Fatigue design is usually a subsystem of the overall pavement design system. Input variables to the fatigue design subsystem are load, environment, construction, structural, and maintenance. Usually construction, structural, and maintenance variables are controlled by the designer and basically affect the load-carrying capacity of the pavement as designed, constructed, and modified in service. Traffic and environmental variables impose a load on the pavement structure, and those are the ones considered in this paper. In the present state of the art, there are adequate methods for estimating traffic data. Environmental models can include a wide variety of inputs, but here the inputs are limited to moisture and temperature effects. Temperature can be predicted with some degree of adequacy, based on existing weather data, but no present method is completely adequate for predicting moisture effects in pavements although work is under way to improve techniques. Future improvements in pavement design systems in terms of traffic and environmental variables will necessarily involve some consideration of the stochastic variations in the predicted values, and the final designs will involve statistical confidence levels in lieu of conventional safety factors. However, adequate data are now available to develop rational fatigue design subsystems.

Other Input Variables: Traffic and Environmental

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In the past 10 years, a great deal of effort has gone into providing a better definition of the overall pavement design system (1, 2). In that system development, many charts and models have been drawn to depict the process of pavement management and design. They all have essentially the form shown in Figure 1, that is, a series of inputs combined through a model, usually mathematical, to generate a predicted response and a predicted history of loads to be transported. The response at some levels may yield distress, and all types of distress combine in some way, imprecisely known, to define performance in conjunction with the loads transported. Likewise, a series of concomitant variables is generated, resulting from the loads transported, the presence of the pavement structure, and other factors. A series of decision criteria and decision rules are applied to provide for rational design and management decisions.

Figure 1 shows that traffic and environment occur as both inputs and outputs to the pavement design process. Those inputs and outputs must not be confused, and the purpose of the paper is to discuss input variables to a fatigue design subsystem. As outlined by Chestnut (3), if the overall pavement design process is the system, then the fatigue design is a subsystem of that total design system.

INPUT VARIABLES

Input variables to the fatigue design subsystem can be listed in 5 categories: load, environment, construction, structural, and maintenance. The construction, structural, and maintenance variables are normally those that are controlled by the designer or pavement management team and that basically affect the load-carrying capacity of the pavement as designed, constructed, and modified in service. The traffic and environmental variables are usually those that impose a load on the pavement structure. Such a load may be induced by traffic or by the environment, i.e., a temperature stress. The construction, structural, and maintenance inputs will not be considered further in this paper because its purpose is to consider the traffic and environmental variables.

Interaction of Inputs

Figure 1 shows that the input variables to the design subsystem are not independent of each other but rather interact to the extent that the effect of one variable on the structural model depends on the level of one or more of the other input variables. That definition of interaction is important to the discussion that follows.

Feedback Information

The term feedback is used in pavement design in two ways. First, as shown in Figure 1, it relates to a change in the input variables that results from or "feeds back" from a change in the response or distress variables. Examples are (a) the increased loads induced by traffic when pavements get rough, or (b) the increased level of maintenance induced when pavements crack and must be repaired.

Another type of feedback is the information that is developed through observation and evaluation of pavement systems and their variables. Those data, in the form of traffic history, weather bureau data, deflection measurements, serviceability measurements, and condition surveys, constitute the feedback information necessary to improve design methods and adequately manage or maintain any particular pavement as well. Because of the inherent complexity of predicting traffic and environmental variables, measuring and recording such data including the effect of the variables on pavement performance provide the only realistic basis for developing improved design methods.

Much of the traffic and environmental input to a design subsystem such as fatigue must depend on recorded history of those variables or "feedbacks."

Variability

One other important concept is that of variability. All aspects of the pavement system involve inherent variations that cannot be measured adequately or predicted in the deterministic sense (4).

It is not possible to predict exactly the weight, amount, and kinds of traffic to be carried by the pavement at any given time during its lifetime. Likewise, it is impossible to predict exactly the temperature or weather conditions that will prevail for a particular design situation. As a result of such variability, pavement design subsystems must ultimately consider the stochastic variation of inputs, models, and model coefficients to predict a design in terms of required levels of reliability.

In the present state of the art, the problem is often one of reducing input variables to manageable proportions. For example, temperature is a continuously varying parameter in both space and time; thus, the modulus of the paving materials also varies constantly. Although it is necessary to estimate useful "design values" that can be used to simplify the design process, designers and researchers should continually work to find more appropriate ways to handle that complex variability.

TRAFFIC VARIABLES

Traffic variables include those related to the vehicle loads applied to the pavement and include total vehicle load; wheel load; tire pressure; wheel or gear configuration; lateral placement; volume or number of applications; lane and directional distributions; sequence of load applications of the various types; load type, i.e., static, dynamic, braking, or accelerating; and variability of traffic.

Traffic variables are among the most capricious with which the engineer must deal. Structural construction variables can be specified and controlled to some degree based on specifications and inspection. Environment cannot be controlled, but there are natural patterns that are generally repeated. Traffic, on the other hand, is a function of people, land use, legal load limits (although not constrained within them), and time. The number of variables that must be considered is large, and the number of combinations is infinite.

Must we then assume that the task of handling traffic is hopeless? No, not at all. There are many ways to attack the problem. They generally fall into 3 categories:

1. Design for the worst expected load condition,
2. Equate all loads to equivalent load applications, and
3. Predict traffic patterns and run a design analysis for the spectrum of load conditions to be encountered.

Predicting Traffic Input for Fatigue Analysis

In a fatigue analysis, it is not adequate to design for the so-called "worst" condition. Nor is it possible in the strictest sense to design for fatigue with equivalent loads, although the AASHO Road Test did develop equivalence values on the basis of equivalent accumulated damage (5). Subsequent design methods using that design concept (6) have used those equivalencies on the assumption that the mixed traffic relations developed by Scrivner et al. are adequate (7, 8).

As outlined by Scrivner, a major assumption required in the mixed traffic equations is that the order of accumulation of traffic is immaterial to the results. In the strictest sense, that is not true, of course. For example, it would be possible under that concept to apply many applications of a light load and then to apply a few overload applications to cause pavement failure. On the other hand, if the overloads were applied first and the pavement failed, it would not be possible to carry the large number of light loads. In practice, however, with a "regular" stream of traffic in which there is a rather random mixture, the assumption seems to work satisfactorily.

The Kentucky Highway Department uses equivalent 18-kip axle load in its design procedure (31). In that method, the expected lane loadings are determined from planning survey data, and all lanes are designed the same as the most heavily loaded lane. A cursory review of the work seems to indicate more concern with rutting than with fatigue, however.

The remaining approach to traffic consideration is to predict traffic as accurately as possible based on past history, projected land use changes and highway improvements, and predicted growth patterns. Each highway department has a technique for making such traffic projections based on data in its survey files. Derdeyn (9) and Heathington and Tutt (10) have studied this problem for Texas and have developed procedures that are acceptably reliable for use in the Texas flexible pavement system (1). Basically, the method includes 3 steps:

1. Count or estimate existing or currently predicted daily traffic by lane and direction at the site;
2. Estimate axle distribution based on comparisons with data from similar highways or from a data bank of statewide traffic; and
3. Predict future axle load distribution for the pavement site based on projected land use and population growth.

Darter has studied such typical traffic prediction methods and compared them with subsequent actual survey data (11). He points out in his report that uncertainties on the order of a factor of 2 can be expected in the data from any such predictions. Thus, if a traffic analysis predicts 10,000 applications, experience shows that the actual number of applications might prove to be as low as 5,000 or as high as 20,000.

To consider traffic adequately, the design method must ultimately include some consideration of uncertainty. Then it will be possible to evaluate the effect of improved traffic predictions in terms of high levels of design confidence and also to consider the resulting costs and benefits (4).

In the design analysis for the load spectrum, usually a series of layered system analyses is run on a computer by available programs. Those programs use a circular tire print, and the average tire pressure is usually used as the unit load. Multiple tires and axles can be handled by the more sophisticated programs. The designer must determine traffic data for his own design situation and input them into his method.

ENVIRONMENTAL VARIABLES

Environmental variables can include a wide variety of inputs such as general geological and soil conditions, oxygen and air surrounding the pavement, and moisture and temperature conditions within and around the pavement. However, for purposes of this discussion, we will limit our consideration of environmental variables to moisture and temperature effects.

It might be said that the pavement is a kind of transplant of materials into the existing body or environment of the earth for a special purpose. The environment works throughout the life of the pavement to "reject" it or destroy it by weathering. In other words, water and temperature variations are continually working on the pavement causing stress, strains, deflections, and permanent deformation, and there is much evidence that pavements are destroyed by the environment in the absence of traffic variables. In addition to moisture alone and temperature alone, there is, of course, the interaction of the 2 variables together in the form of freezing and thawing where the water and undesirable temperature variations result in water migration, formation of ice lenses or frost heaving, and subsequent softening in the spring.

The fatigue subsystem is primarily concerned with the effect of moisture and temperature on the structural properties or strength of the pavement materials or, in other words, the interaction of strength and material properties with the environment.

Moisture

The presence of moisture in a pavement produces several effects:

1. Oxidation of the surface in the presence of water and sunlight to change the properties of the material,
2. Freezing and thawing (formation of ice lenses),
3. Instability that is caused by excessive pore-water pressure and results in the failure of bases and slope stability,
4. Undesirable volume change, and
5. Stresses induced by moisture variation.

In this symposium, the main concern is the fatigue behavior of pavements. We will, therefore, ignore the volume change, roughness, and distress induced directly by moisture variations and will concentrate primarily on changes in material properties due to moisture variations and on stresses induced by soil-suction potentials present in the material or by excessive pore water pressure.

Moisture variations are extremely difficult to handle. They are sometimes considered in "regional factors," based in general on the average rainfall or the wet or dry condition of the geographical area in which the design is being considered. Such techniques are inherent in the Kansas method of pavement design (12). A similar concept was used in Texas (13); in it the general moisture conditions within the state were related to the "temperature constant."

A more precise and more desirable method of considering moisture variations in pavement design is to evaluate the soil-suction potential under the pavement. A great deal of work has been done with that concept, but most of it is related to the prediction of swell or shrinkage and not directly to the prediction of stresses. Measuring devices are being developed to accurately predict the soil-suction potential of a soil, but no really competent work has yet been done on relating that to fatigue.

Work by Lytton and Kher (14) presents an analytical tool for determining the changing moisture distribution with time in expansive clays. The method has been used to predict observed field values (Fig. 2, 14).

Figure 1. Typical pavement design system.

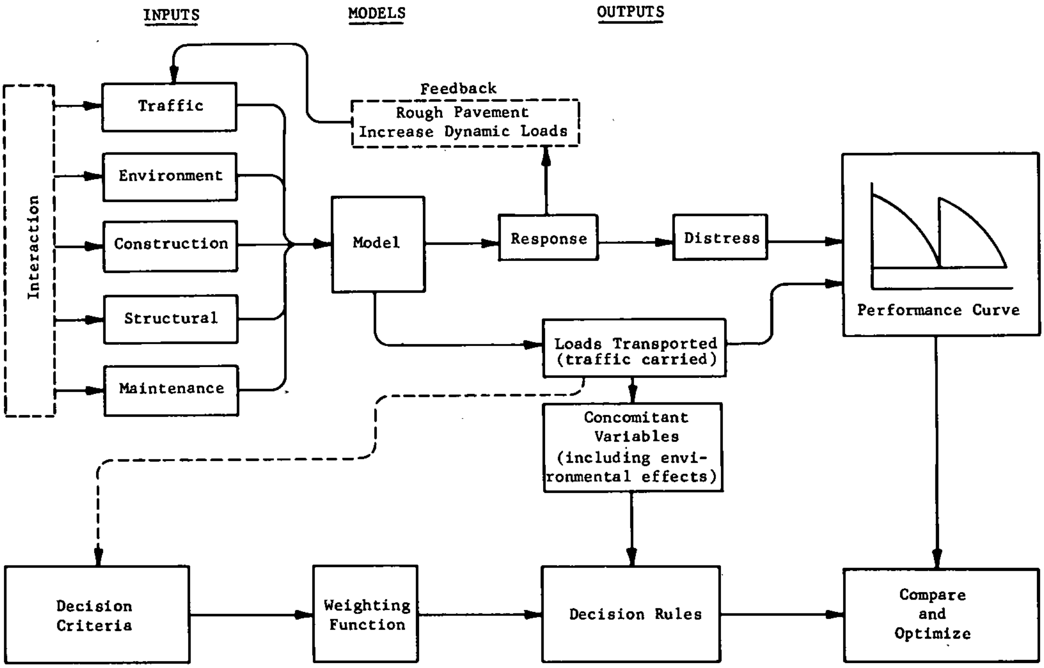
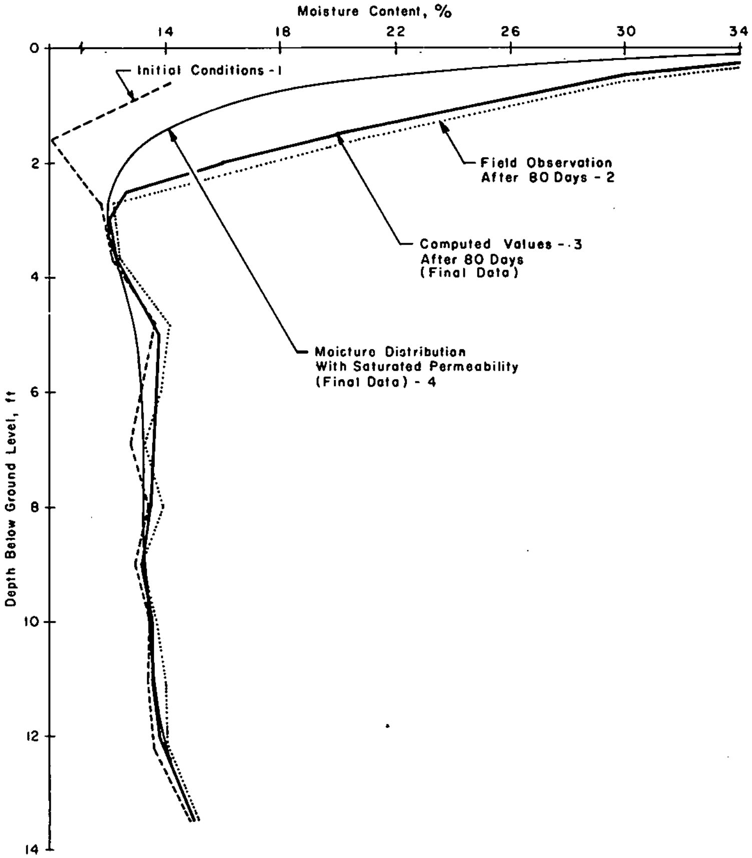


Figure 2. Moisture distribution study at tube 16.



Because moisture cycling is seasonal and not a daily change, moisture variations do not impose the large number of repeated stresses that temperature variations do. However, it is possible that significant changes in moisture content can result in severe pavement cracking. Work is beginning in west Texas at the present time to relate moisture-change stresses to pavement distress; however, no data are yet available.

In terms of evaluating strength for use in design evaluation, most designers evaluate feedback data from existing pavements in similar situations to determine the prevailing moisture conditions. In general, the water content often rises to near the liquid limit in many subgrades and stabilizes. Chu et al. (15) discuss a method of estimating moisture conditions based on laboratory tests.

Temperature

Of all environmental inputs, temperature is the easiest to estimate and use and is, therefore, used in more procedures than other environmental factors. Temperature stresses can often be as high as load stresses, as has been shown in numerous studies, particularly in rigid pavements, where temperature stresses are due to curling, warping, expansion, or contraction. Those same types of stresses are present in asphalt concrete pavements. They are tensile or compressive stresses due to increase or decrease in the general level of temperature and bending stresses due to temperature differential within the pavement structure itself.

The tensile or compressive stresses are due to general or seasonal changes in the level of temperature, as are the resulting changes in material properties, notably asphalt stiffness. The bending stresses, on the other hand, are due to diurnal or daily temperature cycles or variations. Much work has gone into the study of temperature in asphaltic concrete pavements. However, much remains to be learned in applying the resulting information to pavement design.

Temperature Stresses and Distress

In considering temperature, a number of authors have made significant contributions. Of particular note is work by Haas (16) and by Haas and Topper (17). That work refers to "low-temperature cracking" (Fig. 3). In reality, the effects are aggravated by low temperatures that tend to cause brittle mixes. The problem is equally applicable, however, to large changes in temperature, even though at higher levels. In west Texas, for example (18), a significant amount of temperature cracking has been observed and related to temperature variations.

Prediction of Temperature

Several approaches have been taken to the problem of predicting temperature input data.

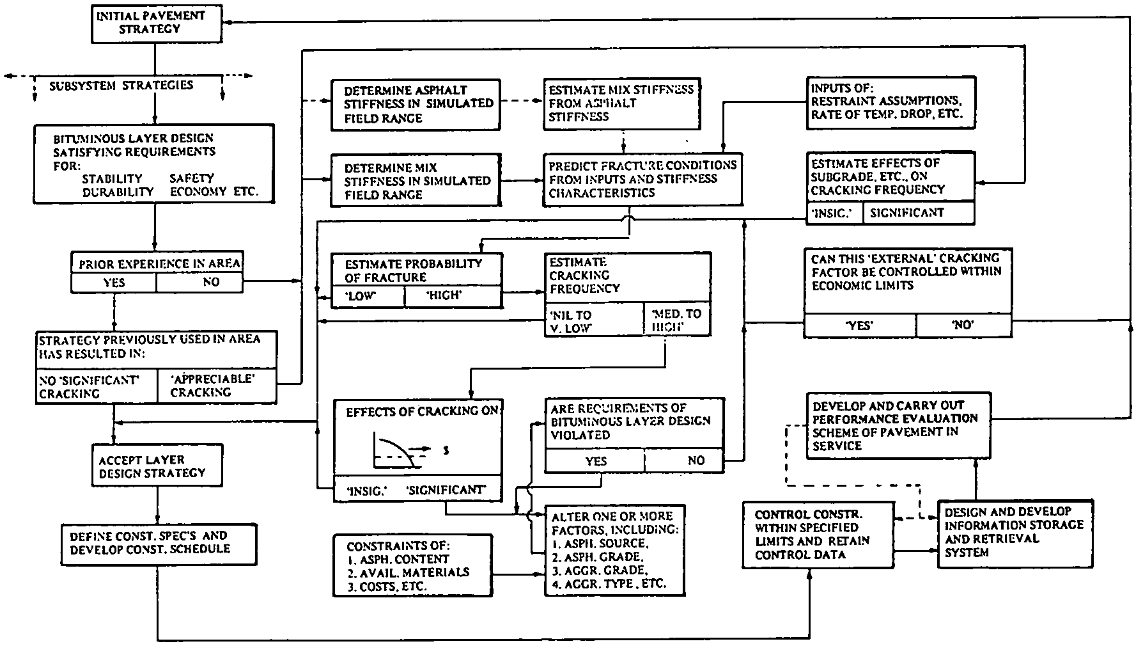
1. General design adjustments have been made for "regional or environmental factors" (6, 19);
2. Design procedures have been developed that will relate to a general climatic area where an annual cycle of temperature, freezing, and so on will be about the same from year to year [that is the general approach taken by Haas and Topper, as shown by Figure 4 (16), in which "prior experience of cracking in the general area" is considered in the design]; and
3. Temperature profile and history of a particular pavement are predicted based on available weather data [significant work has been done in that area by Shahin and McCullough (18)].

Shahin and McCullough have developed a system for predicting daily temperature cycling during an average year. The system has the capability of simulating the temperature cycling at any depth from the surface of an asphalt concrete layer, assuming that the layer is semi-infinite. A model was developed by which asphalt

Figure 3. Factors of possible significance in low-temperature cracking of flexible pavements.

LOW TEMPERATURE CRACKING OF FLEXIBLE PAVEMENTS				General Problem
Surface	Base	Sub-base	Subgrade	Component In Which Cracking May Initiate
Cracking Remains in Surface	Cracking Through Pavement Structure	Cracking Through Pavement Structure	Cracking Through Pavement Structure	Initial Possible Result
1. Low Temp. and Temp. Cycles 2. Action of Water (Stripping) 3. Traffic Loads 4. Sunlight, Air and Age 5. Reflection Cracking 6. Construction "Quality" and Uniformity	1. Low Temperatures 2. Traffic Loads 3. Water Intrusion 4. Intrusion of Fines 5. Reflection Cracking 6. Construction "Quality" and Uniformity	1. Low Temperatures 2. Traffic Loads 3. Water Intrusion 4. Intrusion of Fines 5. Reflection Cracking 6. Construction "Quality" and Uniformity	1. Low Temperatures 2. Freezing Shrinkage 3. Intrusion of Water 4. Construction "Quality" and Uniformity	Possible External Factors
1. Time & Age Dependent Tensile Strength and Strain 2. Asphalt and Aggregate Type and Composition 3. Density, Voids and Asphalt Content 4. Aggregate Grading 5. Bond Between Layers 6. Thermal Conductivity 7. Long Joint Construction	1. Aggregate Type, Composition and Grading 2. Density, Voids and Water Content	1. Aggregate Type, Composition and Grading 2. Density, Voids and Water Content	1. Soil Plasticity and Mineralogical Character 2. Voids, Density and Degree of Saturation 3. Resiliency	Possible Component Factors

Figure 4. Tentative design and management subsystem for response of flexible pavements at low temperatures.



concrete temperatures during a single day can be predicted on an hourly basis. Figure 5 shows a comparison of temperatures predicted from the program and those measured (20).

The inputs to the model are daily mean air temperature, daily air temperature range, daily mean solar radiation, daily average wind velocity, and asphalt concrete thermal properties. The pavement temperature cycling during an average year is simulated by consideration of the day-to-day variations of its inputs. In doing so, Shahin and McCullough assume that the pavement thermal properties are constant. Meanwhile, they found that the daily mean air temperature and solar radiation are the most significant factors affecting pavement temperatures; therefore, equations to account for their variation were developed. From those equations, the daily mean air temperatures can be estimated for any day of the year, providing that the annual average and the range of air temperature are known. Similarly, the daily mean solar radiation can be estimated for any day of the year, providing that the July and annual averages of solar radiation are known. Figure 6 (18) shows a schematic diagram of the system.

Monismith et al. (21) developed a technique for predicting temperature distributions based on the heat-conduction equation:

$$\mathrm{TA(N) = ANNVE + (ANR/2)\ COS(N)}$$

A typical temperature-time relation from their work is shown in Figure 7.

In general, methods such as those illustrated here can be used to predict the expected temperature-time history profiles for a particular design situation. Care must always be exercised, however, to ensure that such complex prediction models are compatible with reality. That can be done by a realistic comparison with measured temperature variations. Measured temperature variations in pavements can also be used to develop direct empirical temperature prediction equations.

Temperature Measurements

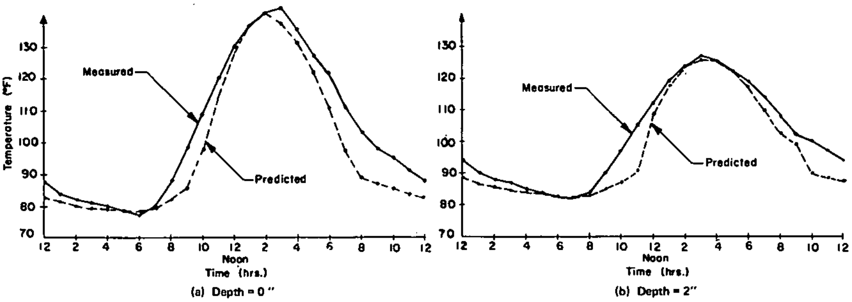
To evaluate temperature prediction models or to develop empirical temperature models requires some knowledge of the real temperature gradient present in a pavement. In 1966, Kallas (20) reported the results of a large series of temperature studies in thick asphalt concrete pavements. Results from those studies (Fig. 8 and Tables 1 and 2) can be used in a variety of ways to estimate temperatures for use in fatigue analysis or design.

Likewise, a large series of temperature measurements was taken at the AASHO Road Test. As shown in Figure 9 (5), deflection measurements on the pavements were highly correlated with the temperature or the time of year. Extremely low deflections were recorded for periods of frost. Because of the large installation of thermocouples, it was possible at the road test to develop isotherms for pavement sections, as shown in Figure 10 (5). An important part of the road test data involved the relation of pavement deflections and temperature. Typical information concerning that relation is shown in Figure 11 (5). Deflection-temperature relations basically involve changes in the material properties, i.e., stiffness, with changes in temperature. In all cases, decreased temperatures resulted in increased pavement stiffness and decreased deflection, as would be expected. The only variance with that relation occurred in the spring when the frost left the ground and moisture, which had accumulated during the freeze-thaw cycles, softened the subgrade and base materials to the point that greater deflections resulted. That relationship is supported by the observed deflections in the asphalt-stabilized base sections where the decreased temperatures could be expected to show low deflections, even though the subgrade was softened slightly by the accumulation of moisture. The observed data confirmed that hypothesis.

SUMMARY

In this brief report, we have considered 3 main categories of inputs to the pavement fatigue design subsystem: traffic, moisture, and temperature.

Figure 5. Measured and predicted pavement temperatures at College Park, Maryland, June 30, 1964.



(a) Depth = 0"

(b) Depth = 2"

Figure 6. System for simulating asphalt concrete temperature cycling.

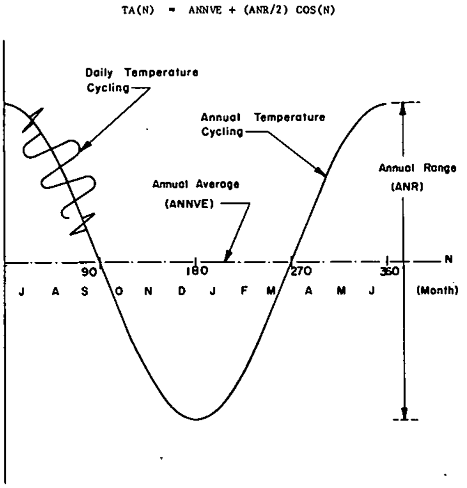


Figure 7. Temperature and time relation at various depths within slab for surface temperature variation of 0 to -40 F.

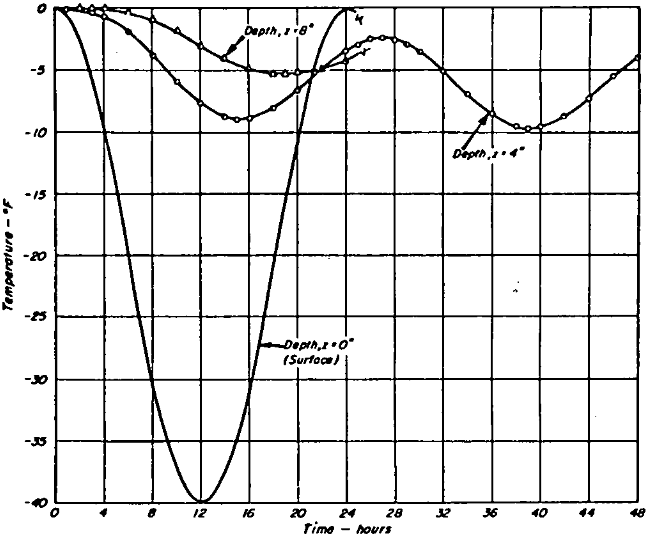


Figure 8. Asphalt concrete pavement temperatures on June 30, 1964.

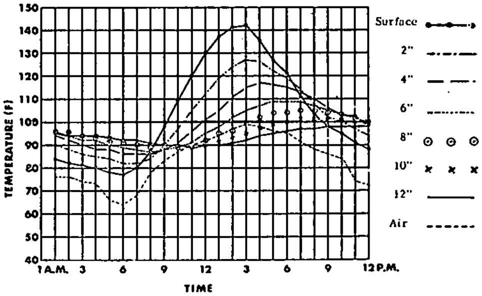


Table 1. Yearly duration of temperature levels of 12-in. asphalt concrete pavement.

	Duration (percentage of year) of Temperature Ranges (F)															Temperature Level (F)				
Measurement Position	0 to 9	10 to 19	20 to 29	30 to 39	40 to 49	50 to 59	60 to 69	70 to 79	80 to 89	90 to 99	100 to 109	110 to 119	120 to 129	130 to 139	140 to 149	Avg	Avg High	Avg Low	High	Low
Air	-	2	7	15	19	17	17	14	7	2	-	-	-	-	-	54	65	41	99	2
Surface	-	1	5	11	17	15	13	14	9	5	4	3	2	1	-	64	87	48	142	9
2-in. depth	-	-	4	11	18	15	12	13	11	7	5	3	1	-	-	64	83	51	127	14
4-in. depth	-	-	2	11	18	17	12	11	14	9	5	1	-	-	-	64	74	55	119	18
6-in. depth	-	-	1	10	20	18	12	10	16	10	3	-	-	-	-	63	71	56	109	20
8-in. depth	-	-	1	9	21	18	12	9	18	11	1	-	-	-	-	64	69	58	105	23
10-in. depth	-	-	1	8	22	18	13	8	20	10	-	-	-	-	-	63	67	59	101	25
12-in. depth	-	-	-	7	24	17	13	8	22	9	-	-	-	-	-	64	66	60	98	27

Table 2. Monthly duration of temperature levels of soil below and adjacent to pavement.

		Duration (percentage of month) of Temperature Ranges (F)						Temperature Level (F)				
Measurement Period	Measurement Position	20 to 29	30 to 39	40 to 49	50 to 59	60 to 69	70 to 79	Avg	Avg High	Avg Low	High	Low
November 1964	6-in. below 6-in. pavement	-	-	14	81	5	-	55	56	53	61	43
	12-in. depth in soil	-	1	35	64	-	-	50	52	48	56	38
	6-in. below 12-in. pavement	-	-	10	84	6	-	56	57	55	61	47
	18-in. depth in soil	-	-	27	73	-	-	51	52	50	56	42
December 1964	6-in. below 6-in. pavement	-	18	78	4	-	-	43	45	42	50	36
	12-in. depth in soil	-	43	57	-	-	-	40	42	38	49	33
	6-in. below 12-in. pavement	-	5	92	3	-	-	45	46	44	50	38
	18-in. depth in soil	-	20	80	-	-	-	42	43	41	48	36
January 1965	6-in. below 6-in. pavement	-	58	42	-	-	-	39	40	37	48	31
	12-in. depth in soil	-	80	20	-	-	-	35	36	34	45	30
	6-in. below 12-in. pavement	-	53	47	-	-	-	39	40	39	48	31
	18-in. depth in soil	-	67	33	-	-	-	37	37	36	45	31
February 1965	6-in. below 6-in. pavement	-	20	80	-	-	-	42	44	40	48	30
	12-in. depth in soil	-	51	49	-	-	-	39	40	37	46	30
	6-in. below 12-in. pavement	-	16	84	-	-	-	43	44	41	48	33
	18-in. depth in soil	-	38	62	-	-	-	39	40	39	46	33
March 1965	6-in. below 6-in. pavement	-	1	87	12	-	-	48	50	45	56	39
	12-in. depth in soil	-	11	88	1	-	-	43	44	40	50	36
	6-in. below 12-in. pavement	-	-	82	18	-	-	48	49	46	54	42
	18-in. depth in soil	-	1	99	-	-	-	43	44	42	48	38
April 1965	6-in. below 6-in. pavement	-	-	6	74	20	-	56	59	53	67	45
	12-in. depth in soil	-	-	43	57	-	-	49	51	47	59	40
	12-in. pavement	-	-	3	78	19	-	56	58	54	64	48
	18-in. depth in soil	-	-	45	55	-	-	49	50	48	56	42

Figure 9. Seasonal deflection on nontraffic loop, 6-kip single axle load.

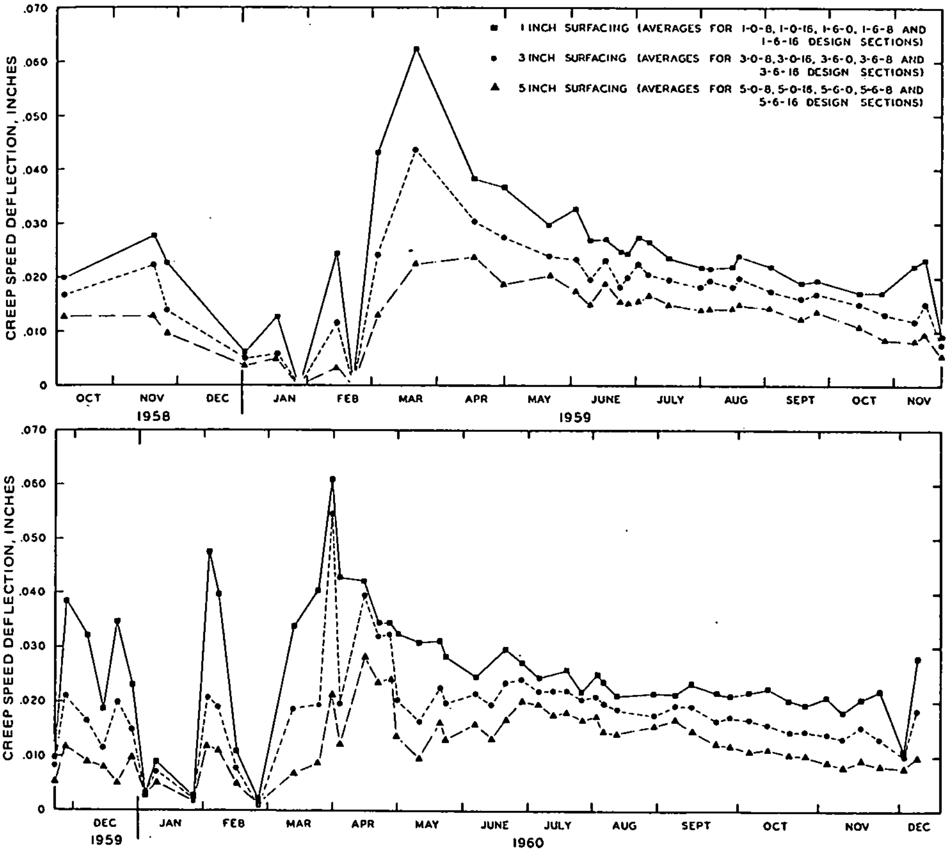


Figure 10. Isotherms (3-0-16 design) of loop 1 for March 25, 1960 (left), and May 25, 1960 (right).

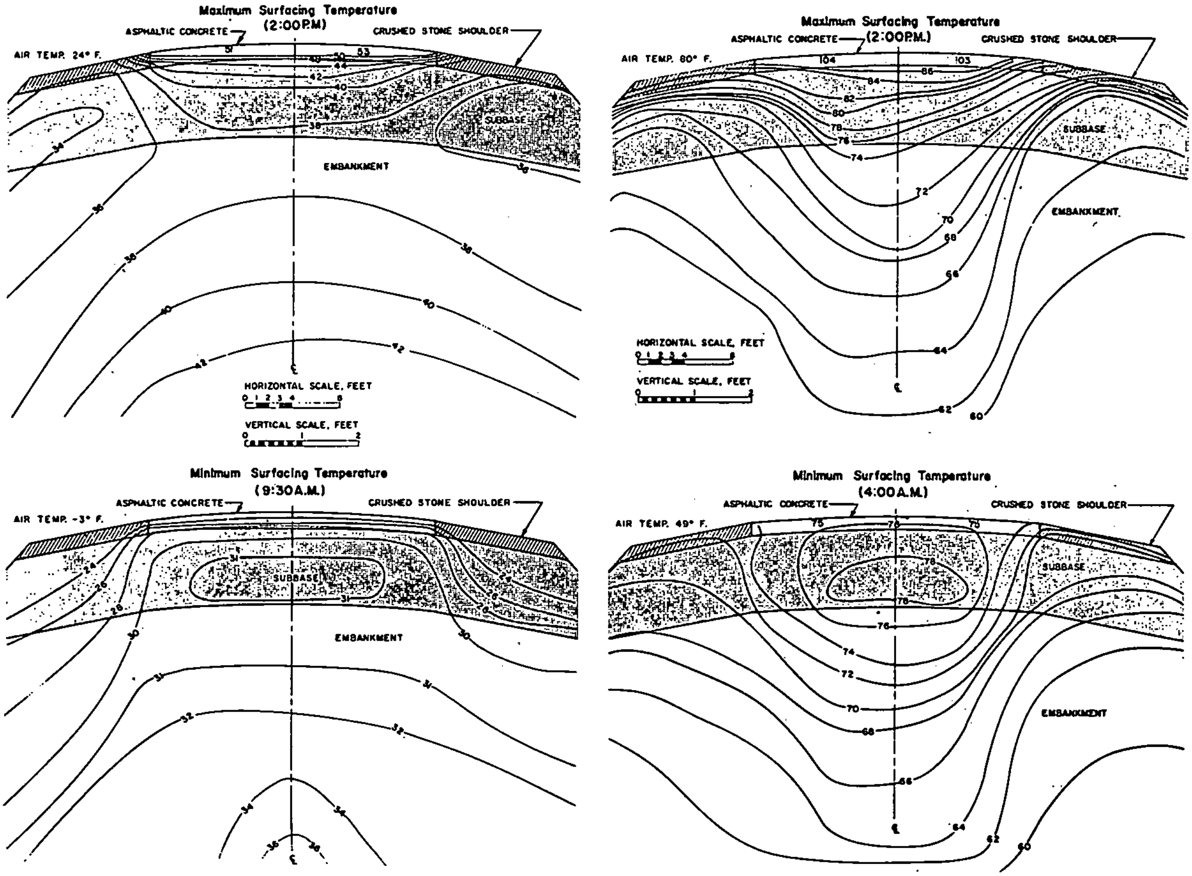
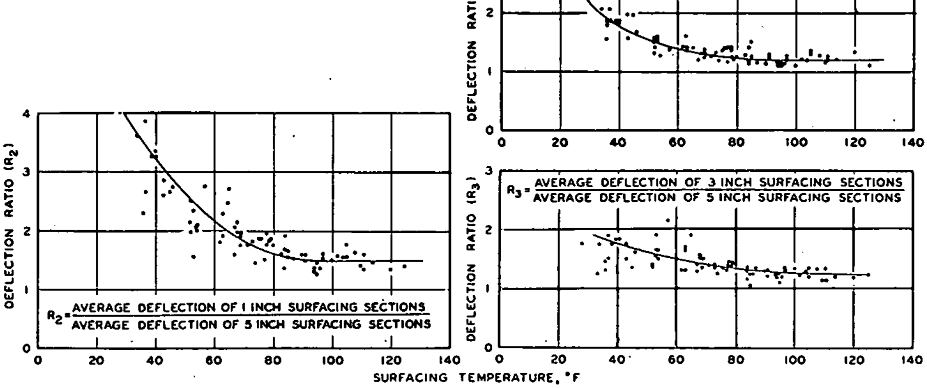


Figure 11. Deflection and temperature relation for loop 1, 6-kip single axle load.



In the present state of the art, there are adequate methods for estimating traffic data based on past experience and prediction models. Temperature can also be predicted with some degree of adequacy based on existing weather data. Moisture is perhaps the hardest to evaluate. No present method is completely adequate to predict moisture effects in the pavement, although work is under way to improve the techniques.

Future improvements in pavement design systems in terms of traffic and environmental variables will of necessity involve some consideration of the stochastic variations in the predicted values. Thus, the final designs will probably involve statistical confidence levels in lieu of conventional safety factors. However, adequate data are now available to develop rational fatigue design subsystems.

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