Estimation of Wet Pavement Exposure from Available Weather Records

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The estimation of wet pavement exposure is critical to the effective management of programs aimed at reducing wet pavement accidents. Without a measure of wet pavement exposure, highway safety engineers cannot tell whether differences in wet pavement accident frequencies between sites or over time represent actual safety problems or merely result from site-to-site or year-to-year variations in rainfall frequency. Laboratory and field tests were conducted to investigate two key aspects of wet pavement exposure estimation: (a) the conditions under which pavement wetness reduces pavement surface friction and (b) the time required for pavements to dry after rainfall. The results of these tests were used to develop an improved method of estimating wet pavement exposure from available weather records. This method has been incorporated into a computer model, known as the WETTIME model, for application by highway agencies. The model estimates the number of hours with wet pavement conditions on monthly and annual bases.

Wet weather accidents are an important element of the safety problem on U.S. highways. Recent research has found that approximately 13.5 percent of fatal accidents (*1*) and as many as 25 percent of all accidents (*2*) may 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 allow traffic engineers to assess the overall priority that should be assigned to wet weather accidents in highway safety programs and to provide a reliable means of comparison for wet weather accident rates of highways located in different climatological regions. This paper presents a method for estimating wet pavement exposure from available weather records.

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:

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

where

R = accident rate (accidents/10^6 vehicle-miles);
A = number of accidents; and
E = exposure (10^6 vehicle-miles).

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:

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

where

R_w = wet pavement accident rate (accidents/10^6 vehicle-miles);
A_w = number of wet pavement accidents; and
E_w = wet pavement exposure (vehicle-miles).

Wet pavement accidents are defined by the road surface condition at the time of the accident as recorded by police officers, motorists, or both on the accident report form. The categories used for road surface condition on accident report forms are typically (a) dry, (b) wet, and (c) ice and snow. Wet pavement accidents are those that 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-miles 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.

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NEED FOR WET PAVEMENT EXPOSURE ESTIMATES

Most highway agencies currently have a program for identifying and treating locations with large numbers of wet pavement accidents, 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 to increase tire-pavement friction (such as pavement resurfacing) and improvement projects to reduce the need for tire-pavement friction (such as realignment or other geometric modifications).

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) that moves along the highway in 0.01-mi increments. For example, a 0.3-mi highway section might be classified as a high-accident section if it had either a wet pavement accident rate at least 20 percent higher than the average wet pavement accident rate or more than five wet pavement accidents per year.

A review of wet pavement accident surveillance programs by the National Transportation Safety Board (NTSB) (*1*) 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/10^6 vehicle-miles);
A_w = number of wet pavement accidents; and
E_w = total exposure under all pavement conditions (vehicle-miles).

This hybrid measure (R'_w) has been used both in state accident surveillance systems and in past wet pavement accident research. 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 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. Thus wet pavement exposure estimates are also needed to account for year-to-year changes in climate.

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, which are 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.) occurred. The hourly precipitation data are available for thousands of stations throughout the United States but are generally complete and reliable only for first-order weather stations, which are typically located at major airports (*3*).

Most previous attempts to estimate wet pavement exposure have been based solely on the hourly precipitation data. However, there are other forms of weather records available on an hourly basis that provide a valuable supplement to the hourly precipitation amounts. These are the hourly surface observations that are available on computer tape from NCDC. These data are also available for first-order weather stations and include hourly data on

- Air temperature;
- Dew point temperature;
- Relative humidity;
- Wind speed;
- Cloud cover; and
- Occurrence of rain, snow, or fog.

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

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 for estimation of wet pavement exposure. Some climatic regions commonly experience cloudbursts, in which large amounts of rain fall in a very short time period. Other regions experience drizzle, in which 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 (*4*) defined wet pavement exposure as the total number of hours during which a measurable amount (0.01 in. 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. A similar definition of wet pavement exposure has been used in studies by NTSB (*1*) and by the states of Arizona (*5*) and Michigan (*6*).

An alternative wet pavement exposure estimation technique was developed by Midwest Research Institute (MRI) in the late

1970s. The MRI method was developed in NCHRP Project 6-11, "Economic Evaluation of the Effects of Ice and Frost on Bridge Decks" (7). The method was further refined by MRI in the 1978 FHWA study "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 during which 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./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 with wet pavement exposure data from a moisture sensor implanted in an Interstate highway bridge near Iowa City, Iowa.

One major weakness of the California/NTSB approach is that it makes no distinction between frozen and nonfrozen 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 the nationwide application attempted by NTSB (*1*).

The original MRI model attempted to account for many of the weaknesses described above but did so imperfectly because of the lack of research into the role of these factors in pavement wetness. The MRI model was more complex than the California/NTSB model because it considered both NCDC's hourly precipitation data and data on the type of precipitation, also available from NCDC.

Each of these previous attempts to estimate wet pavement exposure had limitations resulting from the lack of valid research findings concerning the role of key meteorological and pavement factors in wet pavement exposure. These limitations have been addressed in the development of a new wet pavement exposure estimation model, known as the WETTIME model.

MODEL SCOPE

The WETTIME model examines precipitation and weather data on an hour-by-hour basis and classifies all or portions of each hour as DRY time, WET time, or ICE and SNOW time. Monthly and annual totals of the number of hours of exposure to each type of pavement surface condition are obtained.

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 on the strengths of both the California/NTSB model (*1, 4*) and the original MRI model (*2, 7*) and correct the weaknesses of these models 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 cannot be used alone for this purpose because these data do not distinguish frozen from nonfrozen precipitation. The most readily available data source in which this distinction can be made is the NCDC hourly surface observations. As mentioned earlier, 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 4 to 10 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 later in this paper.

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; and
- Estimation of exposure to ice and snow conditions.

Each element of the model is discussed in this section.

Minimum 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. 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 water film thickness was undertaken as part of the development of the WETTIME model. The relationship between pavement friction and water film thickness for thin water films has been investigated by a number of researchers including Besse (*8*), Giles (*9*), Gegenbach (*10*), Veith (*11*), Pelloli (*12*), Williams and Evans (*13*), and Rose and Gallaway (*14*). These sources do not provide a satisfactory relationship between pavement friction and water film thickness; several of the sources suggest that this relationship may have a negative exponential form at speeds above 25 mph, but no relationship was found at lower speeds.

Because no satisfactory relationship was found in the literature, laboratory and field studies were undertaken to determine the minimum level of wetness that substantially reduces pavement surface friction. The results of these studies, which have been reported by Harwood et al. (*3*) and Kulakowski et al. (*15*), suggest that as little as 0.001 in. of water on a pavement surface can, in some cases, reduce the friction coefficient 75 percent of the way from the dry friction to the wet friction value. This minimum level of wetness is likely to be exceeded during any hour in which there is at least 0.01 in. of rainfall. 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.

Rainfall Intensity and Duration

Existing wet pavement exposure models make no distinction between hours of precipitation based on rainfall intensity or duration. These models operate under the assumption that the pavement was wet for the entire hour during any hour in which at least 0.01 in. of precipitation fell. This is unrealistic because it would be expected that, on the average, the more rain that falls during an hour, the longer the rainfall would last; however, no data were previously available to quantify this phenomenon.

To determine the relationship between rainfall amounts and rainfall duration, Harwood et al. (*3*) obtained and analyzed the U.S. Geological Survey (USGS) urban stormwater data base (*16*). This data base contains rainfall amounts by 5-min periods for 717 selected periods of rainfall at 99 stations located in 22 metropolitan areas throughout the United States. Table 1, which is based on the USGS data from Florida, Maryland, Missouri, and Washington, presents the relationship that was developed. The duration of rainfall in Table 1 extends from the first 5-min period in which rain fell to the last 5-min period in which rain fell during a particular hour. Thus the duration could include short periods during which the rain ceased, but it is likely that the pavement would remain wet during such periods. The relationship in Table 1, which has been incorporated in the WETTIME model, indicates that the duration of rainfall increases with the hourly rainfall amount up to 0.05 in. of rainfall in 1 hour. Above that level, pavement wetness due to rainfall typically lasts for the entire hour.

TABLE 1 VARIATION IN DURATION OF RAINFALL DURING AN HOUR WITH HOURLY RAINFALL AMOUNT (*3*)

Hourly Rainfall Amount (in.)	Duration of Rainfall in WETTIME Model (min)
0.01	15
0.02	30
0.03	45
0.04	45
0.05 and over	60

Runoff Period After Rainfall

There is a period after 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 the pavement while rain is falling can be determined from the kinematic wave method (*17*) as a function of the rainfall intensity (in inches per hour), the pavement surface texture (represented by the Manning coefficient), the length of the drainage path, and the slope of the pavement surface. Estimates of runoff time calculated for typical ranges of values of these parameters indicated that runoff time is usually less than 10 min and is often 5 min or less. Although the kinematic wave approach is not directly applicable to a period after the rain has stopped, 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.

On the basis of the available data, it was found that typical runoff times after 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, a uniform runoff time of 5 min after the end of rainfall was incorporated in the WETTIME model.

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 laboratory and field studies of pavement drying time were undertaken as part of the development of the WETTIME model.

The laboratory study of pavement drying time was conducted in an 8 × 8 × 8–ft chamber constructed so that environmental conditions could be controlled. Air temperature was controlled by a heater and an air conditioner, and 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.

A Class A evaporation pan filled with water was placed in the chamber. Various asphalt and portland cement concrete (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 thickness of the film of water on the pavement surface was monitored with a micrometer depth gauge at 5-min intervals during the drying period, 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 were as follows:

Solar Radiation

Nighttime or overcast (0 Langleys/min);
Partly cloudy day (0.75 Langleys/min); and
Bright, cloudless day (1.15 Langleys/min).

Wind Speed

No wind (0 mph);
2 mph;

8 mph; and
15 mph.

Air Temperature

60°F;
75°F; and
90°F.

Relative Humidity

45 percent;
60 percent;
75 percent; and
90 percent.

Pavement Type

Asphalt concrete; and
Portland cement concrete (PCC).

The pavement drying tests were conducted in accordance with an experimental design based on a Greco-Latin square that 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. In all, 132 pavement drying tests were conducted.

The test data were analyzed, and a predictive model for pavement drying time was developed (*3*). This model is presented in Table 2, which shows the deviation from the mean drying time of 31.6 min for each level of each factor. The expected drying time for a particular combination of factors can be determined from the table; for example, the expected drying time for an asphalt pavement on a partly cloudy day with an air temperature of 75°F, 75 percent relative humidity, and wind speed of 5 mph would be

$$31.6 - 0.7 - 1.6 + 5.6 - 11.6 + 3.9 = 27.2 \text{ min.}$$

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 on 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 mph or more were enough to cause 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 important 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 2 PARAMETER ESTIMATES FOR PAVEMENT DRYING TIME MODEL (*3*)

Factor	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 percent	27.1	− 4.5
50–82.5 percent	30.0	− 1.6
Above 82.5 percent	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
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.

Field tests were conducted to verify the predictive ability of the pavement drying time model in Table 2. These tests included drying time observations for artificially wetted pavements and after actual rainstorms. The model was found to provide realistic estimates of pavement drying time except in a few cases. In these instances, observed drying times were much longer than the predicted times. This phenomenon was probably due to nearly saturated atmospheric conditions that inhibited evaporation from the pavement surface. As a result, a feature was added to the WETTIME model to delay the beginning of pavement drying when the dew point temperature was within 2°F of the ambient air temperature.

Pavement Wetness Due to Fog

The WETTIME model includes consideration of pavement wetness due to fog. In some situations, a pavement can become wet merely due 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 earlier; that is, pavement wetness due to fog occurs only when the NCDC hourly weather observation data indicate that fog was observed and that the dew point temperature is within 2°F of the ambient air temperature.

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WET-PAVEMENT EXPOSURE ESTIMATE                                PAVEMENT TYPE: 1
REVISED MRI RULE                                              ASPHALT CONCRETE
STATION:    KANSAS CITY MO
YEAR:       1984
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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 1 Sample output from the WETTIME model: wet pavement exposure for Kansas City, Missouri, in 1984.

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.

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 there is no better information, ice and snow exposure due to frozen precipitation is estimated by the WETTIME model in a manner similar to the estimation of wet pavement exposure.

Model Summary

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 will now be presented. The rationale for each of these rules was explained in the previous section.

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

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

- 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 15 min past the hour and end at 15 min to the next hour.

- For the first hour of 2 or more consecutive hours of precipitation, the duration of wetness is determined as described previously. Whatever the duration of the rainfall period, it is assumed to occur at the end of the hour.
- For the last hour of 2 or more consecutive hours of precipitation, the duration of wetness is also determined as described previously. Whatever the duration of the rainfall period, it is assumed to occur at the beginning of the hour.
- For a middle hour of a period of 3 or more consecutive hours of precipitation, the rainfall is assumed to last for the entire hour.
- The pavement remains wet during a runoff period of 5 min after the end of rainfall.
- 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.
- The start of pavement drying may be delayed if the ambient air is nearly saturated (as indicated by a dew point temperature within 2°F 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 by solar radiation begins shortly after dawn.
- The duration of pavement drying is determined from a statistical model that predicts drying time (presented in Table 2). The factors that 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 PCC). If no pavement type is specified by the user, asphalt concrete is assumed as the default.
- 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 mph;
Wind present: 2 mph and over.
Air Temperature. 67°F or below;
68°–82°F;
83°F or above.
Relative Humidity. 49 percent or below;
50–82 percent;
83 percent or above.

If fog occurs during an hour, the air is nearly saturated (dew point temperature within 2°F of ambient air temperature), and the wind speed is 3 mph or less, then the hour is counted as WET. Pavement drying after a period of fog follows the same rules as it does after a period of nonfrozen precipitation.

If frozen precipitation of 0.01 in. or more occurs during an hour, then the hour is counted as ICE and SNOW. The pavement drying time after a period of frozen precipitation is counted as WET.

MODEL APPLICATION

The application of the WETTIME model is fully explained in the "User's Guide for the WETTIME Exposure Estimation Model" (*18*). This guide includes an explanation of how to obtain the weather data needed to run the model. Figure 1 presents a sample of the printed output obtained from the model. Monthly and annual estimates of the hours of exposure to different pavement surface conditions are presented.

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

TABLE 3 EXPOSURE SUMMARY BY PAVEMENT SURFACE CONDITION FOR 1984 AT SELECTED FIRST-ORDER WEATHER STATIONS

	Percentage of Annual Exposure		
	Wet	Ice and 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, Iowa	8.7	1.9	89.4
Kansas City	8.3	1.2	90.5
Memphis, Tenn.	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, Oreg.	21.9	0.0	78.1
Lewiston, Idaho	5.1	0.5	94.4
Olympia	23.5	0.3	76.2
Portland, Oreg.	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

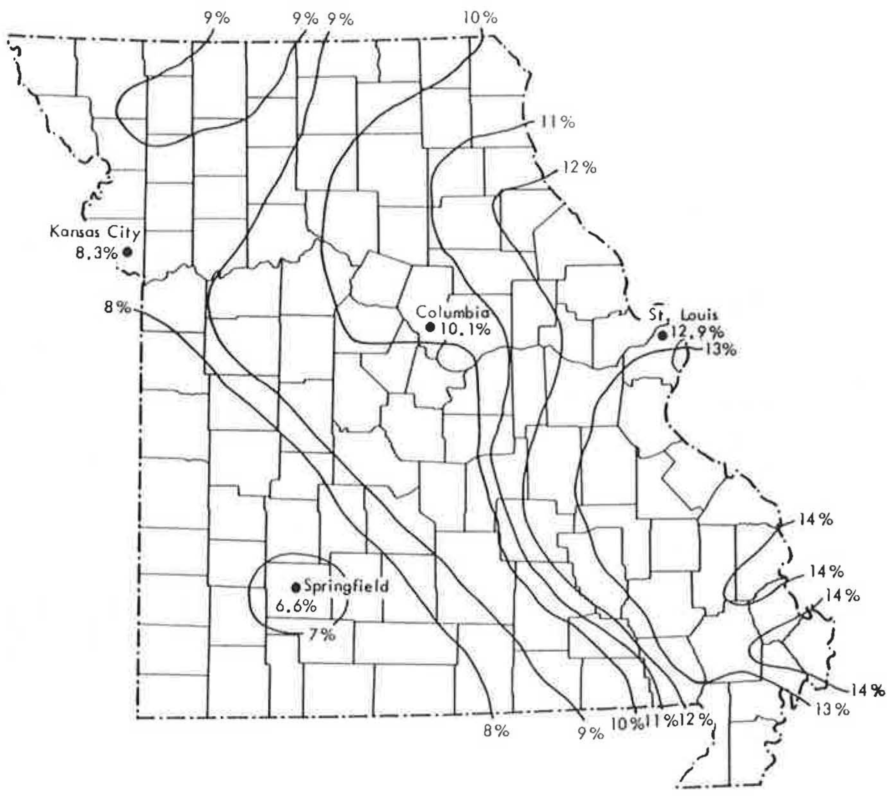

FIGURE 2 Isoexposure contour map for wet pavement exposure in Missouri (*3*).

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 3 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 3 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 4.2 percent in the desert areas of Washington 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. The data in Table 3 apply to highway sections with asphalt pavements; wet pavement exposure for PCC pavements would be slightly lower because they dry more quickly.

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 data needed to apply the WETTIME model are available for only 4 to 10 first-order weather stations in each state. However, a procedure has been developed to use the estimates from the WETTIME model for the first-order stations within a state, together with total annual rainfall patterns, to obtain estimates of wet pavement exposure for minor stations (*3*). With wet pavement exposure estimates for a sufficient number of stations within a state, isoexposure contour maps can be constructed. Figures 2 and 3 present typical isoexposure contour maps for the states of Missouri and Washington, respectively.

Isoexposure contour maps like these could be an important guide to the management of wet pavement accident reduction programs by highway agencies. The maps indicate how widely wet pavement exposure can vary across a state even in a state such as Missouri, which has a relatively homogeneous climate. Even in Missouri, wet pavement accident rates, based on a statewide average for wet pavement exposure, could be high or low by as much as 50 percent.

Seasonal Variations

In general, the total annual vehicle-miles of travel under wet pavement conditions can be determined directly from total travel and the output of the WETTIME model:

$$E_w = E(P_w/100) \quad (4)$$

where

E_w = annual wet pavement exposure (vehicle-miles);
E = total annual exposure (vehicle-miles); and
P_w = annual percentage of hours with wet pavement conditions.

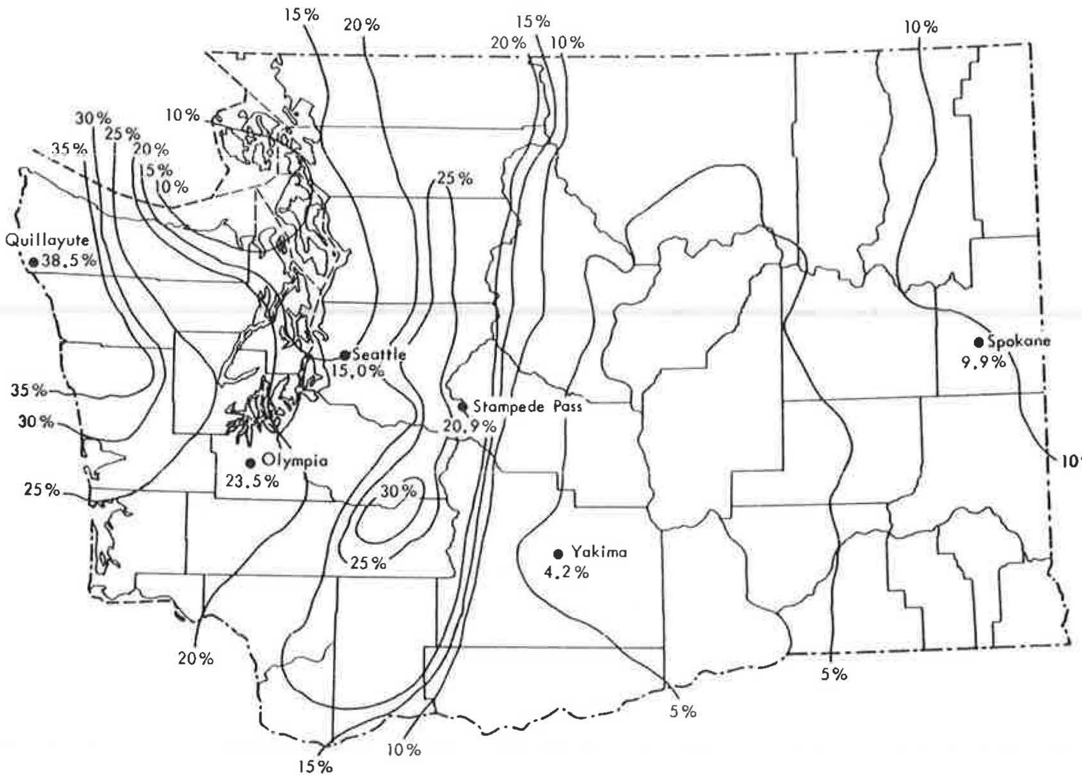

FIGURE 3 Isoexposure contour map for wet pavement exposure in Washington (3).

However, in some regions of the United States, it may be desirable to consider both seasonal variations in wet pavement exposure and seasonal variations in traffic volumes. For example, the California Department of Transportation (4) has observed that their seasonal patterns of rainfall and traffic volume are opposite, with more traffic and less rainfall in the summer months. The month-by-month output of the WETTIME model, as illustrated in Figure 1, can be used as a basis for adjusting the annual wet pavement exposure estimate for monthly variations in travel, in the following manner:

$$P_w = \sum_{i=1}^{12} P_{w_i} \frac{VMT_i}{VMT} \quad (5)$$

where

P_{w_i} = monthly wet pavement exposure percentage in month i;
VMT_i = monthly vehicle-miles of travel in month i; and
VMT = annual vehicle-miles of travel.

However, this method is only recommended for states with particularly large seasonal variations in precipitation patterns or in travel.

SUMMARY AND RECOMMENDATIONS

This paper presents an improved method for estimating wet pavement exposure from available weather records. The method is based on the results of laboratory and field tests that examined the conditions under which pavement wetness reduces friction and the time required for pavements to dry following rainfall. The improved method has been incorporated into a computer program, known as the WETTIME model, for use by highway agencies.

The WETTIME model is recommended as a tool for use in effective management of wet pavement accident reduction programs. Isoexposure contour maps such as those presented in the paper provide a basis for calculation of more accurate wet pavement accident rates for use in accident surveillance. Further research could automate the preparation of isoexposure contour maps and make this information more accessible to highway agencies.

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