Rainfall Estimation for Pavement Analysis and Design

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An integrated model that is being developed under contract to the FHWA combines three different completed environmental effects models: the CMS Model, CRREL Model, and the TAMU ID Model. It will be a comprehensive model that predicts the effects of air temperature, sunshine percentage, wind speed, rainfall, frost, and thawing actions on the performance of pavement. In the course of development, stochastic processes and random methods are employed to analyze past climatological data, and to estimate and predict the effects of the environment on the performance of pavement with specified confidence levels. This paper describes a computerized method that has been developed to generate simulated rainfall patterns for use in pavement analysis and design. The method is both practical and useful because it meets several important criteria. It uses data that are readily available; it predicts realistic rainfall patterns; it permits analysts to select how severe a condition they wish to represent; and it is simple to use. The paper presents the method used to simulate the rainfall patterns; shows how the United States is divided into nine climatic regions and which cities have been selected as representative of those regions; and gives four examples of both the required input data and the resulting simulated rainfall patterns for a 95 percent confidence level. The model also includes the effect of freezing and thawing temperatures on the amount of rainfall that is available to infiltrate the pavement, and this is illustrated in one of the examples.

It is well known that pavement damage is caused mainly by traffic loads, unsuitable materials, and environment. The effects of the first two factors on the performance of pavements can be estimated for design purposes by empirical or mechanistic methods (*1*). However, an estimation of the effects of environmental factors, especially of the effects of rainfall on the performance of pavements, is not adequate.

At present, only the worst conditions are employed in existing design methods. For example, current test procedures still recommend that the modulus of subgrade reaction for rigid pavement design be determined under saturated conditions (*2*), even though the new AASHTO Design Guide (*3*) recommends the testing of materials for actual site conditions, and not for the worst conditions.

An integrated model that is being developed under contract to the FHWA combines three different completed environmental effects models: the CMS Model (*4*), CRREL Model (*5*), and the TAMU ID Model (*6*). It will be a comprehensive model that predicts the effects of air, temperature, sunshine percentage, wind speed, rainfall, frost, and thawing actions on the performance of pavement. In the course of the development, stochastic processes and random methods are employed to analyze past climatological data, and to estimate and predict the effects of the environment on the performance of pavement with specified confidence levels.

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RAINFALL GENERATOR

It is impossible to generate truly random sequences of wet days and amounts of rainfall for estimating future rainfall effects by using a deterministic algorithm. Nevertheless, it is possible to produce by deterministic means sequences of numbers that, to a degree acceptable for predictive purposes, possess the attributes of randomness.

Statistical rainfall data are available from the National Climatic Data Center (*7*). In estimating rainfall amounts and sequences, these statistical data are typically used together with Monte Carlo methods and the simulation of random processes to produce samples automatically from the prescribed statistical distributions of rainfall. This paper describes the use of the uniform type of pseudorandom number and multiplicative congruential theories (*8*) to predict these rainfall patterns.

The form of the generator is

$$X_n = CX_{n-1} (\mathrm{mod}\ M) \tag{1}$$

which means "X_n is congruent to CX_{n-1} modulo M." That is,

$$CX_{n-1} = Q_n M + X_n \tag{2}$$

where Q_n equals a largest integer not exceeding CX_{n-1}/M.

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The congruential relation (1) may be rewritten as a difference equation as follows:

$$X_n = X_0 C^n \pmod{M} \tag{3}$$

where

X_0 = seed,
M = modulus, usually $M = 2^b$,
C = a positive odd integer less than M excluding 1, and
b = the number of bits available in a computer word.

The development of the rainfall generator model includes the following considerations:

1. *Period of the Sequence of Wet Days*. The period of the sequence of wet days is the smallest integer d such that $X_{n+d} \equiv X_n \pmod{M}$ is in terms of the period of the sequence. The maximum possible least period 2^{b-2} is obtained when X_0 and C are selected from the set of least residues prime to 2^b and C is of form $8N + 3$ and $8N + 5$, where N is the number of items. Special care is taken to avoid a repetition of the dates on which rain falls for any particular month.
2. *Dates on Which Rain Falls*. Under some conditions, the same wet dates will appear when the same number of wet days occurs in different months. Certain measures are taken to prevent this kind of situation from occurring in the simulation.
3. *Type of Rainfall*. Rainfall is usually divided into two types: convective and frontal. Convective rainfall generally appears in a thunderstorm in the warm season and occurs sporadically. The precipitation in a frontal system is steady rainfall for several consecutive days because of a stream of warm moist air that originates in the warm sector, just ahead of a cold front.

   The number of thunderstorms that occur in a month is employed as the criterion to distinguish convective rainfall from frontal rainfall. For the different climatic regions that were defined for highways, a different number of thunderstorms are used. Also, the number of days during which bunched (convective) or uniform (frontal) rain falls are distinguished for each month in a given region.
4. *Freeze-Thaw Period*. In accordance with actual highway conditions, it is assumed that the infiltration of rainfall will stop during the cold season when the average monthly air temperature is less than 30°F. The equivalent amount of moisture of the snow that falls during the cold season will infiltrate into the pavement during the first half month of the thawing period when the average monthly air temperature rises from below 30°F to above 30°F.

CONFIDENCE LEVELS

The most recent statistical rainfall data that are available for 30-yr periods are from 1957–1986 (*7*). Normal distributions of rainfall are assumed to apply for any particular month, and average values and standard deviations are determined from the historical data. In considering a severe case of rainfall, we are interested only in estimating the maximum rainfall and, because of this, the one-tailed confidence limit is employed.

$$P\left[\mu > \bar{x} + Z_\alpha \frac{s}{(N)^{1/2}}\right] = 1 - \alpha \tag{4}$$

Therefore

$$\mu = \bar{x} + \frac{s}{(N)^{1/2}} Z_\alpha \tag{5}$$

where

$\bar{x}$ = the mean monthly rainfall,
μ = the maximum rainfall to be considered in a particular month,
Z_α = the normal variate corresponding to a confidence level of $(1 - \alpha)$,
s = the standard deviation of the monthly rainfall, and
N = the number of years represented in the sample.

For design purposes, a computer program has been written so that the user selects a specific confidence level based on the pavement type, the degree of importance of the pavement, and the requirements of the user. In general, a confidence level of 0.95 is employed automatically as a default when the input confidence level is left blank.

SAMPLES

For highway technology, the climatic zones are defined as shown on Table 1 (*9*). Four of nine regions are chosen for rainfall random testing. The representative cities for each region are:

New York City	I-A
San Francisco, California	I-C
Fargo, North Dakota	II-A
Dallas, Texas	II-C

These cities are located across the United States and represent distinctively different climatic regions (Figure 1). The average values and standard deviations of rainfall for the four cities are shown in Table 2 (*7*). A confidence level of 0.95 is used in generating the simulated rainfall, the results of which are shown in Tables 3–6.

In Fargo, North Dakota, the rainfall simulation program indicates that the pavement will be frozen from January through March and again from November through December. The equivalent snow melt is 0.27 in. per day for two weeks during the thawing period.

In Dallas, Texas, no periods of snow on the ground were simulated, and peak monthly rainfall occurs in April and May. In May, a total of 5.76 in. of rain fell, compared with an average of 4.76 in. for that month, the difference reflecting the higher level of confidence specified.

In San Francisco, there is a single wet season from November through March, with no periods during which frozen conditions prevent infiltration into pavement.

In New York, New York, once more, no frozen period is found in this simulation. The number of days of rainfall each month are fairly uniform throughout the year.

The simulated results appear to be reasonable and produce realistic patterns of wet days and total rainfall within a month. The program has been written so that if actual historical rainfall and snowfall data are unavailable, the designer can estimate and analyze the local rainfall information by inputting the number of the climatic region and the confidence level required. Typical statistical data for each of the six larger

TABLE 1 CLIMATIC ZONES ARE DEFINED FOR HIGHWAY TECHNOLOGY

Moisture		Temperature Region		
Region		A	B	C
Potential of Moisture Being Present in Pavement Structure During Typical Year		Severe Winters High Potential for Frost Pentration to Appreciable Depths Into Subgrade	Freeze-Thaw Cycles in Pavement Surface and Base Occasional Moderate Freezing of Subgrade	Low Temperature Not a Problem High Temperature Stability Should Considered
I	High	I-A	I-B	I-C
II	Moderate Seasonally Variable	II-A	II-B	II-C
III	Low	III-A	III-B	III-C

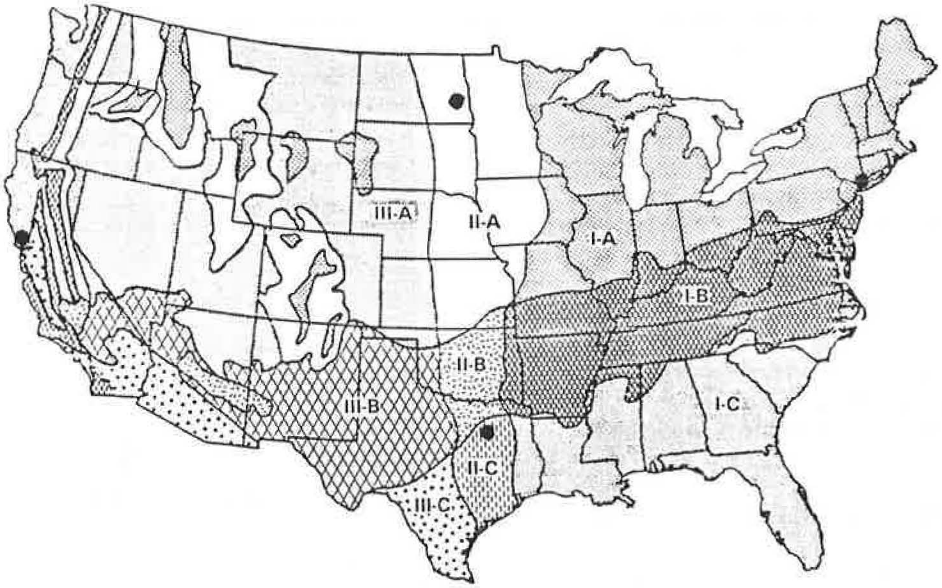

FIGURE 1 Environmental regions and the locations of rainfall samples.

TABLE 2 RAINFALL DATA BASE FOR FOUR CITIES (1957–1986)

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
New York, NY												
Ave. Amount (in)	3.07	3.26	3.60	3.85	3.40	3.39	3.65	3.45	3.46	2.76	3.61	3.68
Stndev.	1.89	1.53	1.65	2.09	1.75	1.95	2.34	1.94	2.15	1.46	2.22	1.82
Ave. Wet Days	10	10	11	11	11	10	11	9	8	8	10	11
Stndev.	3.12	2.56	3.40	1.53	4.08	3.11	9.36	3.11	3.18	2.09	3.77	2.56
No. of Thunderstorms	0	0	1	2	3	3	4	5	2	1	0	0
Stndev.	0.32	0.45	1.26	1.19	1.20	1.98	2.16	1.36	1.27	0.98	0.74	0.49
San Francisco, CA												
Ave. Amount (in)	4.53	3.67	3.15	1.57	0.28	0.10	0.03	0.05	0.27	1.23	2.85	3.06
Stndev.	2.82	2.83	2.35	1.69	0.69	0.20	0.08	0.13	0.47	1.66	2.33	1.62
Ave. Wet Days	10	10	11	6	2	1	1	1	1	4	8	9
Stndev.	4.03	4.02	4.04	4.82	2.87	0.59	0.26	1.14	1.76	2.43	4.59	5.03
No. of Thunderstorms	1	1	0	0	0	0	0	0	0	0	0	0
Stndev.	0.37	0.87	0.89	0.59	0.42	0.19	0.26	0.53	0.67	0.49	0.59	0.42
Fargo, ND												
Ave. Amount (in)	0.56	0.41	0.92	1.98	2.37	3.08	3.12	2.31	1.83	1.78	0.78	0.61
Stndev.	0.44	0.37	0.62	1.36	1.57	1.80	1.76	1.54	1.35	1.68	0.85	0.39
Ave. Wet Days	8	7	7	21	10	11	10	11	8	7	5	8
Stndev.	3.85	2.44	3.61	2.41	2.34	2.05	2.77	13.44	3.54	3.12	2.73	2.35
No. of Thunderstorms	0	0	0	1	4	7	9	7	3	1	0	0
Stundev.	0.00	0.26	0.72	1.60	1.76	2.61	2.02	1.82	2.07	1.11	0.26	0.26
Dallas, TX												
Ave. Amount (in)	1.67	2.11	3.07	4.25	4.76	3.00	2.14	2.16	3.54	4.20	2.41	2.26
Studev.	1.22	1.29	2.00	3.50	3.34	2.15	2.05	1.67	2.53	3.35	1.52	2.13
Ave. Wet Days	6	7	8	8	9	6	5	5	7	6	6	6
Studev.	4.14	2.24	2.64	3.20	3.28	3.36	2.68	2.12	2.80	3.86	3.26	3.13
No. of Thunderstorms	1	2	4	6	7	6	4	4	3	3	2	1
Studev.	0.83	0.96	1.93	2.05	2.70	2.37	2.65	2.25	1.68	1.17	1.47	0.74

TABLE 3 RAINFALL ESTIMATION FOR FARGO, N.D. (1957–1986), $1 - \alpha = 0.95$, II-A

January	1	8	11	12	13	18	22	30	
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
February	1	2	5	8	13	17	18		
	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
March	1	2	4	5	10	13	15		
	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
April	1	2	3	4	5	6	7	8	9
	0.67	0.28	0.27	0.27	0.27	0.27	0.27	0.27	0.27
	10	11	12	13	14	15	18	21	23
	0.57	0.76	0.27	0.27	0.27	0.27	0.46	0.20	0.36
	27	28							
	0.16	0.01							
May	8	10	14	16	18	22	23	27	
	0.23	0.20	0.43	0.34	0.40	0.26	0.15	0.40	
	28	30							
	0.12	0.31							
June	8	10	13	16	17	18	19	23	26
	0.14	0.47	0.18	0.30	0.47	0.40	0.51	0.23	0.28
	27	29							
	0.33	0.31							
July	1	2	3	4	8	12	14	25	
	0.74	0.08	0.12	0.02	0.85	0.42	0.23	0.36	
	26	29							
	0.06	0.76							
August	8	10	14	16	18	20	22	23	27
	0.28	0.11	0.35	0.13	0.23	0.36	0.30	0.38	0.18
	28	30							
	0.21	0.25							
September	2	7	8	12	18	19	21	22	
	0.04	0.44	0.39	0.25	0.43	0.36	0.16	0.17	
October	2	4	8	9	26	28	29		
	0.08	0.62	0.63	0.57	0.16	0.19	0.04		
November	1	12	13	14	19				
	0.00	0.00	0.00	0.00	0.00				
December	2	6	9	15	23	26	27	28	
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

TABLE 4 RAINFALL ESTIMATION FOR DALLAS, TEX. (1957–1986), $1 - \alpha = 0.95$, II-C

January	14	16	17	22	25	28			
	0.27	0.36	0.24	0.27	0.47	0.43			
February	1	4	8	9	13	23	25		
	0.23	0.11	0.71	0.27	0.77	0.01	0.39		
March	1	3	4	6	7	18	23	28	
	0.03	0.73	0.27	0.17	1.15	0.25	0.11	0.97	
April	2	7	8	12	18	19	21	22	
	0.10	1.04	0.92	0.58	1.02	0.86	0.38	0.40	
May	1	2	10	12	18	22	24	28	29
	0.96	0.01	0.73	1.17	1.11	0.47	0.88	0.40	0.03
June	4	9	10	13	21	23			
	0.43	0.45	0.18	1.04	0.60	0.95			
July	3	8	22	24	28				
	0.79	0.26	0.09	0.71	0.91				
August	5	12	13	14	25				
	0.53	0.18	0.45	0.54	0.97				
September	2	3	4	6	16	23	26		
	0.32	0.84	1.42	0.14	0.11	0.24	1.22		
October	1	4	19	25	30	31			
	0.17	1.44	1.19	0.06	1.46	0.89			
November	9	14	15	16	19	27			
	0.78	0.53	0.41	0.26	0.46	0.42			
December	3	5	8	12	18	22			
	0.95	0.35	0.20	0.77	0.12	0.51			

climatic regions have been developed by averaging the data from two cities within each region. The remaining three regions (i.e., II-B, II-C, and III-C) are represented by a single city, as shown in Table 7 and Figure 2. These data will be used in simulating data that are not available within a given region.

The program is intended to be used in pavement design to provide the designer with a realistic set of weather conditions that are consistent with historical records and that are at a desired level of severity as specified by an input level of confidence.

These weather data then provide the moisture, temperature, solar radiation, cloud cover, and wind speed boundary conditions that are needed by the comprehensive computer program to produce for the designer temperature and moisture data with depth and corresponding layer moduli of a specified pavement as they vary through the seasons. The designer may then determine by further calculations whether the pavement will be able to withstand the expected traffic. The entire process depends on a realistic simulation of the weather conditions; the simulation of rainfall has proven to be the most difficult. This paper reports the development of a successful and simple model of rainfall patterns that is sufficiently realistic for pavement design purposes.

CONCLUSION

The amount of rainfall and the dates when it falls are important for the analysis and design of pavements, catchment, and other engineering structures. The rainfall model described here produces simulated sequences of wet days based on weather data from the past several decades.The model is concerned not only with the type of rainfall, to match the convective or frontal precipitation each month, but also with the snowfall-thawing period in considering the infiltration and drainage of moisture into the pavement. The example problems show that this model is fairly realistic and close to in situ highway conditions. It is recommended for use by pavement designers.

ACKNOWLEDGMENT

The results reported in this paper were obtained as part of an ongoing research project on verification and extension of previously developed pavement analysis and drainage models sponsored by the Federal Highway Administration. The authors also acknowledge the contribution of John F. Griffiths in discussion and analysis of weather data.

TABLE 5 RAINFALL ESTIMATION FOR SAN FRANCISCO, CALIF. (1957–1986), $1 - \alpha = 0.95$, I-C

January	8	10	14	16	18	22	23	27	
	0.44	0.38	0.81	0.64	0.76	0.48	0.28	0.75	
	28	30							
	0.23	0.59							
February	1	2	3	4	7	11	13	22	
	0.92	0.10	0.15	0.03	1.06	0.52	0.29	0.45	
	23	26							
	0.08	0.94							
March	1	10	12	15	19	21	23	24	
	0.39	0.44	0.28	0.19	0.46	0.22	0.35	0.55	
	25	28	29						
	0.54	0.01	0.43						
April	5	9	10	21	23	29			
	0.19	0.21	0.63	0.49	0.11	0.45			
May	18	24							
	0.29	0.21							
June	27								
	0.16								
July	4								
	0.06								
August	10								
	0.09								
September	16								
	0.41								
October	4	17	29	30					
	0.36	0.63	0.65	0.09					
November	1	8	11	12	13	17	21	29	
	0.04	0.67	0.94	0.37	0.40	0.55	0.34	0.25	
December	3	5	12	15	16	17	22	25	28
	0.71	0.30	0.37	0.54	0.42	0.39	0.08	0.63	0.13

TABLE 6 RAINFALL ESTIMATION FOR NEW YORK CITY (1957–1986), $1 - \alpha = 0.95$, I-A

January	1	2	12	14	17	21	24	25	
	0.52	0.05	0.64	0.01	0.44	0.29	0.56	0.25	
	26	30							
	0.35	0.54							
February	2	3	6	9	10	19	21	22	
	0.08	0.70	0.49	0.56	0.54	0.06	0.22	0.65	
	25	27							
	0.27	0.15							
March	8	10	14	16	17	18	20	23	
	0.16	0.53	0.20	0.34	0.54	0.45	0.57	0.27	
	27	28	30						
	0.31	0.38	0.35						
April	8	10	13	16	17	19	21	23	
	0.45	0.18	0.57	0.22	0.37	0.58	0.49	0.62	
	26	27	29						
	0.29	0.34	0.41						
May	1	3	4	8	11	13	14	15	
	0.11	0.64	0.41	0.10	0.23	0.04	0.53	0.46	
	17	20	21						
	0.35	0.40	0.65						
June	4	5	9	10	11	22	26	27	
	0.08	0.51	0.21	0.20	0.69	0.24	0.12	0.64	
	29	30							
	0.60	0.68							
July	2	6	8	9	11	17	23	27	
	0.38	0.04	0.69	0.61	0.64	0.13	0.25	0.70	
	28	30	31						
	0.20	0.21	0.51						
August	1	2	10	12	18	22	24	28	29
	0.67	0.01	0.51	0.82	0.78	0.33	0.62	0.28	0.02
September	1	3	4	6	7	17	23	27	
	0.03	0.81	0.30	0.19	1.28	0.28	1.12	1.08	
October	2	7	8	12	18	20	22	23	
	0.06	0.63	0.56	0.35	0.61	0.52	0.23	0.24	
November	1	3	6	9	11	22	23	27	
	0.62	0.60	0.07	0.24	0.72	0.29	0.17	0.75	
	28	30							
	0.02	0.80							
December	1	2	10	12	15	18	19	23	
	0.35	0.23	0.58	0.28	0.44	0.69	0.67	0.01	
	24	28	29						
	0.53	0.42	0.03						

TABLE 7 SELECTED CITIES FOR EACH ENVIRONMENTAL REGION

Moisture Region	Temperature Region		
	A	B	C
I	New York, NY Chicago, IL	Washington, D.C. Cincinnati, OH	San Francisco, CA Atlanta, GA
II	Fargo, ND Lincoln, NE	Oklahoma City, OK	Dallas, TX
III	Reno, NV Billings, MT	Las Vegas, NV San Angelo, TX	San Antonio, TX

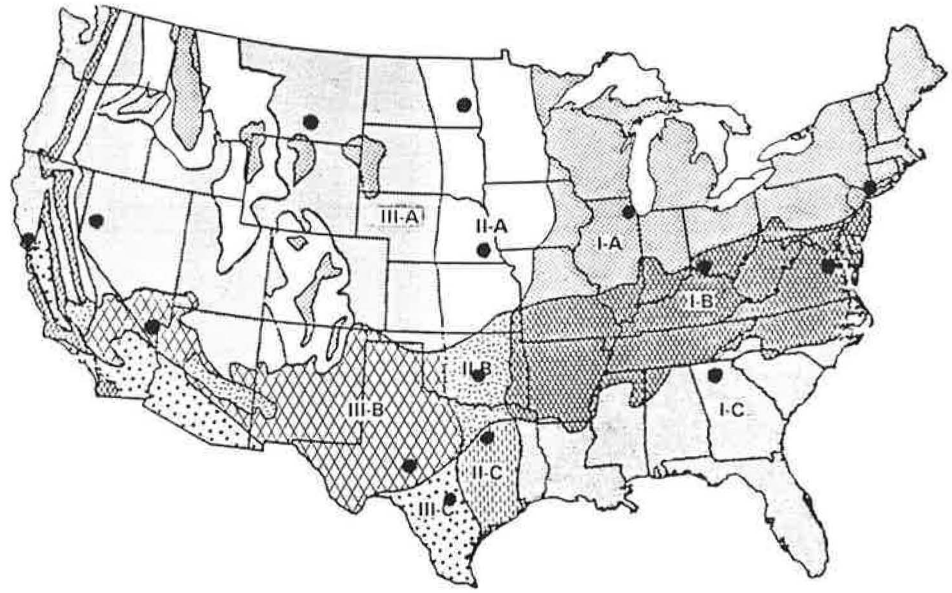

FIGURE 2 Locations of selected cities for each environmental region.

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Publication of this paper sponsored by Committee on Environmental Factors Except Frost.