTI Test Track, State College Bypass at Old Fort, Pennsylvania Route 45 at Old Fort, and U.S. 322 near the Elk's Club. In each of the dry weather tests water was artificially applied to the pavement surface and the subsequent drying of the pavement surface was observed. The second stage of the field testing program consisted of 15 wet weather tests conducted at three sites: State College Bypass at Old Fort, Pennsylvania Route 45 at Old Fort, and U.S. 322 near the Elk's Club. In each of the wet weather tests pavement drying time was observed following an actual rainfall. The third and final stage consisted of five visual observations on Whitehall Road in College Township, just southwest of State College Borough.

In each of the outdoor tests the following measurements were recorded: air temperature, relative humidity, wind speed, sky cover, traffic count by two-axle and by three-or-more-axle vehicles, number of lanes, initial waterfilm thickness, drying time in wheel path, and drying time for the entire pavement. The initial waterfilm thickness was measured with the NASA gauge and averaged approximately 0.05 in. (1.27 mm) in the wet weather tests.

b. Data analysis: The results of the field studies indicated that the pavement drying model presented in Tables 24 and 25 provides reasonable estimates of pavement drying time under a variety of conditions. A comparison of observed and predicted drying times from the test track and highway tests is presented in Figure 28. The closer a point lies to the diagonal line in the figure, the better the agreement between the observed and predicted values. Based on a review of Figure 28, it was decided that the pavement drying model in Tables 24 and 25 should be incorporated in the WETTIME model.

The effect of traffic passages on drying time could not be determined in a controlled experiment because both traffic volumes and environmental conditions varied from test to test. However, there was no tendency for observed drying times to be substantially shorter than predicted drying times which could represent the effect of traffic passages in speeding drying. The field observations indicated that traffic passages tend to dry the normal wheelpaths in approximately 75 percent of the time required for the remainder of the pavement to dry. While traffic normally operates within those well-defined wheelpaths, a vehicle in an emergency maneuver could require friction at any point on the pavement surface. The field observations indicated that the pavement drying model was a good predictor of the time required for the entire pavement surface to dry.

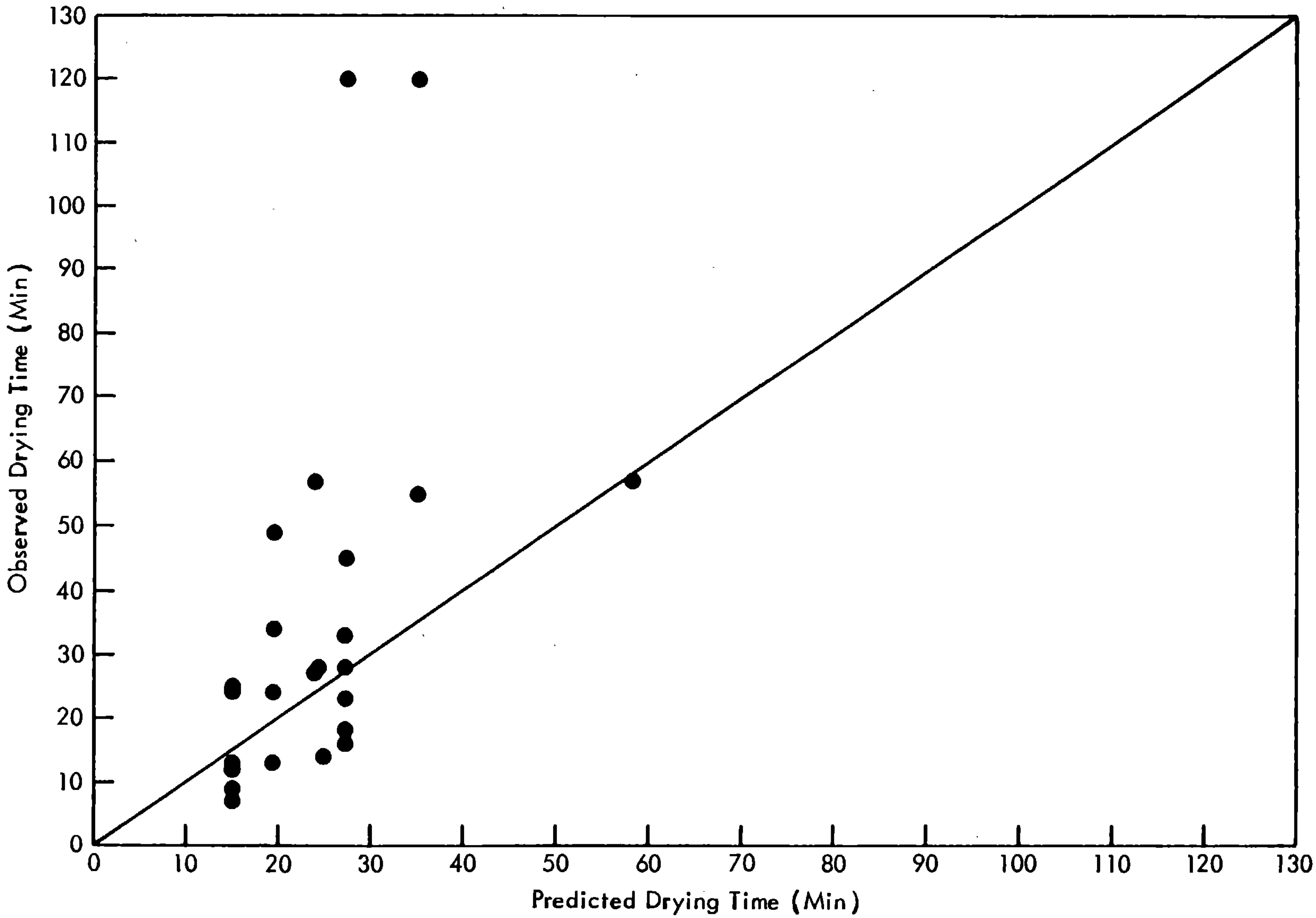


Figure 28 - Comparison of Pavement Drying Times Observed in Field Test With Drying Times Predicted by Model

Rather than very short drying times, a few field observations indicated drying times substantially longer than those predicted by the model. This was particularly evident in the tests conducted on Whitehall Road in State College where no pavement drying was observed under high relative humidity conditions. A quantitative definition of the circumstances under which pavement drying could not begin due to nearly saturated conditions was developed and incorporated in the WETTIME model.

The field drying time results confirmed several of the key findings of the laboratory testing program including the findings that (1) pavements dry faster at low relative humidities, (2) pavements dry faster at high temperatures, and (3) portland cement concrete pavement surfaces dry faster than asphalt pavement surfaces.

c. Interpretation of results: The field drying time tests indicate that the model presented in Tables 24 and 25 is a reasonably reliable method for predicting pavement drying time. Therefore, this method of predicting pavement drying time was incorporated in the WETTIME model.

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