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THE EFFECT OF WEATHER ON ROAD CONSTRUCTION: APPLICATIONS OF A SIMULATION MODEL [1]

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ABSTRACT

A simulation model is applied to a long series (1918–65) of daily rainfall observations to produce an experimental series of operational records on the weather-sensitive portion of a road building project. These records are ana'yzed statistically for various periods of time within the normal construction season and the resulting statistics are examined for their potential usefulness in the management of road construction.

1. INTRODUCTION

In a companion paper (Maunder et al. 1971), the authors applied a soil moisture index, based on available weather observations and experimental soil trafficability, to engineering data to estimate conditions suitable for work in the road construction industry. A model based on values of the soil moisture index was shown to produce a daily series of computed working condition values that were consistent with those actually reported in records made available by the Missouri State Highway Commission. In this paper, the series of values generated by the model is examined for potential usefulness to the road construction industry.

Four specific applications of the experimental series are considered. In particular, the series is used to estimate: (1) the hours of construction time available in various calendar periods, (2) the frequency of characteristic types of workweeks, (3) the relation between types of workweeks and the manpower and machinery requirements for specific road construction activities, and (4) the application of the index to the estimated progress on construction projects on a statewide basis. The purposes of these applications are to illustrate the advantages of simulation modeling techniques for providing useful information to industry and government and to indicate the types of additional benefits that could be derived from such modeling procedures in the presence of more refined information on soil moisture and on the standard physical construction processes. (These are grading, scraping, excavation, paving, etc., associated with road building.)

2. TRANSLATION OF PRECIPITATION DATA INTO SIMULATED OPERATIONAL DATA

The method employed in experimentally generating the series of working conditions to be used in the subsequent analysis has been described elsewhere in detail (Maunder et al. 1971). In brief, the method is based on the comparison of a daily soil moisture index with daily reports from two construction projects. The soil moisture index is based upon daily precipitation records and experimental data describing water losses through evaporation. Comparison of the soil moisture index with daily reports from construction projects identified values of the index that could be used to classify days on the basis of working conditions for road construction. Three types of days were identified and predicted with an acceptable degree of accuracy by the soil moisture index: (1) full workday, (2) partial workday, and (3) no-work day. The 1918–65 precipitation records for Jefferson City, Mo., were used with the classification system and soil moisture index to produce the daily working condition series.

3. HOURS OF CONSTRUCTION TIME AVAILABLE IN CALENDAR PERIODS

Knowledge of working conditions is important for planning in all phases of the road building industry. Construction firms need information on the number of working days expected to be available, both for bidding on road construction contracts and scheduling machinery and manpower. State officials (or more particularly, contract-letting officials) need such information to properly anticipate probable completion dates and to schedule funds for payment to contracting firms as work progresses through the contract periods. Questions for which industry needs answers include:

1. How many hours of work are available during the normal construction season?
2. If the construction project is started at a particular time, and a certain number of hours or days is required for completion, can the job be completed by a prespecified date?
3. If several jobs are initiated at different starting dates, and all require an equal amount of work, when will each one be completed?
4. If a job is started on a particular date, and the succeeding period is "unusually wet," what is the probability of being able to complete the job in the prescribed time?
5. At what point in a wet year does it become virtually impossible to complete a specific construction job on a schedule?
6. On the average, what are the variations in the amount of work time available—that is, is the available work time in a dry year two or three (or more) times that available in a wet year?

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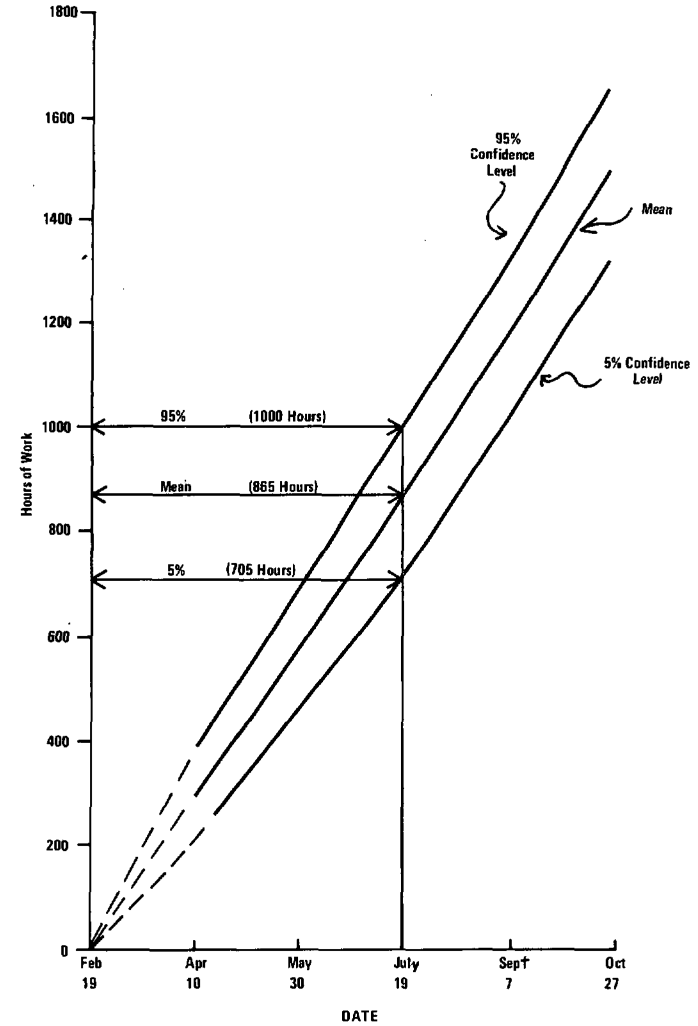

FIGURE 1.—Cumulative work hours (including weekends) for Jefferson City, Mo. (1918–65).

TABLE 1.—*Sample values of cumulative hours of worktime for road construction at Jefferson City, Mo. (Data in parentheses are for a Monday–Friday workweek; data not in parentheses are for a 7-day workweek.)*

Year	April 10–May 29	April 10–July 18	April 10–September 6	April 10–October 26
1920	232 (164)	568 (392)	884 (628)	1188 (852)
1925	300 (228)	580 (408)	904 (636)	1172 (840)
1930	352 (256)	700 (504)	1020 (712)	1328 (916)
1935	204 (124)	444 (300)	768 (536)	1148 (850)
1940	288 (208)	620 (436)	936 (668)	1312 (936)
1945	212 (148)	460 (324)	800 (534)	1052 (764)
1950	304 (232)	624 (472)	952 (696)	1320 (960)
1955	264 (185)	552 (376)	924 (620)	1244 (800)
1960	292 (212)	612 (487)	996 (720)	1304 (980)
1965	296 (204)	548 (372)	808 (584)	1124 (784)

To provide information of importance in answering these questions, we converted the daily series of working conditions into an index expressed in hours of worktime. The conversion was accomplished by weighting "full workdays" by 8 hr, "partial workdays" by 4 hr, and "no-work days" by 0 hr. The resulting index is admittedly arbitrary, but it appeared to be the most appropriate option available given the data limitations. Other worktime indexes could, of course, be developed using different weights more directly suggested by more precise construction project records.

The number of hours available for work during specific periods through a number of seasons can be summarized in a number of interesting ways. The options presented were selected because of their direct bearing on the previously listed questions.

Results of the first summarization are shown in figure 1. Beginning with day number 50 (February 19) in each of the sample years, 1918–65, the cumulative number of hours of working time were recorded for each day through the fall of the year. For any given period during the construction season, there is considerable variation in the cumulative number of hours of work, reflecting the variations in amount and frequency of rainfall from year to year. The curve in figure 1 labeled "mean" is the average value of cumulative worktime, beginning on February 19, and including weekends and holidays as well as the regular workweek. In about 9 yr of 10, the cumulative value of working time will fall somewhere within the 90-percent confidence interval indicated in the figure.

As an example of the applicability of the information presented in figure 1, consider the 200th day of the year (July 19). A work project started on the 50th day of the year (February 19) would have an average of about 865 hr of working time logged by July 19. In 9 of 10 yr, the cumulative number of working hours logged by July 19 would range between about 705 and 1,000. In many instances, construction projects do not operate on a 7-day week or have options as to whether they may operate 5 or 7 days a week. Table 1 was produced, using the worktime index, to illustrate the influence of 5- and 7-day workweeks and the calendar date on available worktime. This table presents the cumulative available worktime for time periods during the main road construction period in Missouri, each time period beginning on April 10. The data are reported for every fifth year and for both 5- and 7-day workweeks.

The influence of 5- and 7-day workweeks is more easily seen when sample data (1918–65) of the type illustrated in table 1 are employed to produce figures 2 and 3. The effect of having 7 days from which to select a workweek of 40 hr is apparent from a comparison of the two figures. The 7-day workweek provides a cumulative work-hour value approximately 45 percent larger than the 5-day workweek for the April 10 to October 26 period.

If one assumes a fixed amount of worktime (say 1,000 hr) and further assumes a variable starting time, then in a given year there will be a run of days that will be the shortest period during which the required worktime is available. There will also be a run of days that will be the most unfavorable for road building, and thus, represent the longest period of time required to complete the desired amount of work. Table 2 contains data de-

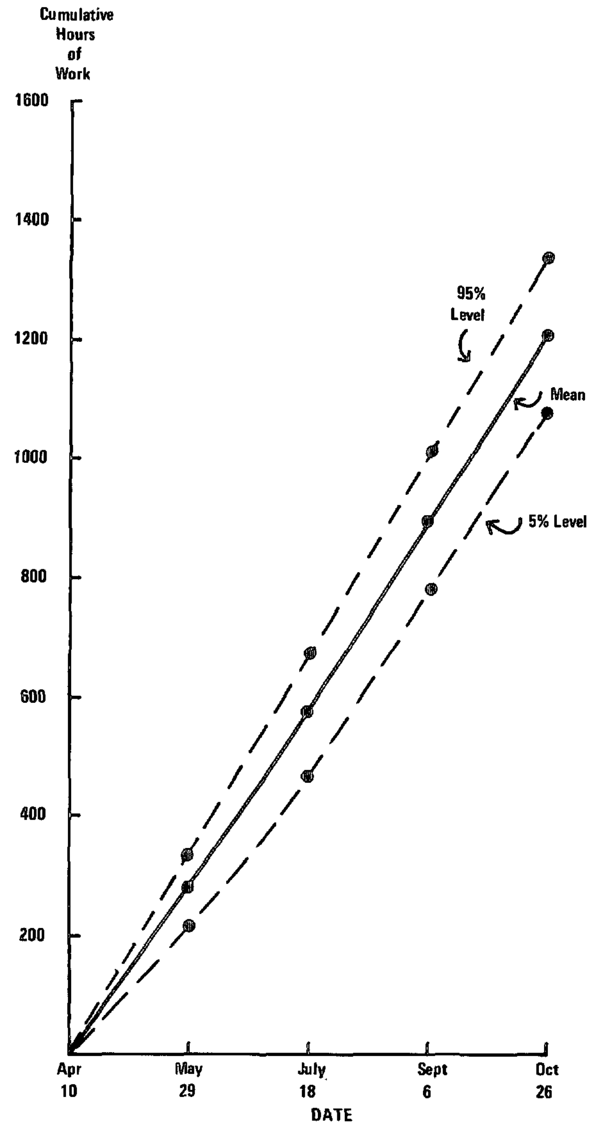

FIGURE 2.—Cumulative work hours for Jefferson City, Mo. (including weekends and holidays) based on rainfall data from 1918–65.

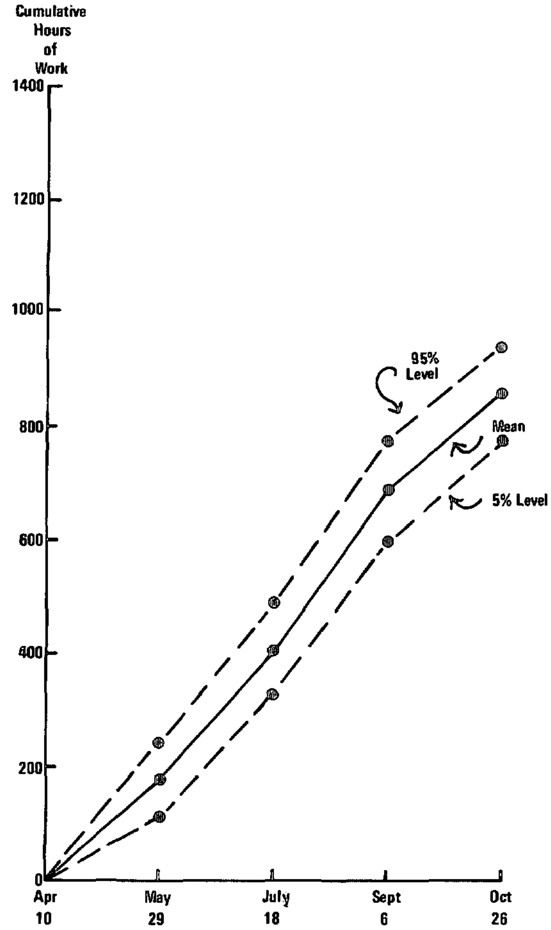

FIGURE 3.—Cumulative work hours for Jefferson City, Mo. (excluding weekends) based on rainfall data from 1918–65.

scribed above for every fifth year in the period beginning with 1920. These data suggest that a road building job requiring 1,000 hr of work is most likely to be completed with the least delay if it is started in late June or early July. At the other extreme, the same job started in late February or early March is likely to experience the greatest delay.

TABLE 2.—*Sample values of the range of cumulative calendar days required to complete 1,000 hr of worktime (weekends included). These values are based on rainfall data for Jefferson City, Mo.*

Year	Minimum time		Maximum time	
	Starting date	Calendar days to completion	Starting date	Calendar days to completion
1920	July 5	157	March 26	176
1925	July 9	158	June 2	171
1930	February 27	141	July 14	155
1935	June 30	149	February 25	194
1940	June 30	140	February 27	168
1945	July 11	155	February 26	204
1950	June 13	142	March 11	166
1955	July 25	140	February 27	169
1960	June 14	138	February 20	164
1965	July 11	157	April 11	181
Sample average	June 20	148	March 30	174

4. INPUT-OUTPUT RELATIONS FOR SELECTED CONSTRUCTION ACTIVITIES

In addition to recording daily information regarding working conditions, resident engineers on State highway projects are required to complete weekly forms that include descriptions of daily construction activities and completion estimates for common and rock excavation, finishing, and the various operations associated with paving. Common and rock excavation are usually items of major importance in highway construction projects. They are also construction activities which are in process during a major proportion of the completion time. Because of

TABLE 3.—*Weekly machinery and labor requirements per 1,000 cubic yd of common excavation*

Amount excavated [e]	Common labor	Bull-dozers [a]	Motor graders [b]	Tractor scrapers [c]	Other [d]	Full days worked [e]
(10^3yd^3)	(hr)	(hr)	(hr)	(hr)	(hr)	
8.00	3.44	2.19	0.00	3.13	2.00	0*
4.20	2.26	8.23	2.51	9.05	0.00	0
3.50	0.57	3.14	2.71	9.71	4.29	1
3.20	0.94	3.14	3.14	11.09	1.88	1
1.25	20.80	11.20	6.41	14.40	0.00	2
22.00	1.25	7.42	0.00	4.14	3.14	2
28.25	1.02	4.55	0.80	3.36	1.03	3
38.00	1.61	6.72	2.00	5.00	1.00	4
29.70	10.24	7.07	1.28	4.87	0.00	4
28.00	0.36	2.79	0.00	6.79	2.25	4
15.50	2.87	2.97	2.29	5.22	0.00	4
18.50	1.08	2.38	1.76	6.27	0.05	5
8.40	8.33	7.02	3.33	12.86	0.77	5
26.00	6.65	4.29	2.35	5.62	1.15	5
11.00	2.36	4.14	4.05	8.00	1.82	5

[a] Types D-6, D-7, D-9
[b] No. 12
[c] Models 631 and DW-21 (rubber-tired)
[d] Euclid end dumps, 8-D and 95 N.W. shovel, ¾-yd cranes, loaders, 2-ton tandem trucks
[e] As estimated by highway engineer
*Less than 1 full workday

TABLE 4.—*Weekly machinery and common labor requirements per 1,000 cubic yd of rock excavation*

Amount excavated [f]	Common labor	Bull-dozers [a]	Transports [b]	Com-pressors [c]	Loaders [d]	Other [e]	Full days worked [f]
(10^3yd^3)	(hr)	(hr)	(hr)	(hr)	(hr)	(hr)	
20.30	31.330	2.365	11.034	1.576	7.709	12.167	0*
31.00	21.177	1.242	11.338	0.000	5.516	9.016	0
19.00	30.421	2.869	16.869	2.000	4.237	8.632	0
10.00	45.046	11.285	9.174	22.339	3.440	2.936	0
17.50	30.296	10.829	13.371	14.200	3.068	3.114	0
8.10	56.728	4.938	14.630	13.210	7.839	6.111	1
18.00	29.556	2.223	3.944	3.139	2.528	0.444	1
15.00	30.933	3.767	6.800	1.467	6.401	12.002	1
18.00	17.722	9.056	10.444	6.833	0.000	5.972	2
12.00	50.008	8.708	11.583	17.333	4.292	3.458	2
6.00	24.583	16.667	33.417	6.000	6.250	4.667	3
17.00	31.176	9.647	15.764	15.529	2.235	12.677	4
18.00	36.667	8.778	11.444	16.278	3.667	4.389	4
15.00	25.484	10.516	15.935	10.323	4.419	3.355	4
23.00	20.065	1.326	11.982	1.848	5.783	1.000	5
17.10	26.491	9.145	14.503	10.760	3.158	3.158	5

[a] Types D-6, D-7, D-9
[b] Euclid end dumps, model 631 tractor scrapers, DW-21 rubber-tired tractor scrapers, cat. truck
[c] Standard
[d] Shovels, cranes
[e] 2-ton truck, motor grader, roller, electric light generator, air drill, special drilling, and shooting equipment
[f] As estimated by the assigned highway department project engineer
*Less than 1 full workday

the importance of the common and rock excavation activities, the length of period over which they are active, the varying climatic conditions under which they are attempted, and the availability of data on which to base the estimates, these two activities were selected for an input-output analysis.

Input-output coefficients for common and rock excavation are calculated by combining completion estimates from the resident engineer's weekly reports with the foreman's weekly time sheets. Data used in estimating the input-output coefficients were obtained from two recently completed construction projects in central Missouri.[5]

The coefficients are actually calculated on the basis of a selected sample of the weekly records made available by the contractors and the State highway commission. Weekly records used for the calculations were selected on the basis of variability of weather-related working conditions and homogeneity with respect to the types of activities occurring within the week. The first selection criterion presented no problems since the time period over which the data from the two projects stretched provides ample variations in weather conditions. The second selection criterion was, however, the source of some difficulty. Other construction activities were in progress during the weeks for which information was obtained from the time sheets. This made it difficult to attain the desired amount of precision in assigning input values to the common and rock excavation activities. The weeks included are simply those for which such errors appeared to be of least consequence. A finer classification would probably have yielded input-output coefficients with less dispersion. However, attempts at refining the classifications using available information on the resident engineer's reports were unsuccessful. The computed data can therefore be taken to be only a crude approximation. With more complete reporting of input and particularly output data, however, it would be possible to increase the precision and, hence, the usefulness of information of the type presented. The implication of this discussion is that the input-output coefficients, although useful in demonstrating the applicability of the workday model based on soil moisture conditions, should be regarded with caution in decisions involving more than an indication of their relative magnitudes.

Input-output coefficients for common and rock excavation are presented in tables 3 and 4, respectively. Estimates of the amount of excavation per week are also included. Input categories are highly aggregated, as indicated by the items included in the related table notes. The coefficients are values (in hr) of the various inputs required for each 1,000 cubic yd of common and rock excavation.

Tables 5 and 6 summarize the data in tables 3 and 4 according to workweek classifications. A Monday to Friday week with 2 or less working days is classified as a marginal workweek. Weeks with more than 2 working days were classified as full workweeks. Ideally, the summarization would have been broken down for each of the possible numbers of working days per week. However, the system employed in this case was restricted

[5] The Missouri State Highway Commission made available the resident engineer's reports, and the two prime contractors on the projects—Clarkson Construction Co. of Kansas City, Mo., and Tobin Construction Co. of Kansas City, Kans.—supplied the weekly time sheets filed by the foremen.

TABLE 5.—*Estimated means and variances of machinery and labor requirements per 1,000 cubic yd common excavation* [a]

Working	Common labor [b]		Bulldozers [b]		Motor graders [b]		Tractor scrapers [b]		Other [b]	
days/week	mean	variance	mean	variance	mean	variance	mean	variance	mean	variance
≤2	4.88	61.93	5.88	12.97	2.46	5.65	8.59	18.24	1.88	2.89
>2	3.83	13.08	4.66	3.46	1.98	1.52	6.44	7.49	0.90	2.18

[a] Calculated from table 3
[b] Hours per 1,000 cubic yd

TABLE 6.—*Estimated means and variances of machinery and common labor requirements per 1,000 cubic yd rock excavation* [a]

Working	Common labor [b]		Bulldozers [b]		Transports [b]		Compressors [b]		Loaders [b]		Other [b]	
days/week	mean	variance	mean	variance	mean	variance	mean	variance	mean	variance	mean	variance
≤2	34.322	154.002	5.728	14.802	10.914	11.976	8.209	62.977	4.503	5.877	8.599	21.338
>2	27.411	33.274	9.347	119.740	17.174	66.856	15.300	30.600	4.252	2.497	4.874	16.281

[a] Calculated from table 4
[b] Hours per 1,000 cubic yd

by data limitations. A comparison of the means for input categories in table 5 (common excavation) for the two workweek classifications shows rather clearly that the number of working days, and presumably weather factors, have an influence on the efficiency of construction operations. For example, an average of 5.88 hr of bulldozer time was required per 1,000 cubic yd of common excavation during marginal workweeks while an average of only 4.66 hr of time was required for the same 1,000 cubic yd of common excavation on full workweeks. Similar savings of inputs are indicated for the common labor, motor grader, and tractor scraper categories. Differences in average costs of common excavation under the two workweek classifications can be computed by multiplying the differences in input coefficients by the rental costs for machinery and the hourly wages of operators. At usual prices for machinery and labor, the differences in average costs represented by these input coefficients are substantial.

Variances for the common excavation input categories are large and, as mentioned previously, are to some extent a result of the broad input classifications. Conclusions drawn from the means are supported by the information on numbers of cubic yards of common excavation, and they bear an increasing relation to number of working days per week.

By contrast, in the data for rock excavation (table 6), the conclusions for common excavation and weather factors are not supported. Mean levels of inputs per 1,000 cubic yd of rock excavation, for example, show no relationship to the two working classifications, variances are large, and weekly output as reported in table 4 seems to have little relationship to working days. The difference between the relationship of the common and rock excavation to weather can probably be attributed to the relation between composition of material excavated and soil moisture.

5. INPUT-OUTPUT COEFFICIENTS AND THE WORKWEEK SERIES

Input-output coefficients estimated from weekly data can be used to expand the simulation model discussed in Maunder et al. (1971). Use of these input-output data will give some insight into the types of information that could be obtained from such an approach using available weather records and more refined data about the physical processes of road construction. The data on input-output coefficients for common excavation are utilized in this illustration because of the observed differences in coefficients for the two types of workweek.

The subroutine for common excavation is constructed as follows:

1. Means and variances of output for the two types of workweeks (full workdays>2 and full workdays≤2) are calculated from column 1 of table 3.
2. The means and variances so calculated are used to define truncated normal distributions [N(7.02:59.29)] for weekly amounts of common excavation completed, for the two types of workweeks assumed.
3. The two output distributions are tied to the workweek information series for the 48-yr period to produce estimates of weekly and annual amounts of common excavation completed.
4. Input coefficients are multiplied by weekly outputs as a basis for calculating annual average coefficients.

Data from the common excavation routine are included in table 7. The data are arrayed and summarized for the 10 yr in which the most common excavation occurred and 10 yr in which the least common excavation occurred. The difference in the average of the amounts of excavation for the two groups of years is substantial. An average of about 823,000 cubic yd of common excavation was possible in the 10 most favorable years as compared to about 624,000 cubic yd in the 10 least favorable years in the 48-yr series.

TABLE 7.—*Common excavation and input requirements for the 10 highest and 10 lowest amounts of excavation completed during the May 1 to September 1 period using only Monday–Fridays*

Group	Amount excavated	Year	Workweek types and numbers ≤2	Workweek types and numbers >2	Common labor	Bulldozers	Motor graders	Tractor scrapers
	(10^3 yd ^{3})							
10 yr in which most common excavation occurred	854.50	1930	6	34	98.35	101.13	42.92	140.36
	852.45	1956	8	32	84.32	102.44	43.43	142.77
	834.40	1962	8	32	81.77	99.39	42.16	138.19
	833.35	1940	11	29	82.75	100.52	42.60	140.23
	820.95	1928	11	29	83.29	101.16	42.86	141.24
	817.68	1964	11	29	81.50	98.99	41.94	138.22
	805.36	1946	11	29	80.12	97.32	41.24	135.83
	804.46	1925	13	27	80.66	97.94	41.48	136.96
	803.20	1957	16	24	81.64	99.07	41.92	139.00
	802.14	1932	9	31	78.78	95.75	40.61	133.12
Average	822.85		10.4	29.6	83.32	98.37	42.12	138.59
Standard deviation	20.0		2.8	2.8	5.4	2.1	0.6	2.9
10 yr in which least common excavation occurred	577.25	1924	19	21	59.89	72.62	30.68	102.41
	584.57	1921	21	19	59.66	72.39	30.62	101.68
	601.90	1948	16	24	61.36	74.46	31.50	104.55
	610.68	1947	19	21	62.41	75.42	32.03	106.38
	612.07	1933	15	25	62.14	75.42	31.91	105.79
	639.88	1935	19	21	66.44	80.55	34.03	113.61
	650.46	1934	11	29	64.32	78.15	33.13	108.90
	650.73	1920	13	27	65.84	79.92	32.33	112.01
	656.21	1965	17	23	66.68	80.92	34.24	113.53
	659.35	1951	18	22	68.21	82.72	34.96	116.56
Average	624.28		16.8	23.2	63.70	77.29	32.54	108.54
Standard deviation	31.4		3.0	3.0	2.9	3.6	1.6	5.2

Requirements of the common labor, bulldozers, motor graders, and tractor scrapers input classifications are as anticipated from the input-output coefficient data in table 3. An individual comparison of years within the two groups reveals that the amounts of excavation are remarkably close together—a factor that could be anticipated from the broad classifications of types of workweeks. More refined classifications would be expected to produce wider dispersion in input requirements. Results reported may therefore be regarded as conservative estimates of differences between the two sets of 10-yr records presented.

Table 8 is similar to table 7 except that a Monday to Sunday instead of a Monday to Friday workweek is assumed. An average of 902,000 cubic yd of common excavation is completed in the top 10 yr as compared to 823,000 cubic yd for the top 10 yr in the Monday to Friday series. Differences between numbers of full and marginal workweeks in both sets of 10-yr averages are seen to account for the change in the amount of common excavation completed. Implications for input requirements are comparable to those for the Monday to Friday workweeks. The main result in table 8 is the increase in numbers of cubic yards excavated for both the top 10 and the bottom 10 yr in the 48-yr series. The major implication of this most simple analysis is the magnitude of the relationship between operational events and the weather. The implications for gains to both contractors and Government authorities that can result from more specific simulation analyses of this type are clear.

6. EXTENSION TO A STATEWIDE WORKABILITY INDEX

The previous sections have employed a method for computing a soil moisture index and a workability index for a specific location, Jefferson City, Mo. Many of the weather-sensitive components of the road construction industry are associated with management or funding of particular construction projects. Data concerning costs and expenditures for road construction are readily available (through Missouri State Highway Commission records) for the State as a whole. An attempt was made to develop a method that would produce a State workability index. This method is described in the discussion that follows.

Missouri is divided into 10 districts by the Missouri State Highway Department. Records of expenses and disbursements are maintained by district for each month. It seemed appropriate to compute a daily soil moisture index for each district, and then to convert these index values into daily district workability indexes. Three weather stations were selected for each of the ten districts, and average daily rainfall (January 1968 through July 1969) values for each district were computed, using the algorithm described in a previous paper (Maunder et. al. 1971). Typical values for two sample days for the 10 districts are shown in table 9.

A "district workability index" (DWI) was computed from these soil moisture values using the equation

$$\text{DWI}=(D_1\times 0)+(D_2\times 1)+(D_3\times 2)+(D_4\times 3)+(D_5\times 4)+(D_6\times 5)+(D_7\times 6)$$

TABLE 8.—*Common excavation and input requirements for the 10 highest and 10 lowest amounts of excavation completed during the May 1 to September 1 period using Monday–Sunday*

Group	Amount excavated	Year	Workweek types and numbers		Average input requirements			
			≤2	>2	Common labor	Bulldozers	Motor graders	Tractor scrapers
	($10^3 yd^3$)							
10 yr in which most common excavation occurred	974.97	1930	4	36	95.14	115.66	49.08	158.83
	931.94	1940	4	36	90.36	109.88	46.64	152.34
	915.47	1964	7	33	89.77	109.11	46.28	151.72
	914.15	1932	3	37	87.40	107.13	45.50	148.30
	903.15	1952	8	32	88.03	107.02	45.41	148.59
	886.13	1960	4	36	85.98	104.55	44.38	145.00
	884.47	1949	9	31	87.17	105.92	44.91	147.41
	876.04	1955	8	32	86.30	104.87	44.46	146.01
	868.80	1935	11	29	86.44	105.00	44.49	146.55
	865.04	1950	6	34	83.74	101.84	42.56	141.14
Average	902.00		6.4	33.6	88.03	101.10	45.37	148.60
Standard deviation	33.6		2.6	2.6	3.2	3.7	1.8	4.6
10 yr in which least common excavation occurred	642.55	1929	10	30	63.77	77.49	32.85	107.96
	674.26	1965	10	30	66.63	80.96	34.32	112.80
	681.48	1926	12	28	66.64	81.01	34.36	112.57
	684.01	1921	12	28	68.35	82.86	35.16	115.99
	704.11	1924	10	30	69.69	84.67	35.89	118.02
	718.18	1944	10	30	71.05	86.32	36.59	120.31
	719.56	1945	14	26	71.76	87.16	36.93	121.72
	730.12	1948	11	29	72.47	88.03	37.31	122.77
	733.15	1958	9	31	72.69	88.31	37.43	123.15
	737.89	1933	9	31	72.45	88.05	37.35	122.49
Average	702.53		10.7	29.3	69.55	84.49	35.82	117.78
Standard deviation	31.1		1.5	1.5	3.1	3.6	1.5	5.2

where

D_1= No. of days with soil moisture >1.80
D_2= No. of days with soil moisture 1.70–1.79
D_3= No. of days with soil moisture 1.60–1.69
D_4= No. of days with soil moisture 1.50–1.59
D_5= No. of days with soil moisture 1.40–1.49
D_6= No. of days with soil moisture 1.30–1.39
D_7= No. of days with soil moisture <1.30.

The "weights" 0, 1, 2, 3, 4, 5, and 6 in the DWI equation were chosen as being a first approximation of the number of hours of road construction that could be logged when the district daily soil moisture index was within the respective intervals. The workability index values, for each of the 10 districts for the 18-mo period February 1968 through July 1969, are given in table 10. The table shows a variation from a high of 186 in July, August, October 1968, and May 1969 for district 6, to a low of 47 in June 1969 for district 4. With 186 as a maximum value for the index, the low represents only 26 percent of the possible index score and, hence, a substantial decrease in available worktime.

The data in table 10 were then weighted according to the relative importance of the various districts to the total State expenditure on road construction. As a first approximation the value of work per district in 1968 was used. For example, in 1968 the total road construction expenditure in Missouri was $110,630,572 of which $32,077,385, or 29 percent, was used in district 4, but only $3,236,498, or 3 percent, in district 3. Because monthly district data on expenditures were not available, the percentages indicated above were used for all months for which a workability index was calculated. This assumes, of course, that the relative importance of road construction in the Missouri districts during the 18-mo period did not change. Using the dollar values available, a monthly state workability index was calculated as follows:

$$SWI=(DWI_1\times W_1)+(DWI_2\times W_2)+\ldots+(DWI_{10}\times W_{10})$$

where

SWI=State workability index

DWI=district workability index (1–10)

W_{1-10}=weights for the 10 districts

(W_1=0.092, W_2=0.038, W_3=0.029, W_4=0.290, W_5=0.067, W_6=0.213, W_7=0.039, W_8=0.095, W_9=0.065, W_{10}=0.072).

TABLE 9.—*District average soil moisture indexes for Missouri*

District	Day 105 Precip.	Day 105 Soil moisture index	Day 106 Precip.	Day 106 Soil moisture index
1	0.73	1.80	0.00	1.70
2	.22	1.48	.29	1.76
3	.40	1.77	.00	1.67
4	.33	1.57	.00	1.47
5	.03	1.49	.00	1.41
6	.00	1.41	.00	1.40
7	.00	1.36	.00	1.35
8	.00	1 36	.00	1.28
9	.01	1.34	.00	1.26
10	.20	1.53	.00	1.43

TABLE 10.—*District workability indexes: February 1968–July 1969*

Month/District	1	2	3	4	5	6	7	8	9	10
1968										
Feb.	158	138	118	121	125	127	110	98	104	105
Mar.	181	181	183	153	101	118	79	66	68	77
Apr.	97	74	75	98	106	102	105	98	94	74
May	174	142	111	144	148	139	144	95	100	110
June	145	127	123	154	113	159	133	165	162	130
July	139	114	131	132	142	186	165	148	158	184
Aug.	125	158	154	136	121	186	120	108	161	185
Sept.	155	129	101	136	125	131	137	131	139	139
Oct.	142	168	153	148	153	186	147	137	128	152
Nov.	175	143	131	140	90	180	93	83	86	161
Dec.	133	182	147	163	138	164	143	142	125	102
1969										
Jan.	84	141	89	110	74	133	101	80	88	60
Feb.	111	151	88	108	84	109	121	85	91	112
Mar.	150	168	117	92	82	138	145	129	91	148
Apr.	87	65	78	82	75	103	70	61	73	67
May	118	123	127	134	147	186	148	166	176	140
June	104	52	67	47	52	140	120	108	180	124
July	84	94	95	71	105	75	127	116	160	172

TABLE 11.—*Missouri workability index and value of road construction completed*

Month	1968		1969	
	State workability index	Amount paid to contractors [a]	State workability index	Amount paid to contractors [a]
April	96.0	9.33	81.6	9.90
May	135.0	10.21	150.6	16.11
June	148.6	9.26	96.0	15.97
July	152.3	12.80	96.4	17.79
August	147.9	14.21		
September	134.6	12.91		
October	154.7	16.34		

[a] Millions of dollars.

The State workability indexes obtained for the main road construction period are shown in table 11 together with the amount of money paid to road construction contractors for the corresponding months. These sample values give some indication of a relationship during the road construction season between the amount paid to the contractors and the workability index as computed. It is reasonable to suppose that a closer relationship would be apparent if the weights for the districts were based on monthly rather than annual dollar values, or if a larger sample of daily rainfall values were chosen for each district.

7. CONCLUSIONS

Many years of precipitation data are readily available from a reasonably dense network of climatological stations operated by the National Oceanic and Atmospheric Administration. These comparatively large samples of observations can provide the basis for useful statistical estimates of seasonal variations and short period probabilities of occurrence of certain favorable and unfavorable sequences of working days.

Given a reasonably precise translation of weather information into simulated "operational values," the functional relationships needed to convert the simulated operational data into quantitative expressions in terms of costs can be developed. The applications of the work index concept that have been reported in this paper are indicative of the types of information that such a marriage of climatic data and operational data from road construction can produce. Although the particular implications of the applications are limited by some subjectivity in the operational data and somewhat stronger than necessary assumptions on the construction processes, the general implication regarding the potential payoff of increased efforts in this area for the industry is clear.

The logical suggestion is, of course, that all participants in the industry could benefit from some additional deliberate research on the effects of weather on road construction. More carefully designed records (perhaps obtained by sampling design to reduce cost and inconvenience) describing detailed and measured progress on construction projects are needed. On-site measurement of weather events and further effort on the part of contractors to record information in addition to that now required for the purpose of cost accounting are among the initial steps that could be taken to identify and measure quantitatively the important impact of weather on, and the value of weather information to, the road construction industry.

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REFERENCE

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