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16. Abstract

The purpose of this report is to present a method that uses climatic data for the prediction of permanent deformation in asphalt overlays on the top of concrete pavements. Thirty years of detailed climatic data from the Dallas area were collected to calculate the temperature variations in asphalt concrete overlays by a heat transfer computer program. After extensive statistical analysis, a regression model was developed to simulate the temperature fluctuations in asphalt overlays, and a small number of mini-seasonal profiles were obtained to describe the temperature variations for the prediction of permanent deformation by a modified finite-element computer program. The regression model can also be used as a means to find a relationship between temperature variations and traffic patterns. This analysis method can be applied to low temperature thermal cracking prediction and resilience studies, and can be used for any pavement system, meteorological condition and geographical location.

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USE OF CLIMATIC DATA FOR THE PREDICTION
OF PERMANENT DEFORMATION IN FLEXIBLE PAVEMENTS

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Research Report 452-2
Research Study 2-8-86-452

Sponsored by
Texas State Department of Highways and Public Transportation
In cooperation with
U.S. Department of Transportation, Federal Highway Administration

Texas Transportation Institute
Texas A&M University System
College Station

November, 1989

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

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

AREA

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

MASS (weight)

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

VOLUME

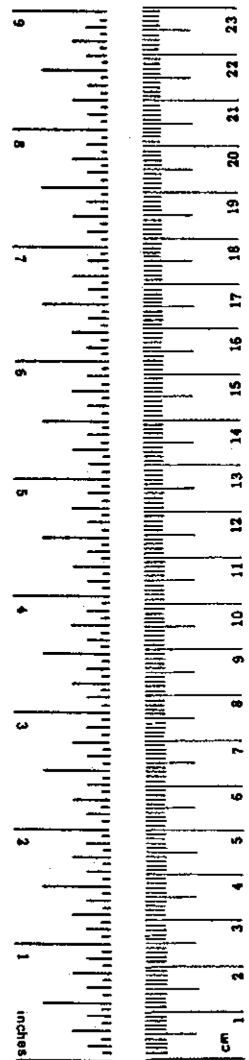
Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

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

TEMPERATURE (exact)

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

* SI is the symbol for the International System of Measurements



APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

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

AREA

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

MASS (weight)

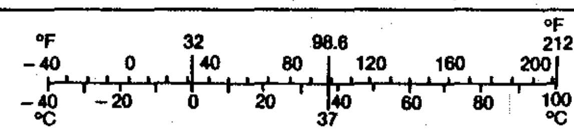
Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

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

TEMPERATURE (exact)

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



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

ABSTRACT

The purpose of this report is to present a method that uses climatic data for the prediction of permanent deformation in asphalt overlays on the top of concrete pavements. Thirty years of detailed climatic data from the Dallas area were collected to calculate the temperature variations in asphalt concrete overlays by a heat transfer computer program. After extensive statistical analysis, a regression model was developed to simulate the temperature fluctuations in asphalt overlays, and a small number of mini-seasonal profiles were obtained to describe the temperature variations for the prediction of permanent deformation by a modified finite-element computer program. The regression model can also be used as a means to find a relationship between temperature variations and traffic patterns. This analysis method can be applied to low temperature thermal cracking prediction and resilience studies, and can be used for any pavement system, meteorological condition and geographical location.

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IMPLEMENTATION STATEMENT

The regression models developed in this research offer the capability of defining the temperature profile within an asphalt concrete overlay at any location in Texas and at any time of day and year. The regression models can be used with traffic data, and the effects of temperature profile and traffic can be superimposed to evaluate the development of permanent deformation, rutting. This is achieved by incorporating the regression models and traffic density function into the modified ILLIPAVE computer program.

This procedure provides a realistic technique by which to analyze rutting case histories in asphalt concrete overlays over PCC pavements in Texas.

DISCLAIMER

INTRODUCTION

GENERAL

The permanent deformation, or rutting, of asphalt concrete pavements has in recent years attracted much attention because excessive rutting in pavements can create a serious safety hazard. However, most investigators have concentrated their efforts on developing mix design methods which permit mechanical optimization of the stability of asphalt mixes, while placing little emphasis on performance requirements related to pavement structure, climate, and traffic. Few methods of dealing with permanent deformation in a quantifiable and rational way have been used in practical pavement design. In most studies, one single temperature or a few seasonal temperatures with a uniform temperature distribution in the asphalt layers have been used to describe the variations of temperature. Usually, no relationship between temperature distributions and traffic distributions is considered.

One well known method is the Shell Method described in the Shell Pavement Design Manual (1). In this method, variations of temperature within asphalt layers and of traffic are considered with the following major assumptions (2, 3):

1. The total thickness of the asphalt layer is divided into several sub-layers, and the temperature and mix properties are uniform and constant within each sub-layer.

2. The effective asphalt temperature for a year (T year) can be obtained from the weighted mean annual air temperature (w-MAAT). The weighing factor w takes the location and pavement structure into account. In other words, one effective temperature can be used to represent the total temperature variations in the whole analysis period.

3. Traffic density is uniformly distributed over the whole life of the pavement. There is no relationship between different temperature distributions and traffic patterns.

The impetus behind these assumptions is that temperature and traffic are difficult to predict and to determine accurately. However, mix properties, such as stiffness, are very susceptible to temperature changes. It is very doubtful that the effective asphalt temperature used for total rutting depth calculations could simulate the real life rutting accumulation of asphalt concrete pavements. For example, it is impossible to tell how much more rutting occurs during hot summer seasons than occurs during cold winter seasons, or how different traffic patterns could affect permanent deformation.

In a study conducted by ARE Inc. (4), seasonal temperature variations for different locations have been taken into account. Four typical zones for the climatic conditions of Texas, each containing four seasonal temperatures for the whole asphalt layers, were developed:

ZONE	SEASON	TEMPERATURE °F
WET-FREEZE:	Winter	35
	Spring	65
	Summer	95
	Fall	60
WET-NO-FREEZE:	Winter	75
	Spring	95
	Summer	105
	Fall	60
DRY-FREEZE:	Winter	35
	Spring	65
	Summer	95
	Fall	50
DRY-NO-FREEZE:	Winter	55
	Spring	75
	Summer	95
	Fall	75

Since temperature gradients within asphalt layers were neglected, this approach results in a very rough estimation of the temperature distributions in asphalt layers. In the study of the Brampton Test Road conducted by the University of Waterloo (5), the seasonal variations of the area and the temperature profiles within asphalt layers were both considered. The study was done based on the following three assumptions:

1. Permanent deformation occurs daily over the interval 7:30 to 17:30 hours.
2. Permanent deformation occurs only in the period April through October
3. Permanent deformation can be ignored at temperatures below 50°F.

Based on these assumptions, the average monthly temperature distributions shown in Figure 1 were obtained. The seven temperature profiles were used to represent the temperature variations within asphalt layers for a period of one year. Although the seasonal temperature variations and temperature gradients in asphalt layers are considered in this study, the following problems still remain to be addressed:

1. In Texas the temperatures in asphalt layers after 5:30 P.M. is well above 50°F during summer months.
2. The temperature differences in asphalt layers could be easily more than 30°F on hot summer days in Texas. One single profile does not reflect such large variations.

In the three methods discussed above the variations of temperatures in asphalt layers with depth of the layers has not been properly considered. Neither has the daily changes in the temperature combined with the changes in traffic pattern over the same period of time. Since rutting is influenced not only by the temperature and traffic loads, but also by the distribution and combination of temperature and loads with time, a more detailed analysis of these two major factors needs to be considered in the rutting analysis of asphalt pavement structures.

Based on the assumptions behind and results of the existing temperature models, a new model is needed which considers the varying

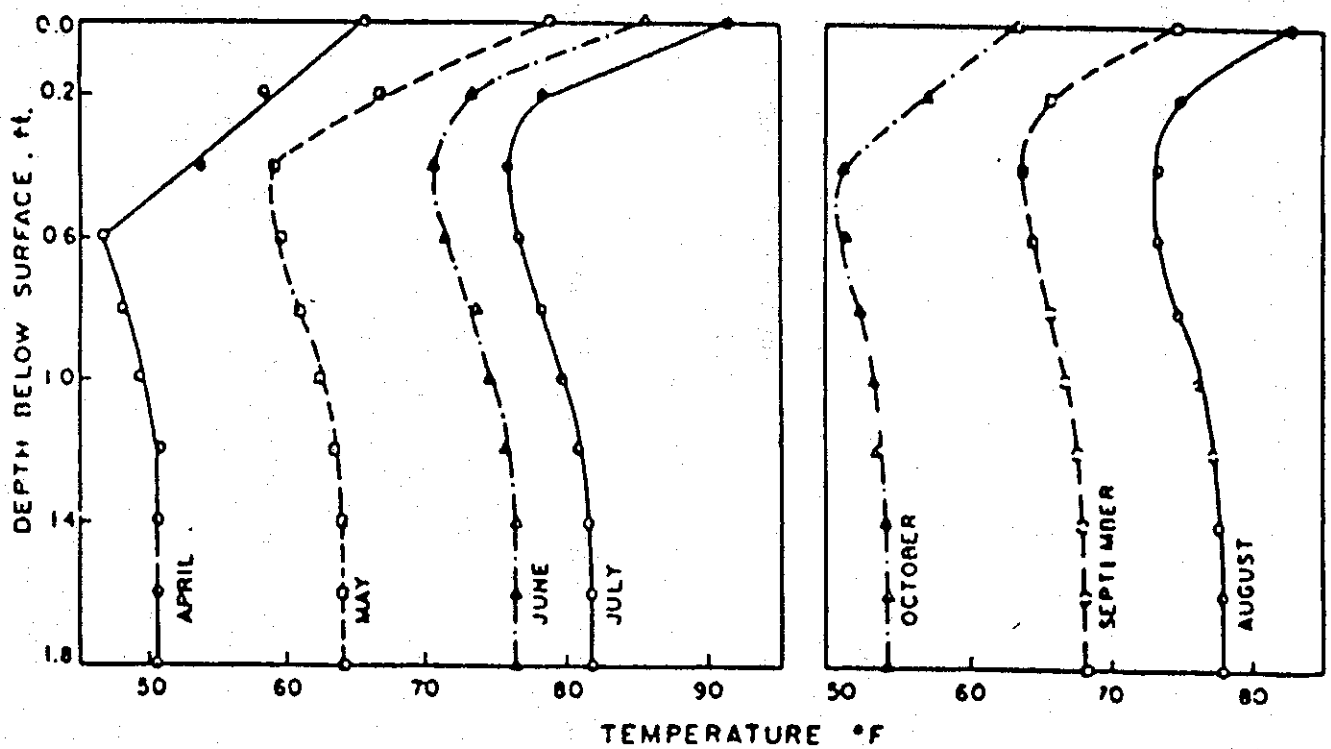


Figure 1. Average Monthly Pavement Temperature-Depth Relations.

temperatures and temperature profiles within the asphalt pavement layers, based on local and long term climatic history.

As part of an extensive research program to develop a rational procedure for predicting permanent deformation of asphalt concrete overlays on concrete pavements in Texas, a new methodology (Figure 2) has been developed at Texas A&M University. In this method, the prediction of rutting depths is based upon a new method of characterizing permanent deformation in terms of three parameters, and the use of this new method in a modified ILLIPAVE finite element computer program (6, 7, 8). The three parameters, ϵ_0, ρ, and β, are obtained from the results of creep or repeated load triaxial tests at different temperatures. To use this information it is necessary to develop a temperature distribution model which predicts the temperature range occurring in the field. This temperature range can then be used in the creep or repeated load triaxial tests and in characterizing the asphalt properties of permanent deformation at the predicted field temperatures.

OBJECTIVES

The objectives of this study are:

1. To develop a mathematical model which describes the temperature distributions in asphalt concrete overlays.
2. To provide a number of temperature profiles, which reasonably represent the temperature variations in the asphalt overlays in Texas, for use in the prediction of permanent deformation.
3. To develop a method which effectively accounts for temperature distribution in the asphalt pavement layers and the traffic density functions in the evaluation of permanent deformation.

The schematic outline of the procedure for temperature and traffic considerations is shown in Figure 3.

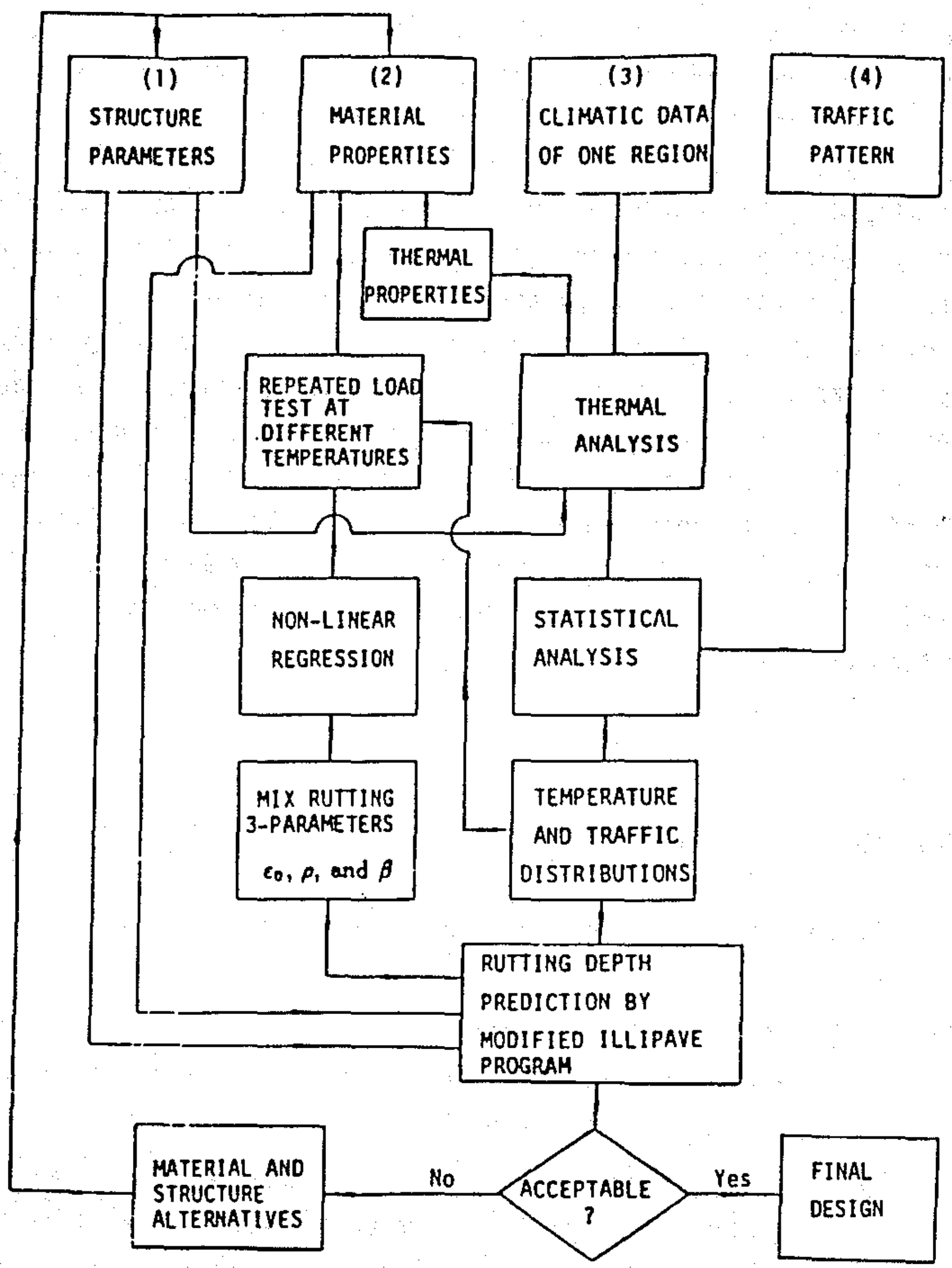


Figure 2. Schematic Outline for Rutting Depth Prediction.

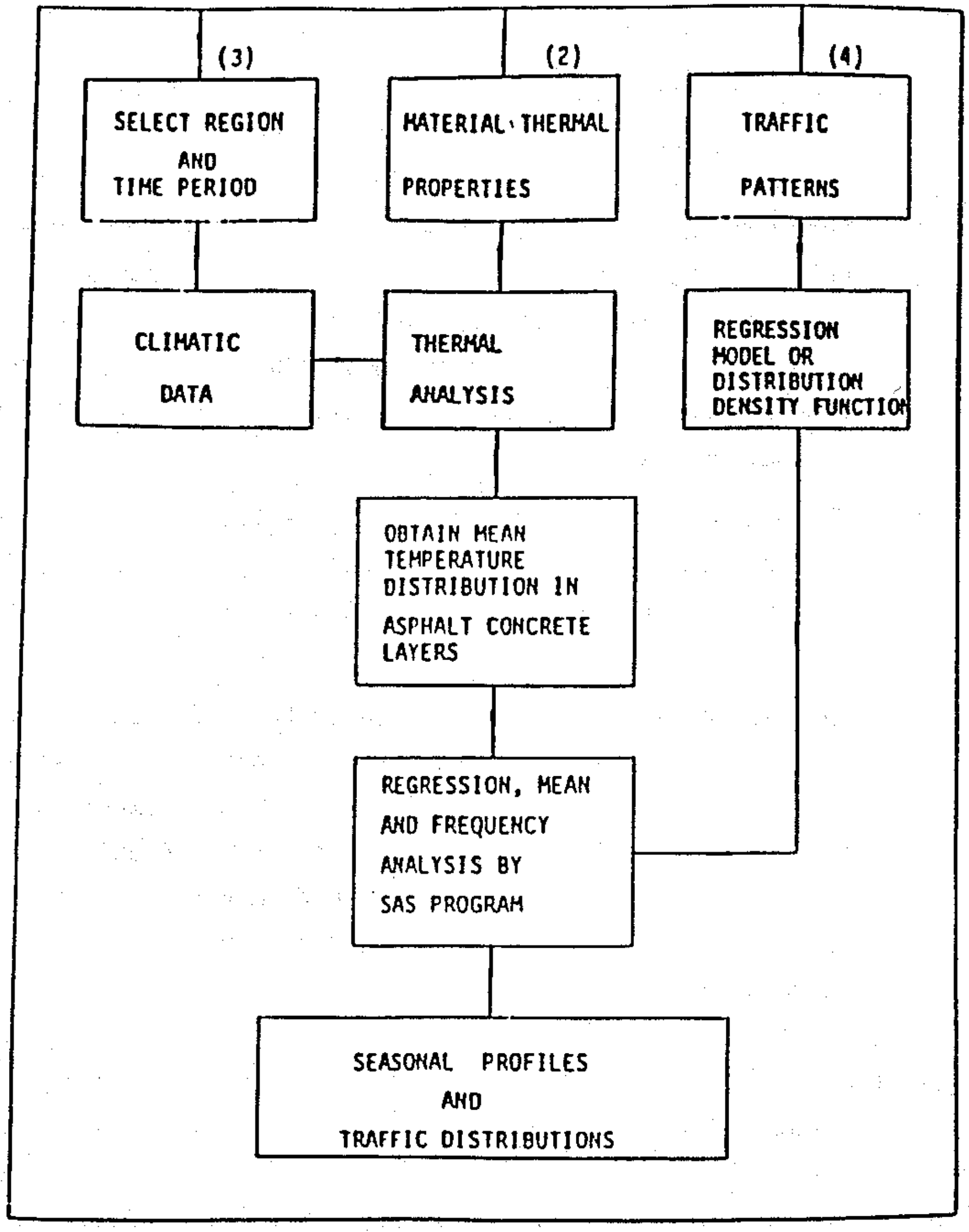


Figure 3. Schematic Outline of the Procedure for Temperature and Traffic Considerations.

CLIMATIC CONSIDERATIONS

ASSUMPTIONS

In order to simplify the analysis and to perform reliable statistical analysis, several assumptions were made.

1. Permanent deformation occurs mostly in the period from May to October. For the remaining half year, it is assumed that the whole period may be treated as one single season. One temperature, a seasonal mean temperature with a uniform temperature distribution in the asphalt layer over the whole period, was used.
2. The accumulation of permanent deformation is independent of loading history and only dependent on total cycles of loading, loading frequencies and loading magnitude under certain temperature conditions.
3. The air temperature at a particular time of a day is correlated with the temperatures of the previous and future days at the same time of day. The same is true for the temperature in the asphalt layer. In other words, a correlation exists between today's 8 A.M. temperature, and yesterday's 8 A.M. temperature and today's 8 A.M. temperature and tomorrow's 8 A.M. temperature.

Assumption 1 is based on the fact that most rutting is accumulated during hot summer months. Under this assumption, the period of analysis can be reduced substantially. Assumption 2 is a reasonable and necessary assumption to characterize asphalt concrete materials. Under this assumption, it is assumed that asphalt mixes are viscoelastic materials and that the stiffness of the mix is a function of temperature and loading frequency only. Assumption 3 is based on the nature of meteorology, and the assumption is essential to reduce the variance in statistical analysis.

CLIMATIC REGIONS AND DATA COLLECTION

It is well established that the climate in Texas is quite changeable from day to day, from year to year, and from place to place. Texas was, therefore, been divided into 4 regions (Figure 4), each representing distinct climatic features (I-cold, and dry, II-moderate and wet, III-moderate and dry, IV-hot and wet). The map of average monthly high temperature of July (Figure 5) was also used to help in establishing the regions.

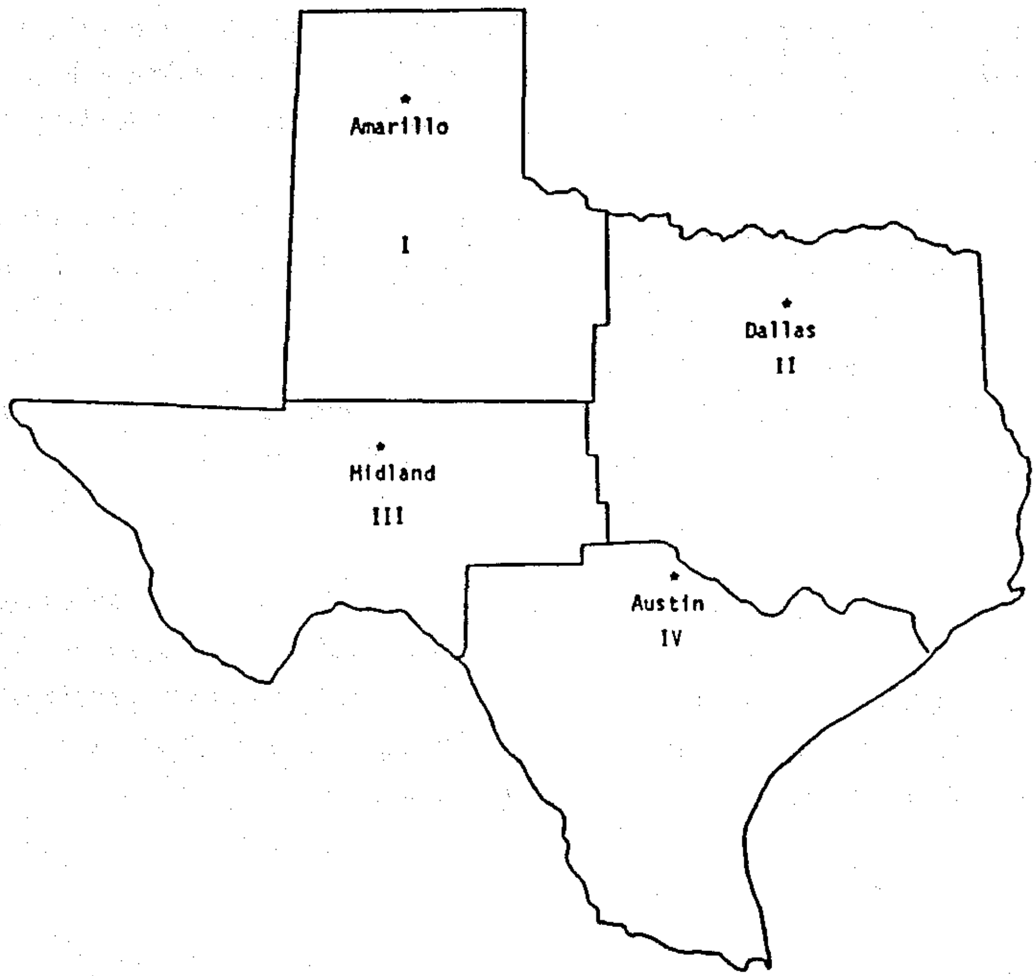
In each region, one station which was able to provide sufficient climatic data records was chosen. One criterion used in choosing the station was that the maximum temperature difference between the average monthly high temperature at a location within a given region and the temperature of the representative station did not exceed station 5°F. However, some disagreements in low temperatures between points of location were ignored because rutting is much less significant at lower temperatures.

Thirty year climatic date (from 1955 to 1984) for each selected regional station (Amarillo, Dallas, Midland, and Austin) were obtained from the National Climatic Data Center in Asheville, North Carolina. However, only 180 days (May 1 through October 27) each year were considered in actual temperature calculations.

TEMPERATURE CALCULATIONS

To determine the relationship between environmental conditions and the temperature profiles in pavement layers, a model developed by Dempsey (9) was used. This model was originally developed to evaluate frost action in multilayered pavements. In this study, the model was used to calculate the temperature profiles in pavement layers.

Dempsey's heat transfer model is a one-dimensional, forward finite-difference model which provides a means for predicting temperatures in multilayered pavement systems. A flow diagram of the computer program and a more detailed description of the program can be found in Reference 9. The accuracy of the temperatures predicted by this model depend mainly on the quality of the input data, especially the environmental



I ---	Amarillo	(93)	91 - 98^{0}F	
II --	Dallas	(96)	90 - 99^{0}F	(88 - 90^{0}F in small area)
III -	Midland	(95)	92 - 102^{0}F	(83 - 92^{0}F in small area)
IV --	Austin	(95)	90 - 100^{0}F	(88 - 90^{0}F in small area)

Figure 4. Regional Map of Texas.

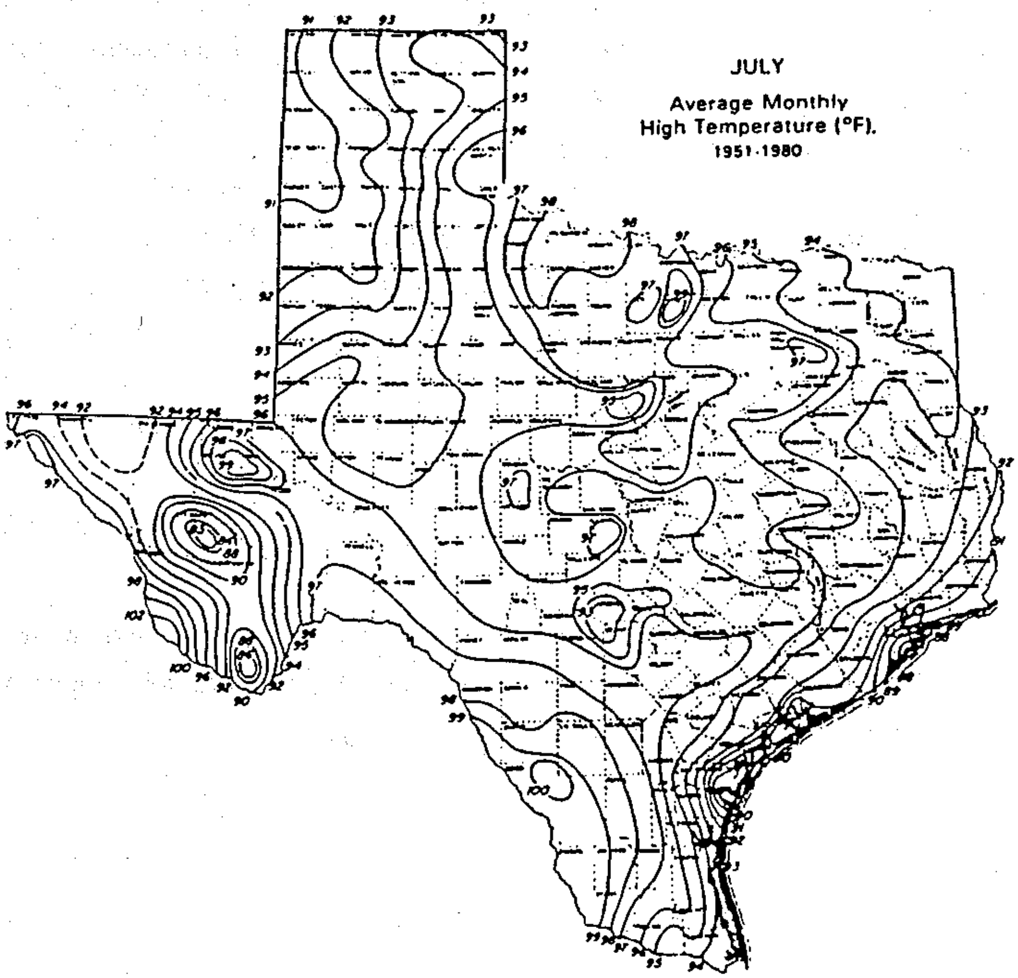


Figure 5. Average Monthly High Temperature of July.

data, and not the numerical method of solution. Based on many calculations (9), it has been found that substantial variations in the thermal properties of the pavement materials do not cause large errors in the predicted temperatures compared to field measured data. The benefit of this conclusion is obvious. By running the program using a typical pavement structure and typical thermal properties of pavement materials, the results obtained can be applied to a wide range of pavement structures with different thermal properties.

The pavement system used in this analysis is shown in Figure 6. The required input data for the program are listed in Appendix A. The results of the program consists of the temperature profile of the 40 nodal points for each hour of each day considered. In this study, the temperature profiles within the asphalt overlays were the only concern. Therefore, the program was changed in the following two areas:

1. The subroutine used for the analysis of frost action was deleted, and
2. A new subroutine called STAT (Appendix B) was developed to perform primary data analysis on the results of temperature calculations in the asphalt overlay.

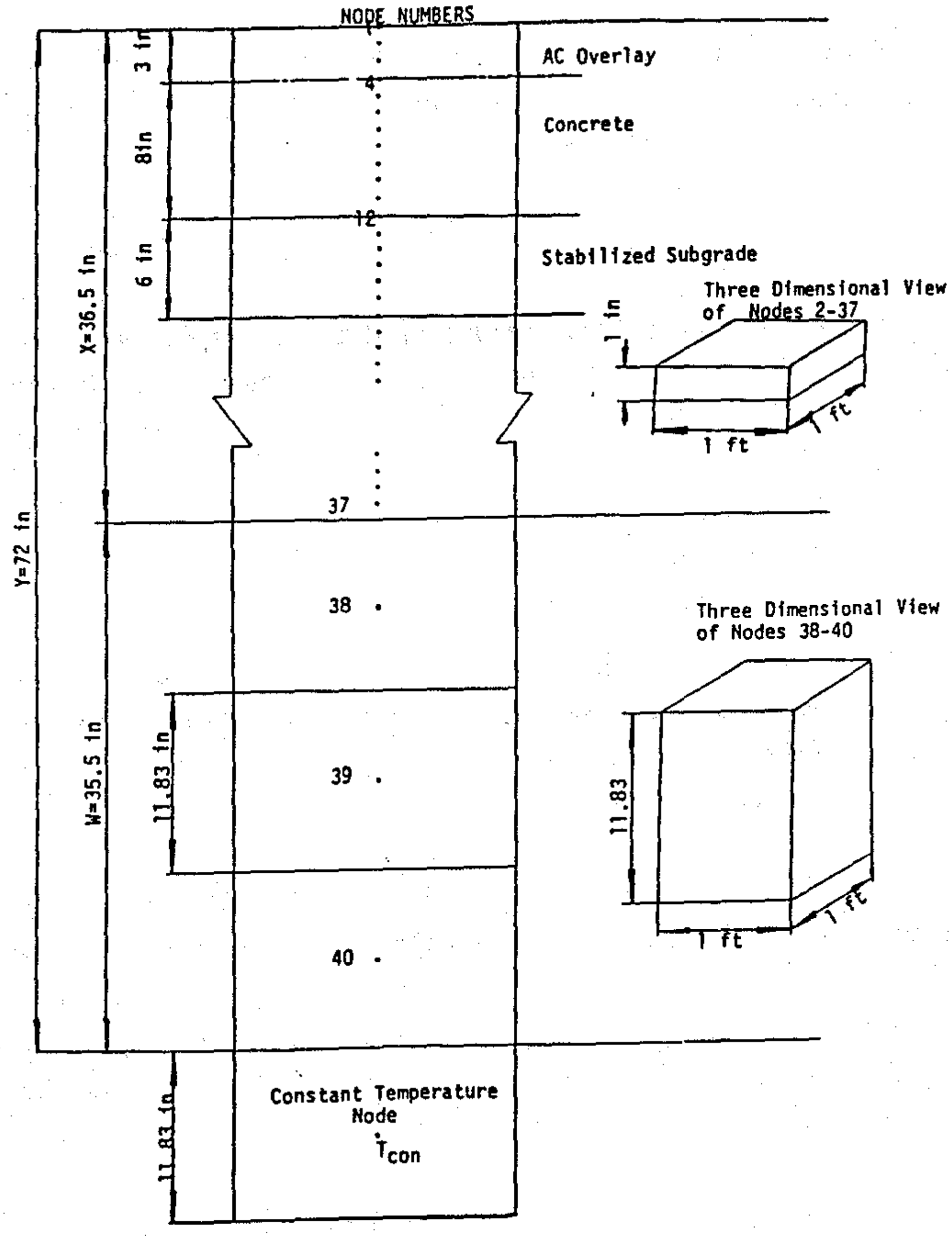


Figure 6. A Typical Finite-Difference Pavement System.

STATISTICAL ANALYSIS

PRIMARY DATA ANALYSIS

A vast amount of output results were generated from the temperature calculations. For example, the number of the calculated temperatures for a 5 inch asphalt overlay is:

$$(1 + 5_{\text{sub-layers}}) \times 180_{\text{days}} \times 30_{\text{years}} = 777{,}600 \qquad (1)$$

To handle such a large volume of data is was necessary to use statistical analyses techniques. To reduce the variability and to improve the accuracy, the analysis procedure was therefore divided into two steps:

1. Primary data analysis to reduce the variance as well as the data size for further analysis.
2. Statistical analysis to develop a temperature distribution model and a number of temperature profiles by the SAS program (10) which includes linear regression, mean analysis and frequency analysis.

The primary data analysis was done using STAT. In this subroutine, the variance was reduced by first calculating a weighted 5 day mean temperature and assigning this mean value to the temperature in the middle of the five day period. This was done for every day of a year, every hour of a day, for 30 years, and each nodal point in the asphalt overlays. The formula reads as follows:

$$T_{i,j,k,m} = \frac{T_{i,j-2,k,m} + T_{i,j-1,k,m} + T_{i,j,k,m} + T_{i,j+1,k,m} + T_{i,j+2,k,m}}{5} \qquad (2)$$

where:

T - Temperature in the asphalt layer,

i - Time of the day (i = 1, 2,•••24 hours), j - Day of the year (j = 3, 4,•••178),

K - Nodal point in the asphalt overlay (k = 1, 2,•••n+1, η is the total number of sub-layers) and

m - Year (m = 1, 2•••30 years).

Equation 2 is based on the previously discussed assumption that the temperature in an asphalt layer is a variable and depends on the temperatures of the days surrounding it.

In the next step the 180 warmer days were divided into 36 5-day periods. An arithmetic average of temperature for the 5 day periods was calculated for each year of the 30 year period, each hour of the day, and each nodal point in the asphalt overlays. The applicable formulas read as follows:

$$T_{i,l,k,m} = \frac{T_{i,j,k,m} + T_{i,j+1,k,m} + T_{i,j-2,k,m} + T_{i,j+3,k,m} + T_{i,j+4,k,m}}{5} \qquad (3)$$

where:

l - Period (l = 1, 2,•••36) and

l - integer $\frac{(j-1)}{5}$ + 1(j = 1, 2,•••180).

Finally, an arithmetic average over 30 years was calculated and the temperatures at the center of each asphalt sub-layer were obtained by using linear interpolation between the two adjacent points in each sub-layer. In this way, the amount of data was reduced to $n_{\text{sub-layers}}$ x 36_{periods} x 24_{hours} total data points. In other words, 864 temperature profiles were developed, each with n calculated temperatures. Also, the variability was substantially reduced.

STATISTICAL ANALYSIS

The mathematical model for temperature distribution within the asphalt pavement was obtained by SAS linear regression analysis (Appendix C). The regression model was divided into two parts: one was for day time; the other was for night time. The general forms of the models are shown as follows:

$$T = a_0 + a_1x + a_2y + a_3z + a_4yz + a_5x^2 + a_6y^2 + a_7y^2z + a_8y^3 \qquad (4)$$

for the day time temperature, where:

T - Temperature at the center of each sub-layer,

x - Period of the year (x = 1, 2,•••36),

y - Hour of the day ($7 < y < 19$),

n - Number of sublayers (η = 2, 3,•••5),

z - Sub-layer (z = 1, 2,•••η) and

a_0, a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8 - Regression constrants

$$T = b_0 + b_2x + b_2y + b_3z + b_4x^2 + b_5y^2 + b_6y^3 + b_7y^4. \qquad (5)$$

for the night time temperature, where:

T - Temperature at the center of each sub-layer,

x - Period of the year (x = 1, 2,•••36),

y - Hour of the day ($y < 7$ or $y > 19$),

z - Sub-layer (z = 1, 2, •••η),

n - Number of sublayers (η = 2, 3,•••5) and

b_0, b_1, b_2, b_3, b_4, b_5, b_6, b_7 - Regression constants.

The coefficients for each thickness of the asphalt layer (2, 3, 4, and 5 in.) and the associated R^2 values for each equation are listed in Table 1.

The temperature changes varying with the depth can be determined by differentiating equations 4 and 5 with respect to z:

$$\frac{\partial T}{\partial z} = a_3 + a_4 y \quad a_7 y^2 \qquad \text{for the day time and}$$

$$\frac{\partial T}{\partial z} = b_3 \qquad \text{for the night time.}$$

As can be seen, the temperature variation with depth is a parabolic function during the day time and a constant value during the night time. The positive values of b_3 (Table 1) indicate that the temperature increases with depth at a constant rate during the night time.

After the regression analysis, the 864 profiles were rearranged according to the temperatures at the center of the top sub-layer, and the time sequence was ignored based on the assumption that the asphalt mix stiffness is a function of temperature and loading frequency only (assumption 2). The rearranged profiles were then divided into 6 temperature ranges (Table 2). The mean temperature at the center of each sub-layer for each temperature range was calculated and the frequency of each temperature range was calculated. Finally, 6 seasonal profiles from the 6 temperature ranges were obtained from the output of the SAS program (Table 2). The six temperature profiles were used to represent the temperature variations in asphalt overlays for the whole 180 day period (May 1 through October 27).

RESULTS

Tables 2 through 5 summarize the SAS output for each asphalt overlay thickness (2, 3, 4, and 5 in.). Table 3 is a summary and example of some of the key data obtained in the SAS analysis for a 3 in. overlay. The first column lists the profile number of each seasonal profile arranged

Table 1. Coefficient and R^2 Values (Dallas Area).

Coefficients in Regression Equations				
a_i	2 in.	3 in.	4 in.	5 in.
a_0	-10.86578376	-7.37747191	-5.29491432	-3.98878098
a_1	2.72235732	2.68441704	2.64857345	2.61542996
a_2	11.67046823	10.46812755	9.68542806	9.17967480
a_3	18.99788240	19.32725122	19.06918040	18.38998565
a_4	-4.42976066	-4.26659265	-4.03574420	-3.76321398
a_5	-0.08258815	-0.08113541	-0.07976100	-0.07848716
a_6	0.12485806	0.21952908	0.27372750	0.29877541
a_7	0.19240163	0.17992750	0.16595360	0.15136661
a_8	-0.02729960	-0.02926142	-0.03002847	-0.02990725
R_2	0.993	0.992	0.991	0.987
b_0	62.41359215	62.66070339	62.93120679	63.24057562
b_1	2.19724661	2.22547650	2.25007514	2.27035799
b_2	-4.70931105	-4.51637361	-4.29690296	-4.05387724
b_3	2.60459596	2.41021465	2.19595202	1.97227020
b_4	-0.06465221	-0.06541879	-0.06607928	-0.06661050
b_5	0.89622492	0.80313852	0.72095031	0.64618326
b_6	-0.04680822	-0.03955661	-0.03355423	-0.02844901
b_7	0.00072631	0.00057167	0.00044851	0.00034834
R^2	0.985	0.983	0.982	0.980

Table 2. Temperature Distribution of 2 in. Asphalt Overlay (Dallas Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	% Time
1	< 75	68	70	25.69
2	75-85	79	81	25.69
3	85-95	90	89	14.93
4	95-105	100	97	14.47
5	105-115	110	105	12.38
6	115-125	118	112	6.84
			TOTAL	100

Table 3. Temperature Distribution of 3 in. Asphalt Overlay (Dallas Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	3	% Time
1	< 75	68	70	72	25.69
2	75-85	79	81	82	25.69
3	85-95	90	89	88	14.93
4	95-105	100	97	94	14.70
5	105-115	110	105	101	12.15
6	115-125	118	112	107	6.84
			TOTAL		100

Table 4. Temperature Distribution of 4 in. Asphalt Overlay (Dallas Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	3	4	% Time
1	< 75	68	70	72	73	25.58
2	75-85	79	81	82	84	25.58
3	85-95	90	89	88	87	15.05
4	95-105	100	97	94	91	14.58
5	105-115	110	105	101	97	12.15
6	115-125	118	112	107	103	6.83
				TOTAL		100

Table 5. Temperature Distribution of 5 in. Asphalt Overlay (Dallas Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	3	4	5	% Time
1	< 75	68	70	72	74	75	25.58
2	75-85	79	81	82	84	85	25.58
3	85-95	90	89	88	87	86	15.05
4	95-105	100	97	94	91	88	14.58
5	105-115	110	105	101	97	94	12.15
6	115-125	118	112	107	103	99	6.83
					TOTAL		100

according to the temperature range listed in column 2 which is based on the temperatures at the center of the top sub-layer. Columns 3 through 5 list the mean temperatures of the sub-layers for each temperature range. Column 6 gives the percentage time for each temperature range. For example, Profile No. 1 occurs 25.69 percent of the time in the period of analysis or, in other words, 25.69 percent of the time the temperature at the center of the top sub-layer is lower than 75°F. During this period the temperature within the 1-inch sublayers are 68, 70 and 72, °F respectively. A complete output of the SAS program for 3 in. asphalt layers is listed in Appendix C. The data listed in Table 3 have been obtained from Appendix C.

COMPARISONS OF 4 DIFFERENT REGIONS

The same calculations were also done for the other 3 regions: Austin (Tables 6 to 10), Midland (Tables 11 to 15), and Amarillo (Tables 16 to 20). The differences of temperature distributions can be seen by making comparisons among the distributions for the different regions.

The temperature distribution of 3 inch asphalt layer in the Dallas area was chosen as a basic distribution to compare with other areas. The comparisons were based on four factors: the maximum differences of the surface temperatures, the minimum differences of the surface temperatures, the average differences of the surface temperatures, the standard derivations of these differences. All calculations of these differences were based on absolute values at the 864 (24_{hours} x $36_{periods}$) discrete data points of the two temperature distributions. The results of these comparisons are listed in Table 21 and the following conclusions can be drawn from these results:

Table 6. Coefficient and R^2 Values (Austin Area).

Coefficients in Regression Equations				
a_i	2 in.	3 in.	4 in.	5 in.
a_0	-11.16129250	-7.31370860	-5.85662045	-4.37353627
a_1	2.53540650	2.49142392	2.45160263	2.41447206
a_2	11.95612570	10.70758599	10.04691194	9.47960491
a_3	19.72385503	20.22308858	19.72192219	18.87160892
a_4	-4.53785909	-4.40943536	-4.13289892	-3.83117453
a_5	-0.07552952	-0.0739145	-0.07250842	-0.07118501
a_6	0.10561130	0.20071134	0.25049733	0.28226202
a_7	0.19592768	0.18487506	0.16911556	0.15346072
a_8	-0.02689337	-0.02879659	-0.02957107	-0.02964268
R_2	0.993	0.992	0.990	0.986
b_0	65.00155559	65.08225109	65.19363065	65.40996014
b_1	1.86268427	1.91188544	1.94425980	1.97347444
b_2	-4.4544547	-4.25784016	-4.07334665	-3.87019658
b_3	2.60962121	2.42796717	2.18803030	1.94981818
b_4	-0.05440791	-0.05567339	-0.05650277	-0.05724273
b_5	0.83154403	0.74257733	0.67348421	0.60935132
b_6	-0.04270870	-0.03585179	-0.03081410	-0.02638700
b_7	0.00064977	0.00050423	0.00040100	0.00031343
R^2	0.979	0.977	0.976	0.974

Table 7. Temperature Distribution of 2 in. Asphalt Overlay (Austin Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	% Time
1	< 75	69	71	22.69
2	75-85	79	81	27.43
3	85-95	90	89	16.44
4	95-105	100	97	13.66
5	105-115	110	105	12.96
6	115-125	118	112	6.83
			TOTAL	100

Table 8. Temperature Distribution of 3 in. Asphalt Overlay (Austin Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	3	% Time
1	< 75	69	71	73	22.69
2	75-85	79	81	83	27.20
3	85-95	90	89	88	16.67
4	95-105	100	97	94	13.77
5	105-115	110	105	101	12.96
6	115-125	117	112	106	6.71
			TOTAL		100

Table 9. Temperature Distribution of 4 in. Asphalt Overlay (Austin Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	3	4	% Time
1	< 75	69	71	73	75	22.69
2	75-85	79	81	83	84	27.43
3	85-95	90	89	88	88	16.44
4	95-105	101	97	94	91	13.66
5	105-115	110	105	101	97	12.96
6	115-125	118	112	107	102	6.83
				TOTAL		100

Table 10. Temperature Distribution of 5 in. Asphalt Overlay (Austin Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	3	4	5	% Time
1	< 75	69	71	73	75	76	22.92
2	75-85	79	81	83	84	85	27.08
3	85-95	90	89	88	88	87	16.55
4	95-105	101	97	94	91	88	13.66
5	105-115	110	105	101	97	94	12.73
6	115-125	118	112	107	102	98	7.06
					TOTAL		100

Table 11. Coefficient and R^2 Values (Midland Area).

	Coefficients in Regression Equations			
a_i	2 in.	3 in.	4 in.	5 in.
a_0	-15.94867203	-12.72391387	-11.30128473	-10.32068399
a_1	2.20927914	2.18069850	2.16437505	2.15610972
a_2	12.67221863	11.51273616	10.78493523	10.23111181
a_3	21.83544456	22.00686994	21.50330905	20.57014513
a_4	-5.01099983	-4.79538267	-4.49985007	-4.16732488
a_5	-0.07162787	-0.07059277	-0.06964514	-0.06856288
a_6	0.13927009	0.23230185	0.28533553	0.31416558
a_7	0.21647325	0.20134491	0.18434904	0.16709370
a_8	-0.02984335	-0.03177170	-0.03253488	-0.03245459
R_2	0.995	0.994	0.991	0.988
b_0	60.89035084	61.57073499	61.95978976	62.21687884
b_1	1.96859912	1.96648326	1.97667169	1.99805429
b_2	-5.1555700	-4.93245102	-4.70293250	-4.45021087
b_3	3.06512626	2.81965909	2.55495960	2.28558586
b_4	-0.05970345	-0.06001458	-0.06036876	-0.06066460
b_5	0.98573435	0.88308960	0.79687068	0.71768992
b_6	-0.05167477	-0.04379128	-0.03750947	-0.03207345
b_7	0.00080561	0.00063898	0.00051036	0.00040331
R^2	0.982	0.979	0.978	0.977

Table 12. Temperature Distribution of 2 in. Asphalt Overlay (Midland Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	% Time
1	< 75	67	70	36.23
2	75-85	80	81	18.98
3	85-95	90	88	12.85
4	95-105	100	96	12.73
5	105-115	110	105	15.16
6	115-125	117	111	4.05
			TOTAL	100

Table 13. Temperature Distribution of 3 in. Asphalt Overlay (Midland Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	3	% Time
1	< 75	67	70	72	36.46
2	75-85	80	81	82	18.75
3	85-95	90	88	87	12.85
4	95-105	100	96	92	12.62
5	105-115	110	105	100	14.70
6	115-125	117	111	105	4.63
			TOTAL		100

Table 14. Temperature Distribution of 4 in. Asphalt Overlay (Midland Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F)				% Time
		1	2	3	4	
1	< 75	67	70	72	74	36.46
2	75-85	80	81	82	83	18.75
3	85-95	90	88	87	86	12.73
4	95-105	100	96	92	89	12.73
5	105-115	110	105	100	96	14.47
6	115-125	117	111	105	100	4.86
				TOTAL		100

Table 15. Temperature Distribution of 5 in. Asphalt Overlay (Midland Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F)					% Time
		1	2	3	4	5	
1	< 75	67	70	72	74	75	36.00
2	75-85	80	81	82	83	84	18.98
3	85-95	90	88	87	86	84	12.96
4	95-105	100	96	93	90	87	12.73
5	105-115	110	105	100	96	92	14.58
6	115-125	117	111	105	100	96	4.75
					TOTAL		100

Table 16. Coefficient and R^2 Values (Amarillo Area).

	Coefficients in Regression Equations			
a_i	2 in.	3 in.	4 in.	5 in.
a_0	-16.75236660	-14.32946948	-13.69368501	-12.72169418
a_1	2.61600799	2.59557063	2.56177830	2.53758598
a_2	11.70466087	10.62325889	10.07906508	9.58525011
a_3	20.55916583	20.85583763	20.25502520	19.40540579
a_4	-4.72092768	-4.54275912	-4.23776898	-3.92849525
a_5	-0.08231950	-0.08125296	-0.08010476	-0.07900827
a_6	0.15097142	0.23788303	0.28093597	0.30710503
a_7	0.20387890	0.19061556	0.17352672	0.15742044
a_8	-0.02856312	-0.03035507	-0.03099853	-0.03091843
R_2	0.992	0.992	0.990	0.986
b_0	54.71594696	54.85746040	54.97881233	55.46384511
b_1	2.33845805	2.34995979	2.36017662	2.35999902
b_2	-5.22492078	-5.00181794	-4.79006700	-4.52094982
b_3	3.02542929	2.81787879	2.55486364	2.29544949
b_4	-0.06950748	-0.07011246	-0.07056120	-0.07062619
b_5	1.01676951	0.91116794	0.82887409	0.74416558
b_6	-0.05416591	-0.04599359	-0.03995853	-0.03411721
b_7	0.00086055	0.00068700	0.00056310	0.00044757
R^2	0.985	0.984	0.982	0.980

Table 17. Temperature Distribution of 2 in. Asphalt Overlay (Amarillo Area) .

Profile No.	Temp. (°F)	Sub-layer Temp. (°F)		% Time
		1	2	
1	< 75	65	67	44.10
2	75-85	80	80	16.90
3	85-95	90	87	13.43
4	95-105	100	96	13.66
5	105-115	110	105	11.92
			TOTAL	100

Table 18. Temperature Distribution of 3 in. Asphalt Overlay (Amarillo Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F)			% Time
		1	2	3	
1	< 75	65	66	69	44.79
2	75-85	80	80	80	16.90
3	85-95	90	87	85	13.08
4	95-105	100	95	91	13.66
5	105-115	110	104	99	11.57
			TOTAL		100

Table 19. Temperature Distribution of 4 in. Asphalt Overlay (Amarillo Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F)				% Time
		1	2	3	4	
1	< 75	64	67	69	71	45.14
2	75-85	80	80	80	81	16.78
3	85-95	90	87	84	82	12.73
4	95-105	100	95	91	88	13.66
5	105-115	110	104	99	95	11.69
				TOTAL		100

Table 20. Temperature Distribution of 5 in. Asphalt Overlay (Amarillo Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F)					% Time
		1	2	3	4	5	
1	< 75	64	67	69	70	72	45.25
2	75-85	80	80	80	80	80	16.67
3	85-95	90	87	84	82	80	12.62
4	95-105	100	95	91	88	85	13.77
5	105-115	110	104	99	95	91	11.69
					TOTAL		100

1. There is little difference among temperature distributions the Dallas, Midland, and Austin areas. In other words, one temperature distribution of one area (Dallas area) for one asphalt structure can be used to represent the temperature distributions of the two other areas for the same asphalt structures. Figure 7, which is based on Table 3 and Table 8, presents the comparisons of the temperature distributions between the Dallas area and the Austin area.
2. Significant differences of temperature distributions were found between the Amarillo area and the one of other three areas.

Table 21. Comparisons of Temperature Distributions with Dallas Area.

Areas	Mean Value	Standard Deviation	Maximum Value	Minimum Value
Austin	0.97	1.00	4.40	0.00
Midland	2.48	1.20	4.10	0.00
Amarillo	6.86	4.04	9.60	4.50

Based on this analysis, a new regional map was drawn by simply dividing Texas into 2 regions: the northern region (I) and the southern region (II) (Figure 8). During the warmer seasons (from May 1 to October 27), regression equations (Table 18), which are based on the historic climatic data of the Amarillo area (Region I), can be used to describe the temperature variations within asphalt layers. Regression equations (Table 1), which are based on the historic climatic data of the Dallas area (Region II), can be used to describe the temperature variations within asphalt layers for the rest of Texas.

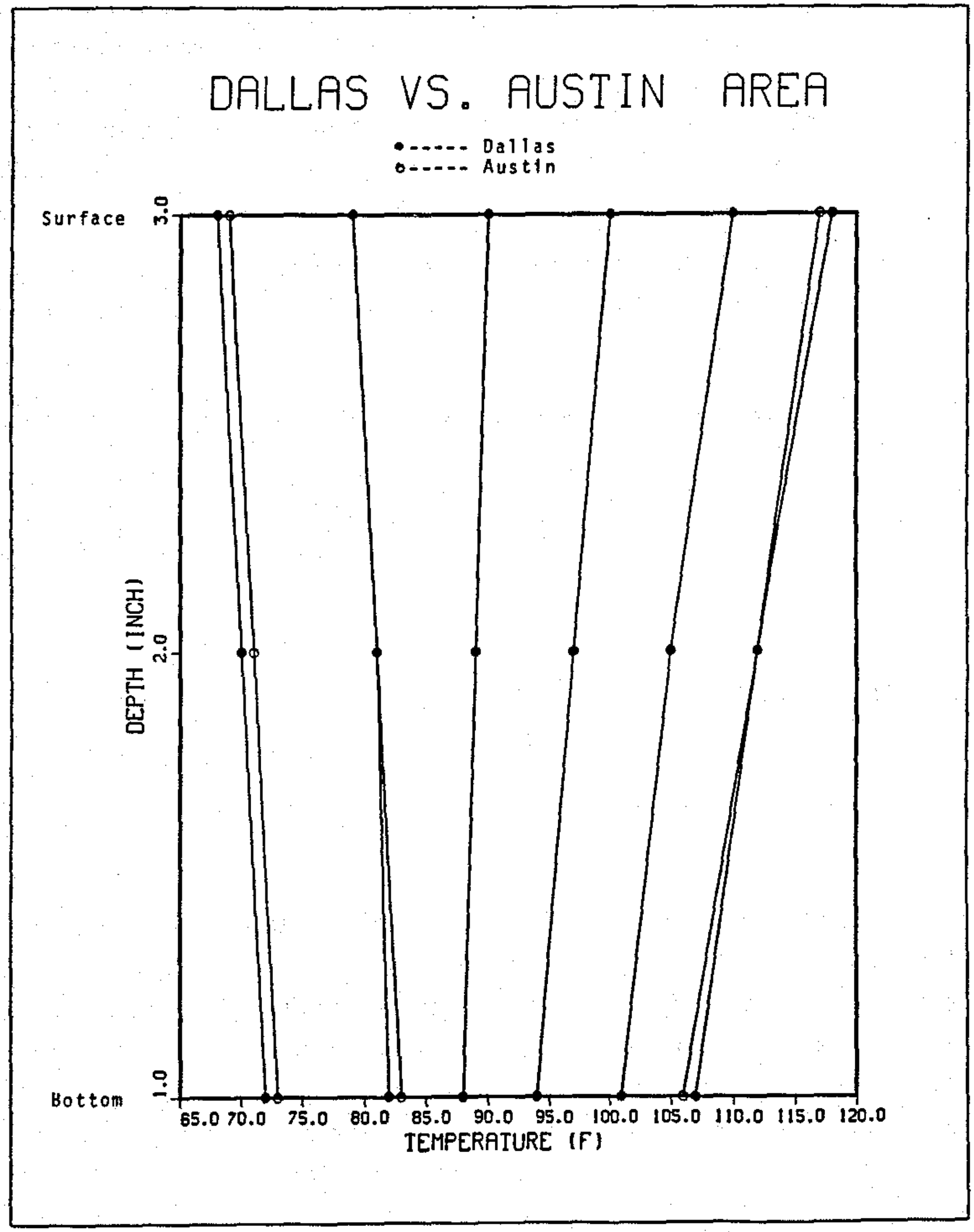


Figure 7. Comparison Between Dallas Area and Austin Area.

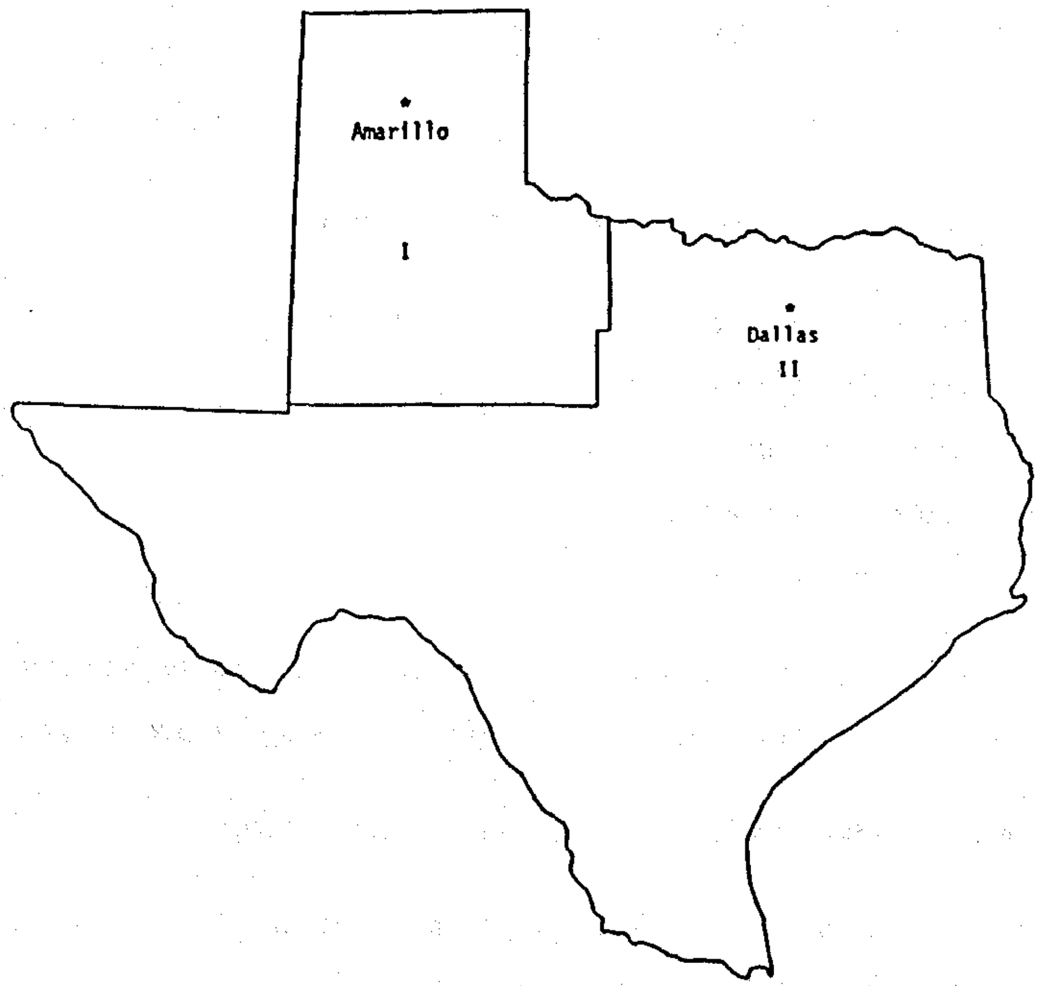


Figure 8. New Regional Map of Texas.

WINTER PERIOD

The same analytical procedure can be also applied to the winter period (185 days, from October 28 to April 30). The general forms of the temperature distributions obtained by the linear regression analysis for the winter period are shown as follows:

$$T = a_0,\ a_1x + a_2y,\ a_3z,\ a_4x^2 + a_5yz + a_6y^2 + a_7y^2z + a_8x^2z + a_9x^3 + a_{10}y^3 \quad (6)$$

for the day time temperature of winter period, where:

T - Temperature at the center of each sub-layer,

x - Period of the year (x = 1, 2,•••36),

y - Hour of the day ($7 < y < 19$),

η - Number of sublayers (η = 2, 3,•••5),

z - Sub-layer (z = 1, 2,•••η) and

a_0, a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9, a_{10}, - Regression constrants

$$T = b_0 + b_1x + b_2y + b_3z + b_4x^2 + b_5y^2 + b_6x^3 + b_7y^3 + b_7x^4 + b_8y^5. \quad (7)$$

for the night time temperature of winter period, where:

T - Temperature at the center of each sub-layer,

x - Period of the year (x = 1, 2,•••36),

y - Hour of the day ($y < 7$ or $y > 19$),

z - Sub-layer (z = 1, 2, •••η),

η - Number of sublayers (η = 2, 3,•••5) and

b_0, b_1, b_2, b_3, b_4, b_5, b_6, b_7 b_8 - Regression constants.

The coefficients for each thickness of asphalt layer (2, 3, 4, and 5 in.) and the associated R^2 values for each equation are listed in Table 22.

Table 22. Coefficient and R^2 Values (Dallas Area, Winter Period).

	Coefficients in Regression Equations			
a_i	2 in.	3 in.	4 in.	5 in.
a_0	-9.40151315	-1.57961832	2.92859041	5.41475832
a_1	-3.95307726	-3.84059766	-3.73613798	-3.63889402
a_2	10.92359260	8.58483015	7.19319408	6.41461337
a_3	20.28828729	20.18800468	19.51818704	18.46738578
a_4	0.17895451	0.17289903	0.16730848	0.16209765
a_5	-4.12527662	-3.94778249	-3.70200950	-3.41475469
a_6	0.05788937	0.24229388	0.34237769	0.38628314
a_7	0.17377163	0.16235548	0.14918622	0.13515834
a_8	-0.00123485	-0.00119229	-0.00114060	-0.00108475
a_9	-0.02246086	-0.02677807	-0.02875480	-0.02915095
a_{10}	-0.00171006	-0.00161885	-0.00153589	-0.00145933
R_2	0.972	0.972	0.971	0.969
b_0	56.33204934	56.74866303	57.06077229	57.52514408
b_1	-0.78783658	-0.80128838	-0.80053192	0.81930226
b_2	-2.99021058	-2.98002570	-2.86903999	-2.80873176
b_3	2.15513514	1.99555283	1.82776658	1.66783047
b_4	-0.11930756	-0.11917448	-0.12053576	-0.11939222
b_5	0.50043323	0.47337867	0.43645740	0.41036317
b_6	-0.01956822	-0.01785313	-0.01588947	-0.01447468
b_7	0.00840510	0.00845138	0.00855027	0.00854417
b_8	0.0000066	0.0000055	0.0000045	0.0000037
b_9	-0.00012004	-0.0001214	-0.00012265	-0.00012290
R^2	0.971	0.972	0.972	0.973

The results from the statistical analysis for the winter period of the Dallas area are listed in Tables 22 to 26 for the different thicknesses of asphalt layers. The percentage of time that the surface temperatures are higher than 75°F is less than 15% during the winter period and it is about only 1.5% of time that the surface temperature is over 95°F (Table 23). This verifies the assumption stated previously that winter temperatures are not conducive to permanent deformation.

Table 23. Winter Temperature Distribution of 2 in. Asphalt Overlay (Dallas Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	% Time
1	< 45	41	43	18.69
2	45-55	50	51	26.80
3	55-65	60	60	25.00
4	65-75	70	68	14.86
5	75-85	80	76	8.56
6	85-95	90	85	4.62
7	> 95	97	92	1.46
			TOTAL	100

Table 24. Winter Temperature Distribution of 3 in. Asphalt Overlay (Dallas Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	3	% Time
1	< 45	41	43	44	18.69
2	45-55	50	51	53	26.80
3	55-65	60	60	51	25.00
4	65-75	70	68	66	14.86
5	75-85	80	77	74	8.67
6	85-95	90	85	81	4.50
7	> 95	97	92	87	1.46
			TOTAL		100

Table 25. Winter Temperature Distribution of 4 in. Asphalt Overlay (Dallas Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	3	4	% Time
1	< 45	41	43	44	45	18.58
2	45-55	50	51	53	54	26.91
3	55-65	60	60	60	60	25.00
4	65-75	70	68	66	64	14.86
5	75-85	80	77	74	71	8.67
6	85-95	90	85	81	78	4.62
7	> 95	97	92	88	84	1.35
			TOTAL			100

Table 26. Winter Temperature Distribution of 5 in. Asphalt Overlay (Dallas Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	3	4	5	% Time
1	< 45	41	43	44	46	47	18.58
2	45-55	50	51	53	54	55	26.91
3	55-65	60	60	60	60	59	25.00
4	65-75	70	68	66	64	63	14.86
5	75-85	80	76	73	71	69	8.67
6	85-95	90	85	81	78	75	4.62
7	> 95	97	92	88	84	80	1.35
					TOTAL		100

COMPUTER MODEL

GENERAL

The computer model used in this study was the modified ILLIPAVE computer program. The current version of ILLIPAVE is a finite element computer program with the ability to incorporate linear and nonlinear characterization of materials; an interface relationship between the pavement layers; and predict rut depth, slope variance, fatigue cracking and present serviceability index with time. A finite element configuration representing the pavement cross section, load conditions and materials properties such as unit weight, Poision's ratio, earth-pressure coefficient at rest, as well as a modulus for stress dependent materials are required input. Four alternative models are available for describing the resilient modulus for stress dependent granular and cohesive soil layers under repeated loads (11).

The method used by the program to represent permanent deformation characteristics of the asphalt material is based on three parameters ϵ_0, ß, and ρ. The parameters are developed by a curve fit that relates permanent strains to loading cycles using SAS nonlinear regression techniques (10). The data used for the nonlinear regression analysis can be obtained from creep or repeated load triaxial tests at different temperature levels. The curve describing this relationship is represented by

$$\epsilon_a = \epsilon_0 e^{(-p/N)ß} \tag{8}$$

where:

ϵ_a is a permanent strain,
N is the number of load repetitions,
$\frac{e_0}{e_r}$, ρ, and ß are material parameters (11), and
ϵ_r is the resilient strain imposed in the laboratory.

PERMANENT DEFORMATION PREDICTION

Permanent deformation (rut depth) in the wheel path of a flexible pavement is attributed to the accumulation of permanent strains produced by repetitive traffic loads. The model of permanent deformation is based on an evaluation of the vertical resilient strain in each layer by the finite element method and on the fractional increase of total strains for each material layers of the pavement as determined by the three material properties, ϵ_0, ρ, and ß. The finite element analysis is used to take both linear and nonlinear stress-strain behavior of the materials into account. This approach can be applied to not only a single axle load but also multiple axle loads on the surface. The mathematical derivation of the equations to predict permanent deformation for a single axle load as well as multiple axle loads are described elsewhere (8).

For a single axle load, the permanent deformation, δ_a, is given by:

$$\delta_a (N) = \sum_{i=1}^{\eta} \frac{\epsilon_{o_i}}{\epsilon_{r_i}} e^{-\left(\frac{\rho_i}{N}\right)^{\beta_i}} \int_{d_{i-1}}^{d_i} \epsilon_c(z)dz \qquad (9)$$

where:

n = number of pavement layers,

ϵ_r = resilient strain imposed in the laboratory test to obtain the three parameters of the material in the i^{th} layer,

N = expected number of load cycles,

d_i = depth of i^{th} layer, and

ϵ_c = vertical resilient strain in the layer i from the finite element solution.

The term $\frac{\epsilon_{o_i}}{\epsilon_{r_i}} e^{-\left(\frac{\rho_i}{N}\right)^{\beta_i}}$ is defined as the fractional increase of total strains. The integral on the right side of Equation 9 can be solved numerically using the trapezoidal rule of integration for the given vertical strain of each element beneath the center of tire loads.

For a tandem axle load with single wheels, the equation of permanent deformation is expressed as:

$$\delta_a(N) = \sum_{i=1}^{\eta} \frac{\epsilon_{o_i}}{\epsilon_{r_i}} e^{-\left(\frac{\rho_i}{N}\right)^{\beta_i}} \int_{d_{i-1}}^{d_i} \left(1 + \frac{\Delta\sigma(z)}{\sigma_{max}(z)}\right) \epsilon_c(z)dz \qquad (10)$$

The term $\Delta\sigma$ is the difference between σ_{max} and σ_{min}. σ_{max} is determined by super position of the vertical stress under a single wheel plus the overlay vertical stress at a distance corresponding to the tandem axle spacing. Since the distribution of the vertical stresses is assumed to be symmetric and the interaction effect of the dual tires is ignored, σ_{min} is simply twice the vertical stresses at half the tandem spacing. The individual values of σ_{max}, σ_{min}, and ϵ_c vary with the depth of the pavement and the size of tire loads. Thus, the estimate of total permanent deformation at the surface can be calculated numerically layer by layer from Equation 10.

Similar to the case of the dual load, Equation 10 can be extended for other multiple axle configurations and may be expressed as:

$$\delta_a(N) = \sum_{i=1}^{\eta} \frac{\epsilon_{o_i}}{\epsilon_{r_i}} e^{-\left(\frac{\rho_i}{N}\right)^{\beta_i}} \int_{d_{i-1}}^{d_i} \left(1 + \sum_{j=1}^{k-1} \frac{\Delta\sigma_j}{\sigma_{max}}\right) \epsilon_c(z)dz \qquad (11)$$

where:

k = number of axles in each axle group, and

$\Delta\sigma_j$ = the stress difference between the j^{th} and $(j + 1)^{th}$ axle group.

PREDICTIVE EQUATIONS FOR ϵ_o/ϵ_r, ρ, and β

As noted previously, the values of ϵ_o/ϵ_r, ρ, and β are material constants derived from creep or repeated load testing. To obtained appropriate values of ϵ_o/ϵ_r, ρ, and β for the material of each pavement component, it is necessary to determine how these three parameters are affected by the stress state, density, moisture content, asphalt content, temperature and other material characteristics. The effects of these factors are important in calculating permanent deformation of the pavement layers because the laboratory test conditions are significantly different from the actual field conditions. The test conditions affect the relationship between the permanent strain and the magnitude of the calculated permanent deformation. A preliminary regression analysis of ϵ_o/ϵ_r, ρ, and ß in terms of the available variables was performed for different types of materials and the most reliable equations relating the three parameters to mixture parameters (based on the highest R^2 and lowest standard error) were determined using multiple regression analysis. The regression equations used for asphalt concrete are discussed below and the equations for other materials can be found from Reference 11.

A preliminary analysis shows that ϵ_o/ϵ_r, ρ, and ß of asphalt concrete and most sensitive to resilient modulus and deviator stress, but the parameters are also sensitive to asphalt content and temperature. Because of this, several forms of equations including the more sensitive variables were considered in the multiple regression analysis of each parameter in terms of asphalt content, temperature, deviator stress, and resilient modulus. The useful equations are:

$$\log\left(\frac{\epsilon_o}{\epsilon_r}\right) = -5.04349 + 0.01812.A_c + 0.011045.A_c^2 + 0.01127T$$

$$-0.203249 \log \sigma_d + 1.12228 \log E_T \qquad (12)$$

$$R^2 = 0.44$$

$$\log \rho = 8.105675 - 4.241965A_c + 0.54159A_c^2 + 0.03865T$$

$$-0.014874\sigma_d + 0.000005E_T \qquad (13)$$

$$R^2 = 0.62$$

$$\log \beta = -2.51475 + 0.60816A_c - 0.05282A_c^2 - 0.00214T$$

$$+0.16597 \log \sigma_d - 0.0000002E_T \qquad (14)$$

$$R^2 = 0.43$$

where

A_c = asphalt content, % ;

T = temperature, °F ;

σ_d = deviator stress, psi, and

E_T = resilient modulus, psi.

Although the equations above do not explain variability from a statistical viewpoint, they are indicative of the relationship between the variables and give an estimate of the effects of these variables. It is apparent that other variables related to the type, shape, and surface texture of the aggregate must be included in order to arrive at more accurate equations. Unfortunately, these data are not customarily measured or recorded in the repeated load testing programs reported in the literature. The equations show, as expected, that permanent deformation increases with increasing temperature, deviator stress, and asphalt content.

APPLICATION AND RESULTS

The results from the statistical analysis provided the required temperature range for creep or repeated load triaxial testing. Within that range, several tests were performed at different temperature levels in order to determine the parameters ϵ_0, ß, and ρ. The values of the three parameters between the prescribed temperature intervals were obtained by interpolations between two adjacent points. The program can handle up to 12 different seasonal profiles and 10 sub-layers for different pavement structures.

A sample calculation was performed using the modified ILLIPAVE program. The structure of the pavement and the traffic loading is shown in Figure 9. The traffic was assumed to be one million standard passes over a 20 year period based or an average daily traffic (ADT) of 140. Resilient moduli were obtained from the temperature vs. modulus curve, and the associated temperature at different depths were determined from the profiles obtained from the statistical analysis in Table 4. The

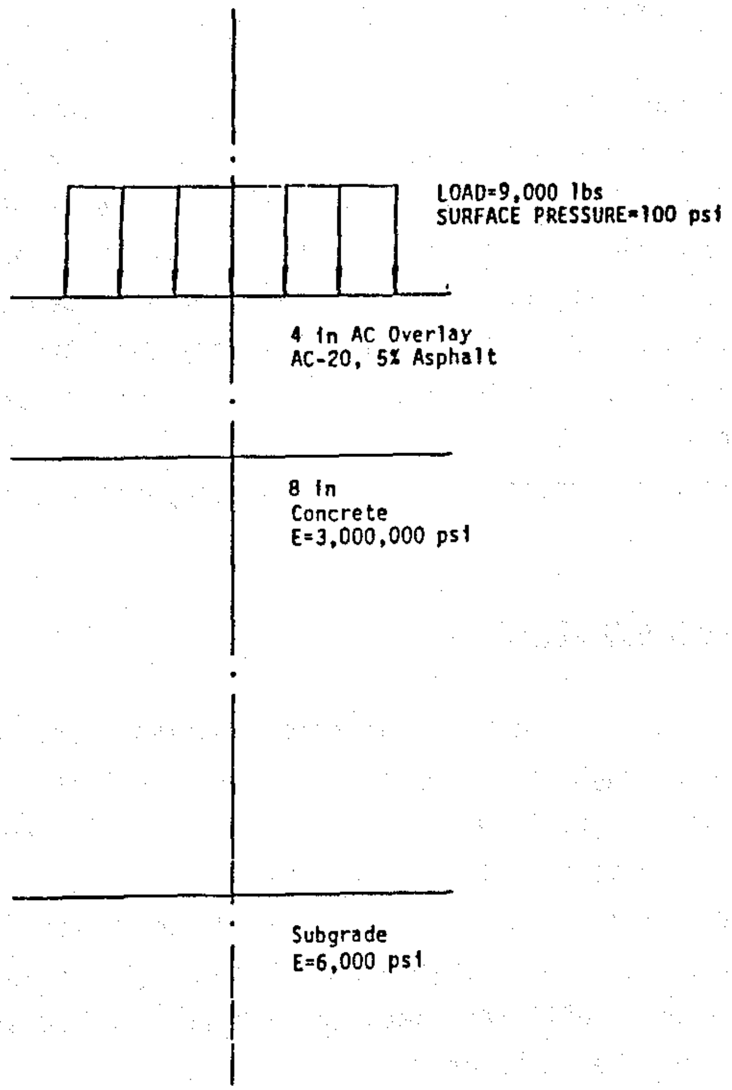


Figure 9. Pavement Structure Used in Example Analysis.

values for ϵ_0, β, and ρ were generated from equations 12, 13 and 14 using typical. The results are shown in Figure 10.

After a large number of sample runs, it was determined that the model reasonably represents the permanent deformation in asphalt layers when the air temperature is below 80°F and that the model under-estimates the rutting depth when the air temperature is over 80°F. Two possible reasons for under-estimation at the higher air temperatures might be:

1. The three parameters obtained from creep or repeated load triaxial test, which were used to represent the permanent deformation of asphalt materials, do not account for the lateral plastic deformation. In other words, no confined stain boundary condition is imposed in most creep or repeated load triaxial tests. The lateral plastic deformation is insignificant when temperature is low and the material behaves elastically; but it can be significantly increased when the temperature increases.

2. In the modified ILLIPAVE computer model, only the vertical stress is used to calculate vertical permanent deformation. No vertical permanent deformation caused by lateral plastic movement is accounted for.

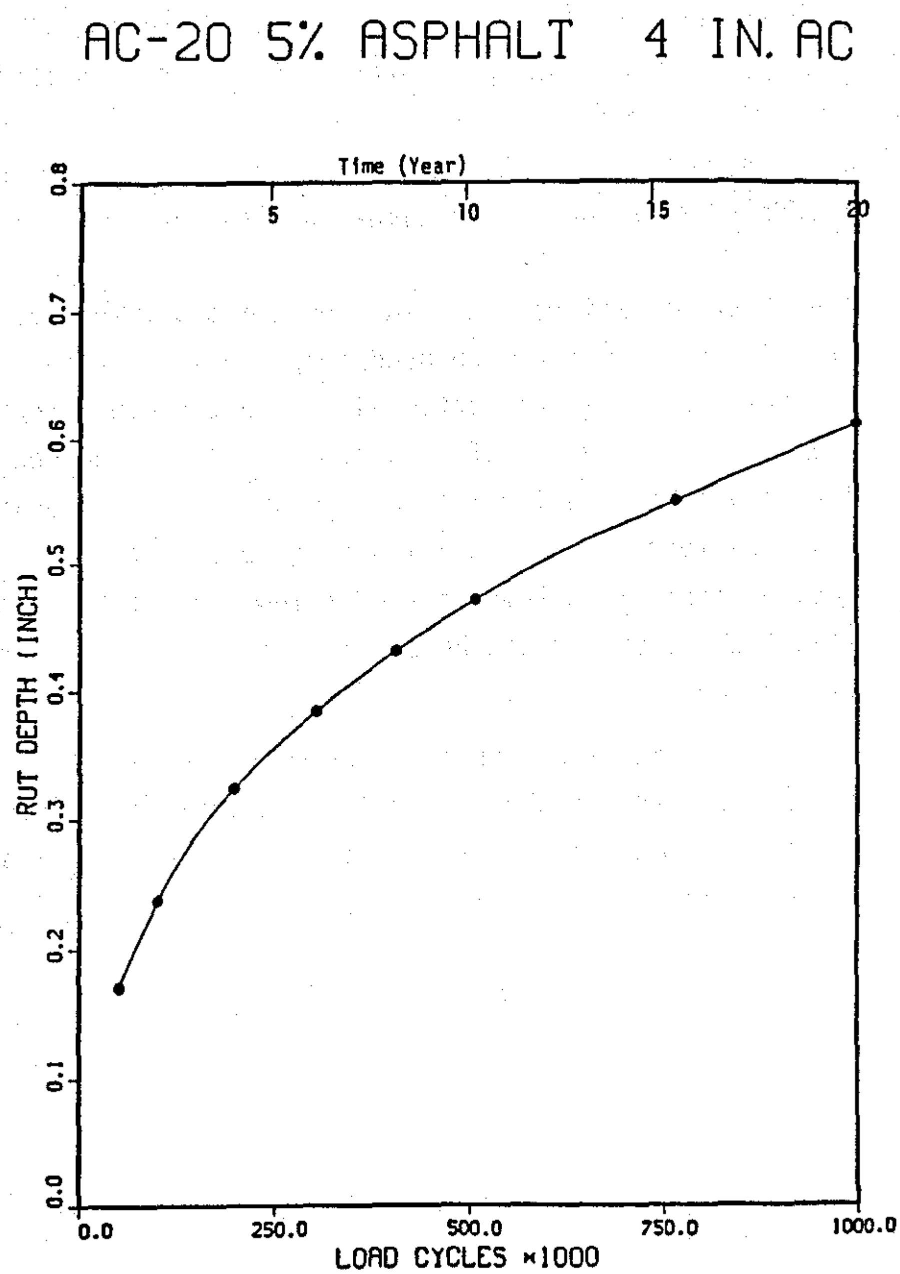


Figure 10. Permanent Deformation of Example Pavement.

TRAFFIC CONSIDERATIONS

Climate and traffic are the two main external factors that influence the accumulation of rutting depth for asphalt concrete pavements. Under the same climatic conditions, different traffic patterns with the same traffic volume (ADT) can result in different rutting depths for an asphalt pavement structure. It is therefore important to combine the effect of traffic distribution with temperature distribution. Traffic and temperature are two independent variables. As illustrated in the previous chapters, the temperature distributions in asphalt concrete layers vary with different locations and different pavement structures such as the thickness of the asphalt layers. Traffic distributions vary with the types of roads built for different transportation purposes. The only link between the two is the time history which they both occupy. If distribution functions, containing the variables with respect to time only, can be developed both for temperature and traffic, the necessary relationship between temperature and traffic combining their effect on rutting can then be determined.

Equations 4 and 5 developed by the regression analysis are the temperature distribution functions of the pavement structures with asphalt overlays on the top of concrete pavements. The temperature distributions at the center of the top sub-layers (0.5 in. below the surface) can be obtained by setting z equal to 1. These functions contain the variables with respect to time only. The traffic distribution functions can be obtained by collecting traffic data and plotting the relative frequency histogram (Figure 11), or by assuming traffic density functions (Figure 12). The area of all rectangles in the frequency histogram equals to 1. If a continuous curve connects all the middle points at the top of each rectangle bar, the relative frequency histogram is equal to the traffic density function.

The relationship between the temperature and traffic distributions can be found using the temperature distributions at the top sub-layers and the traffic density functions. The same temperature ranges (Table 3) are used to group the whole traffic volume into the six categories by mapping each time increment (1 hour period), from which traffic volume is entered into the category according to the temperature range, and by

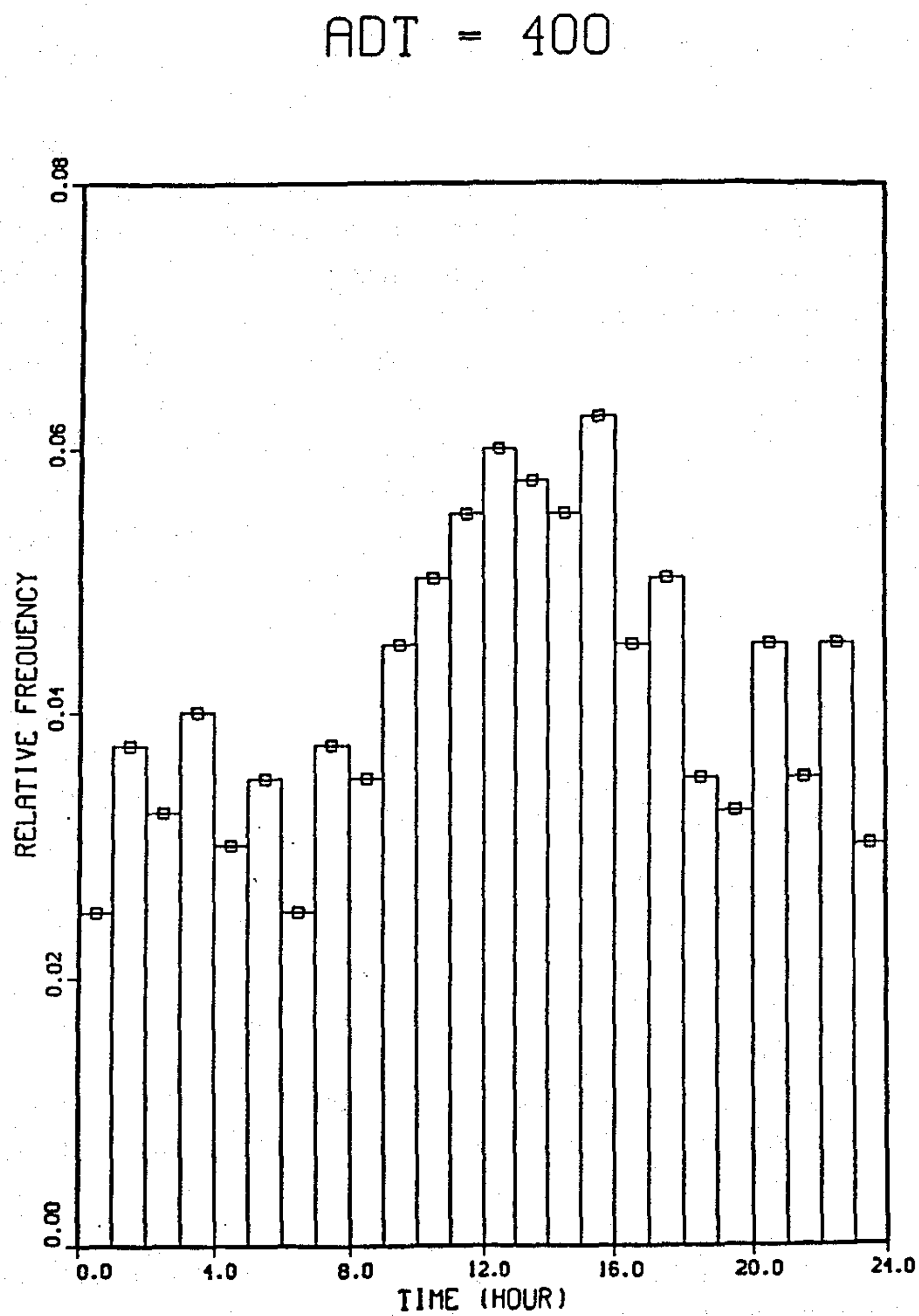


Figure 11. Relative Frequency Histogram.

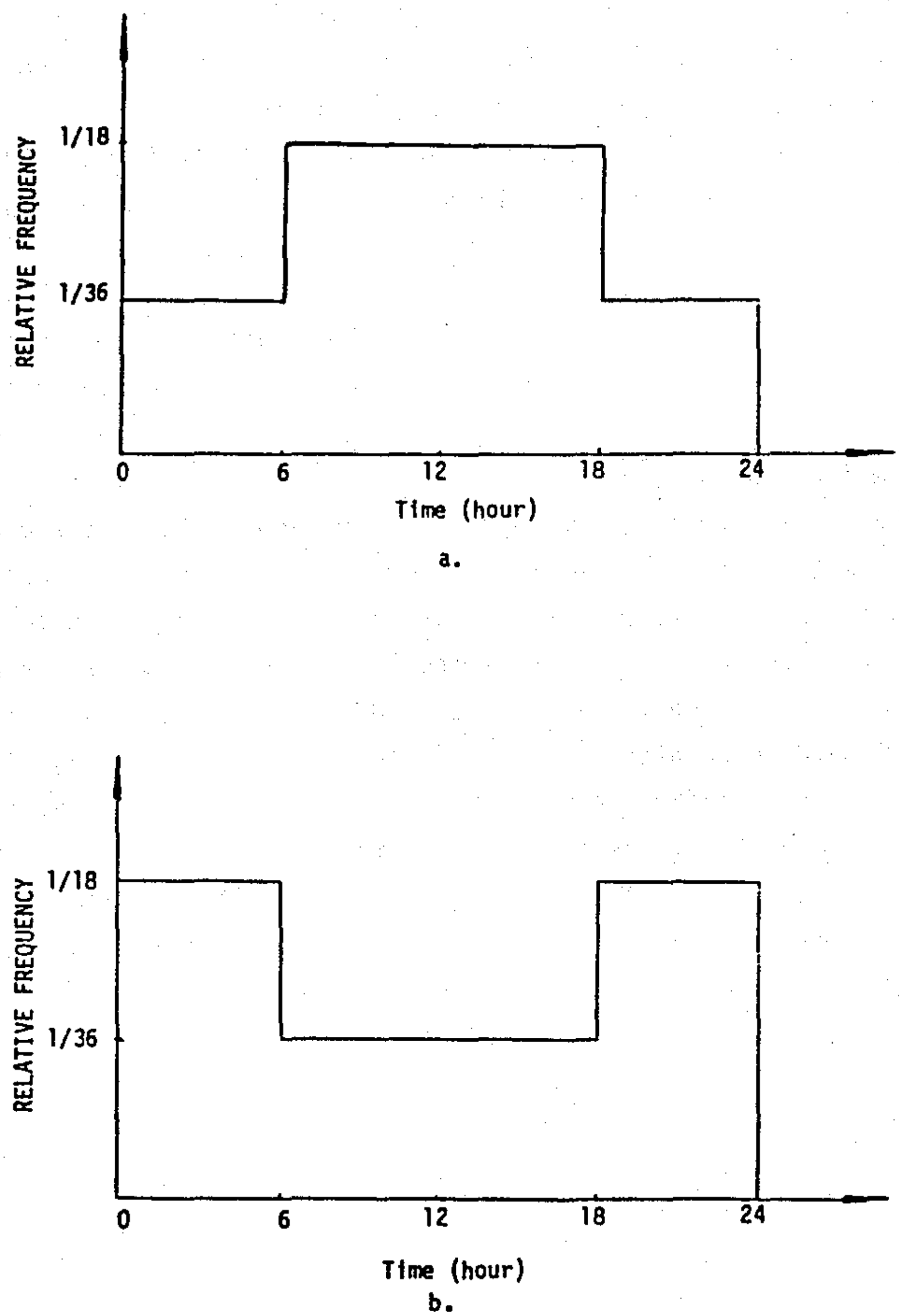


Figure 12. Traffic Density Functions.

superimposing with temperature for each category. The following two examples demonstrate the procedures used to calculate traffic distributions for given temperature distributions.

Figure 12a shows a traffic density function in which the traffic volume during the day time (6 A.M. to 6 P.M.) is twice as much as during the night time. The temperature regression model for the 3 in. asphalt overlay is used in the calculation and the results are listed in Table 27. The percentage traffic of Profile No. 1 shows that 18.24 percent of the traffic occurs during the 25.69 percent of the total time period in which the temperature at the center of the top sub-layer is lower than 75°F. Comparing with percent traffic and percent time in Table 27, as expected, fewer (Table 27, Profile Nos. 1 through 3) passes occur during low temperature periods and more passes (Profile No. 4 through 6) during high temperature periods.

The traffic density function shown in Figure 12b is the opposite traffic pattern to that shown in Figure 12a, where passes occur during the night time (low temperature periods) and fewer passes occur during the day time (high temperature periods). The same temperature regression model for 3 in. asphalt overlay was used and the results are listed in Table 28. The percentage traffic of Profile No. 1 tells that 32.2 percent of the traffic occurs during the 25.69 percent of the total time period in which the temperature at the top sub-layer is lower than 75°F. Comparing with percent traffic and percent time in Table 28, as expected, more traffic (Table 28, Profile Nos. 1 through 3) passes through over low temperature periods and less traffic (Profile No. 4 through 6) passes through over high temperature periods.

Table 27. Temperature Distribution as a Function of Traffic of a 3 in. Asphalt Overlay (Dallas Area).

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	3	% Time	% Traffic
1	< 75	68	70	72	25.69	18.24
2	75-85	79	81	82	25.69	19.97
3	85-95	90	89	88	14.93	18.70
4	95-105	100	97	94	14.70	17.72
5	105-115	110	105	101	12.15	17.87
6	115-125	118	112	107	6.83	7.50
			TOTAL		100	100

Table 28. Temperature Distribution as a Function of Traffic of a 3 in. Asphalt Overlay.

Profile No.	Temp. (°F)	Sub-layer Temp. (°F) 1	2	3	% Time	% Traffic
1	< 75	68	70	72	25.69	32.62
2	75-85	79	81	82	25.69	30.08
3	85-95	90	89	88	14.93	14.52
4	95-105	100	97	94	14.70	9.37
5	105-115	110	105	101	12.15	9.44
6	115-125	118	112	107	6.83	3.97
			TOTAL		100	100

ADDITIONAL APPLICATIONS

Pavements exposed to the open environment are greatly influenced by environmental conditions. The performance of the pavements and the materials in the pavement systems are all affected by meteorological conditions. In order to properly evaluate the effect of these conditions on a pavement, it is necessary to have a knowledge of the climate in which the structure is built.

The regression mode of temperature variations in asphalt concrete layers just described has applications to an extensive range of asphalt pavement systems which are influenced by different environmental factors. Generally speaking, it applies to any material characterization in which the material properties are the function of temperatures. The study of permanent deformation for the Dallas area demonstrated one of several applications in which the stiffness of asphalt mixes is the function of temperatures. Some of the other applications are summarized as follows:

1. The model can be used to study the effect of resilience of asphalt concrete pavements since the modulus of elasticity of asphalt varies with temperatures. Much time is required to collect temperature data from field measurements for one area. It is far easier to use the temperature regression model to analyze climatic data readily available at most weather stations than to measure temperatures from the field. This approach can be used for any geographical location, for any type of climate, and for pavement systems with different thermal and physical properties.

2. The same method used for permanent deformation analysis can be used directly for thermal cracking analysis in asphalt pavement systems. Low temperature thermal stress induced by temperature changes depends on the temperature drop per unit of time because the magnitude of the stress is proportional to the temperature drop. If the same method is applied to the winter period, a similar regression model with 2 time variables (X-time of day, Y-day of a year) can be obtained:

$$T = f_1(x,\ z) + f_2\ (y) \tag{15}$$

Differentiating Equation 15 with respect to the time t the temperature drop per unit time is obtained:

$$\frac{\partial T}{\partial t} = \frac{\partial f_1(x,z)}{\partial X}\frac{\partial X}{\partial t} + \frac{\partial f_2(y)}{\partial Y}\frac{\partial Y}{\partial t} \tag{16}$$

where:

$\frac{\partial X}{\partial t}$ and $\frac{\partial Y}{\partial t}$ are constrants determined by the time ratios.

Equations (15 and 16) give the temperature drop for a given time increment t and depth z. Further analysis can provide more detailed information such as mean and maximum temperature drops during certain time periods.

SUMMARY AND CONCLUSIONS

SUMMARY

An investigation was conducted to develop a more realistic procedure for evaluating temperature variations in asphalt concrete overlays over concrete pavements. Daily detailed climatic data from representative weather stations in four climactic regions of Texas were used to calculate temperature fluctuations in the asphalt layer based on the past 30 years of climatic data. An extensive statistical analysis procedure was developed that provided a regression model for each region which describes temperature variations in the asphalt concrete overlay. The resulting regression models provide essential temperature data for calculating permanent deformation using the modified ILLIPAVE computer program.

A relationship between temperature distribution and traffic distribution can be found by combining the temperature regression model with a traffic density function. Other examples of applications of the procedure include the analysis of low temperature cracking and resilient modulus of the asphalt concrete layers.

CONCLUSIONS

From the result of this study, the following conclusions can be made:

1. This study takes another step forward in the simulation of the temperatures in asphalt concrete layers by considering the temperature variations and temperature gradients, induced by the local climatic changes, in asphalt concrete layers.
2. The proposed analysis method which is based on long term local climatic data provides reliable information for the prediction of permanent deformation based on testing conducted under laboratory conditions.
3. The temperature regression model can be used to find a relationship between temperature variation and traffic pattern

and to study their combined effect on rutting since different traffic patterns cause different rutting depths for a given asphalt pavement and structure.

4. The regression equations, equations 4 and 5, with high R^2 values can be applied to conditions where material properties are a function of temperature. The prediction of permanent deformation and the prediction of low temperature thermal cracking are examples of how this analysis may be extended.

5. The method demonstrated here can be used for any pavement system, meteorological condition, and geographical location.

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APPENDIX A

Required Data for Dempsey's Model

APPENDIX A

Required Data for Dempsey's Model

1. Pavement identification.
2. Location of test site.
3. Starting date of evaluation.
4. Total depth of the finite difference pavement system, in.
5. Depth of normal node, in.
6. Time increment, hr.
7. Maximum allowable convection coefficient for stability criteria, Btu/hr-ft^2-F, (3.0 for all layers).
8. Number of pavement layers.
9. Number of termination nodes.
10. Thermal conductivities of each layer, Btu/hr-ft-F, (0.70 for asphalt concrete, 1.92 for concrete and stabilized layers, and 0.92 for subgrade).
11. Heat capacities of each layer, Btu/lb-F, (0.22 for asphalt concrete, 0.24 for concrete and stabilized layers, 0.29 for subgrade).
12. Total unit weights of each layer, pcf, (148 for asphalt concrete, 155 for concrete, 145.5 for stabilized layer, and 128.7 for subgrade).
13. Depth of each pavement layer, in.
14. Moisture content of each pavement layer, percent.
15. Temperature of the constant temperature node, F.
16. Radiation constants A and B (0.202 and 0.539).
17. Geiger radiation constants G and J (0.77 and 0.28).
18. Atmospheric vapor pressure, mm.
19. Cloud base factor (0.85).
20. Number of pavement temperature profiles to be printed each day.
21. Times at which the temperature profiles to be printed out each day, hr.

22. Number of days to be evaluated, days.

23. Times of sunrise and sunset each day, hr.

24. Extraterrestrial radiation, Btu/ft-day, (generated by the program based on the location).

25. Initial pavement temperature profile, F.

26. The year being considered.

27. Maximum daily air temperature on the day before the starting day and the minimum daily air temperature on the day after the last day in the evaluation period, F.

28. Date of the day being evaluated.

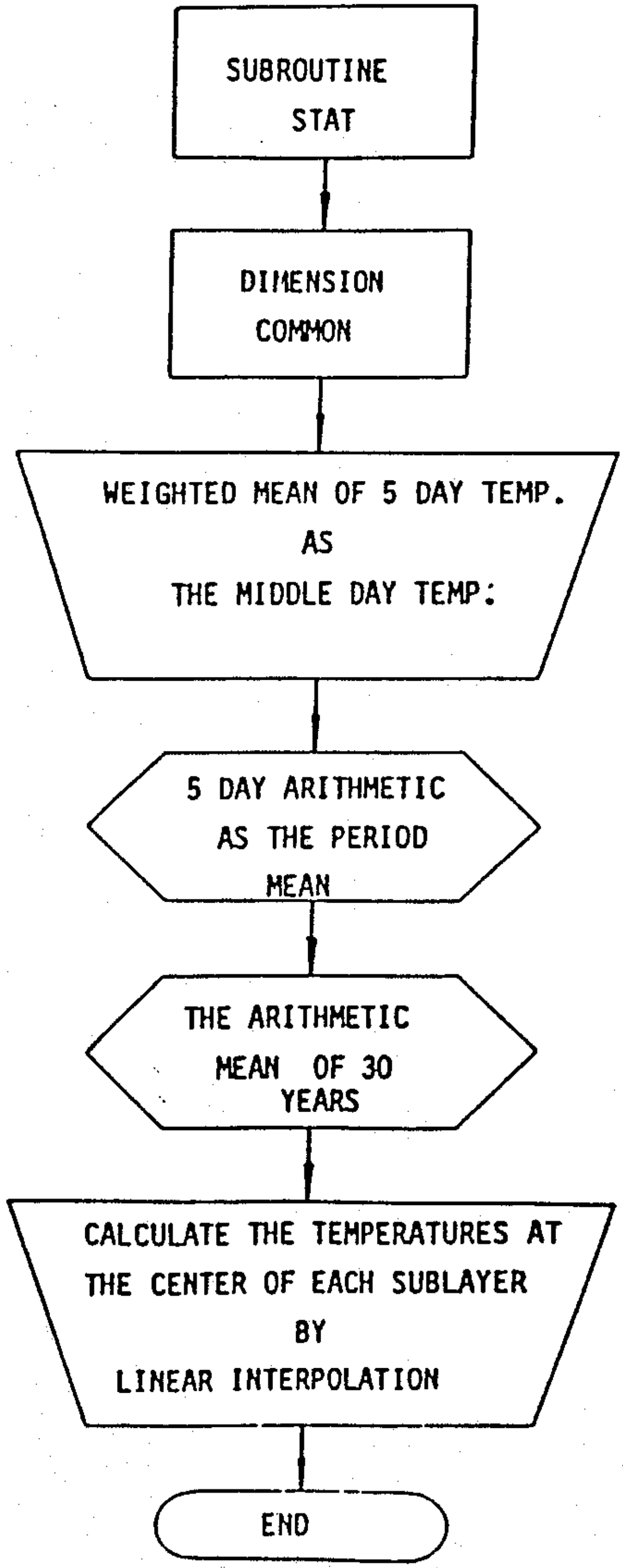
29. Maximum daily temperature, F, (on data tape).

30. Minimum daily air temperature, F, (on data tape).

31. Average daily wind velocity, mph, (on data tape).

32. Percentage of possible daily sunshine, %, (on data tape).

APPENDIX B. Computer Flow Diagram of STAT Subroutine



APPENDIX C

Example of Output From SAS Analysis

```
1         SAS(R) LOG   OS SAS 5.16          MVS/XA JOB HEAT1    STEP SAS                                         3:02 FRIDAY, MAY 8, 1987

NOTE: COPYRIGHT (C) 1984,1986 SAS INSTITUTE INC., CARY, N.C.  27511, U.S.A.
NOTE: THE JOB HEAT1 HAS BEEN RUN UNDER RELEASE 5.16 OF SAS AT TEXAS A&M UNIVERSITY (01452001).

NOTE: CPUID   VERSION = 82  SERIAL = 000261  MODEL = 0580 .

NOTE: SAS OPTIONS SPECIFIED ARE:
       SORT=4

1          DATA TEMP;
2          INPUT DATE TIME  LAYER PROFILE TEMP;
3          CARDS;

NOTE: DATA SET WORK.TEMP HAS 2592 OBSERVATIONS AND 5 VARIABLES. 433 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.34 SECONDS AND 100K.

2596       ::::::::::
2597       DATA TEMP1; SET TEMP; IF 7 <=TIME AND TIME <=19;

NOTE: DATA SET WORK.TEMP1 HAS 1404 OBSERVATIONS AND 5 VARIABLES. 433 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.11 SECONDS AND 100K.

2598       DATA TEMP2; SET TEMP; IF  TIME <=6 OR TIME >19;

NOTE: DATA SET WORK.TEMP2 HAS 1188 OBSERVATIONS AND 5 VARIABLES. 433 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.10 SECONDS AND 100K.

2599       PROC GLM  DATA=TEMP1; MODEL TEMP=DATE TIME LAYER DATE*DATE TIME*LAYER
2600       TIME*TIME TIME*TIME*LAYER TIME*TIME*TIME;
2601       OUTPUT OUT=NEW PREDICTED=YPREDIC RESIDUAL=YRESIDU;
NOTE: THE DATA SET WORK.NEW HAS 1404 OBSERVATIONS AND 7 VARIABLES. 317 OBS/TRK.
NOTE: THE PROCEDURE GLM USED 0.69 SECONDS AND 416K AND PRINTED PAGE 1.

2602       DATA THREE; MERGE TEMP1 NEW;

NOTE: DATA SET WORK.THREE HAS 1404 OBSERVATIONS AND 7 VARIABLES. 317 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.13 SECONDS AND 148K.

2603       PROC PLOT DATA=THREE;
2604       PLOT YPREDIC*TEMP YRESIDU*YPREDIC;
NOTE: THE PROCEDURE PLOT USED 0.24 SECONDS AND 196K AND PRINTED PAGES 2 TO 3.

2605       PROC GLM  DATA=TEMP2;
2606       MODEL TEMP=DATE TIME LAYER DATE*DATE TIME*TIME
2607       TIME*TIME*TIME TIME*TIME*TIME*TIME;
2608       OUTPUT OUT=NEW2 PREDICTED=YPREDIC RESIDUAL=YRESIDU;
NOTE: THE DATA SET WORK.NEW2 HAS 1188 OBSERVATIONS AND 7 VARIABLES. 317 OBS/TRK.
NOTE: THE PROCEDURE GLM USED 0.56 SECONDS AND 416K AND PRINTED PAGE 4.

2609       DATA FOUR; MERGE TEMP2 NEW2;

NOTE: DATA SET WORK.FOUR HAS 1188 OBSERVATIONS AND 7 VARIABLES. 317 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.12 SECONDS AND 148K.

2610       PROC PLOT DATA=FOUR;
2611       PLOT YPREDIC*TEMP  YRESIDU*YPREDIC;
NOTE: THE PROCEDURE PLOT USED 0.22 SECONDS AND 196K AND PRINTED PAGES 5 TO 6.

2612       DATA RANGESET KEEP RANGE PROFILE ;SET TEMP;
```

```
2613        IF LAYER=1 ;
2614        IF TEMP < 75. THEN RANGE=1;
2615        IF 75.<=TEMP<85 THEN RANGE=2;
2616        IF 85.<=TEMP<95 THEN RANGE=3;
2617        IF 95.0 <=TEMP <105 THEN RANGE=4;
2618        IF 105.<=TEMP <115  THEN RANGE=5;
2619        IF 115.<=TEMP <125 THEN RANGE=6;
2620        IF 125.<=TEMP <135 THEN RANGE=7;
2621        IF TEMP> 135. THEN RANGE=8;

NOTE: DATA SET WORK.RANGESET HAS 864 OBSERVATIONS AND 6 VARIABLES. 366 OBS/TRK.
NOTE: DATA SET WORK.KEEP HAS 864 OBSERVATIONS AND 6 VARIABLES. 366 OBS/TRK.
NOTE: DATA SET WORK.RANGE HAS 864 OBSERVATIONS AND 6 VARIABLES. 366 OBS/TRK.
NOTE: DATA SET WORK.PROFILE HAS 864 OBSERVATIONS AND 6 VARIABLES. 366 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.16 SECONDS AND 172K.

2622        PROC SORT DATA=TEMP ;BY PROFILE ;

NOTE: 4 CYLINDERS DYNAMICALLY ALLOCATED ON SYSDA FOR EACH OF 3 SORT WORK DATA SETS.
NOTE: DATA SET WORK.TEMP HAS 2592 OBSERVATIONS AND 5 VARIABLES. 433 OBS/TRK.
NOTE: THE PROCEDURE SORT USED 0.35 SECONDS AND 280K.

2623        PROC SORT DATA=RANGESET ; BY PROFILE ;

NOTE: DATA SET WORK.RANGESET HAS 864 OBSERVATIONS AND 6 VARIABLES. 366 OBS/TRK.
NOTE: THE PROCEDURE SORT USED 0.17 SECONDS AND 292K.

2624        PROC FORMAT;
2625        VALUE P
2626        1='PROFILE 1'
2627        2='PROFILE 2'
2628        3='PROFILE 3'
2629        4='PROFILE 4'
2630        5='PROFILE 5'
2631        6='PROFILE 6'
2632        7='PROFILE 7'
NOTE: FORMAT P HAS BEEN OUTPUT.
2633        8='PROFILE 8';
NOTE: THE PROCEDURE FORMAT USED 0.08 SECONDS AND 176K.

2634        DATA ALL ; MERGE TEMP RANGESET  ; BY PROFILE ;

NOTE: DATA SET WORK.ALL HAS 2592 OBSERVATIONS AND 6 VARIABLES. 366 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.23 SECONDS AND 148K.

2635        PROC SORT DATA = ALL ; BY LAYER RANGE ;

NOTE: DATA SET WORK.ALL HAS 2592 OBSERVATIONS AND 6 VARIABLES. 366 OBS/TRK.
NOTE: THE PROCEDURE SORT USED 0.32 SECONDS AND 280K.

2636        PROC MEANS ; BY LAYER RANGE;
NOTE: THE PROCEDURE MEANS USED 0.33 SECONDS AND 208K AND PRINTED PAGES 7 TO 9.

2637        PROC FREQ DATA=ALL;
2638        TABLES RANGE*LAYER;FORMAT RANGE P.;
NOTE: THE PROCEDURE FREQ USED 0.20 SECONDS AND 400K AND PRINTED PAGE 10.
NOTE: SAS USED 416K MEMORY.
```

```
NOTE: SAS INSTITUTE INC.
      SAS CIRCLE
      PO BOX 8000
      CARY, N.C. 27511-8000
```

SAS 3:02 FRIDAY, MAY 8, 1987 1

GENERAL LINEAR MODELS PROCEDURE

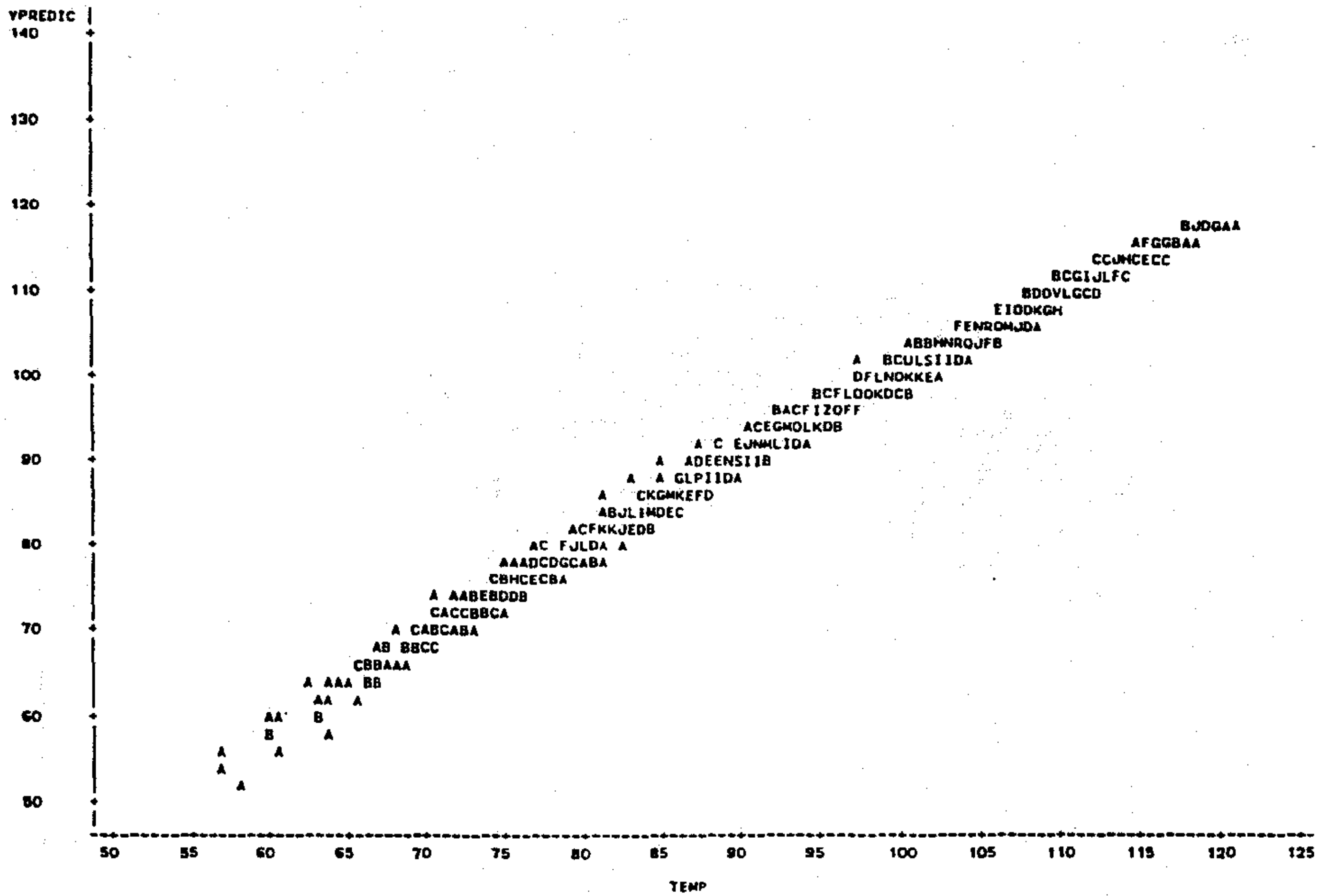
DEPENDENT VARIABLE: TEMP

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	8	228181.77424685	28522.72178086	22717.04	0.0001	0.992383	1.1754
ERROR	1395	1751.51310868	1.25556495		ROOT MSE		TEMP MEAN
CORRECTED TOTAL	1403	229933.28735553			1.12051995		85.33175926

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
DATE	1	15282.60901698	12171.90	0.0001	1	64628.49891468	51473.64	0.0001
TIME	1	40298.86899271	32096.20	0.0001	1	864.84405024	688.81	0.0001
LAYER	1	9654.97656932	7689.75	0.0001	1	2067.89608226	1646.99	0.0001
DATE*DATE	1	85910.79148859	68424.01	0.0001	1	85910.79148859	68424.01	0.0001
TIME*LAYER	1	2219.17177259	1767.47	0.0001	1	3819.46199437	3042.03	0.0001
TIME*TIME	1	68244.65008334	54353.74	0.0001	1	67.28072021	53.89	0.0001
TIME*TIME*LAYER	1	4666.50435761	3716.66	0.0001	1	4666.50435761	3716.66	0.0001
TIME*TIME*TIME	1	1904.20186571	1516.61	0.0001	1	1904.20186571	1516.61	0.0001

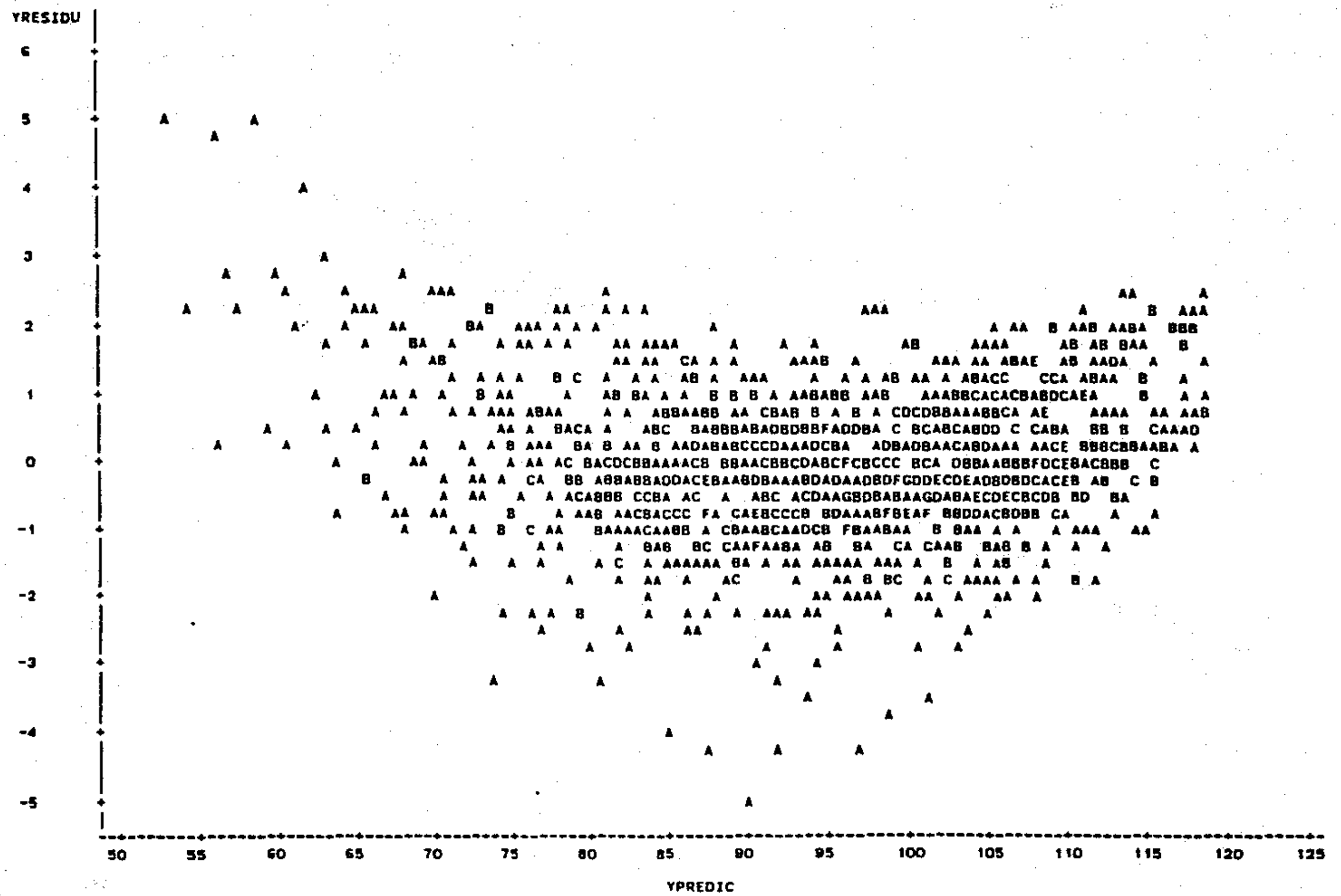
PARAMETER	ESTIMATE	T FOR H0: PARAMETER=0	PR > |T|	STD ERROR OF ESTIMATE
INTERCEPT	-7.37747191	-4.23	0.0001	1.74499359
DATE	2.68441704	226.88	0.0001	0.01183198
TIME	10.46812755	26.25	0.0001	0.39885928
LAYER	19.32725122	40.58	0.0001	0.47623918
DATE*DATE	-0.08113541	-261.58	0.0001	0.00031017
TIME*LAYER	-4.26659264	-55.15	0.0001	0.07735701
TIME*TIME	0.21952808	7.32	0.0001	0.02998930
TIME*TIME*LAYER	0.17992750	60.96	0.0001	0.00295135
TIME*TIME*TIME	-0.02926142	-38.94	0.0001	0.00075138

PLOT OF YPREDIC*TEMP LEGEND: A = 1 OBS, B = 2 OBS, ETC.



NOTE: 5 OBS HIDDEN

PLOT OF YRESIDU*YPREDIC LEGEND: A = 1 OBS, B = 2 OBS, ETC.



GENERAL LINEAR MODELS PROCEDURE

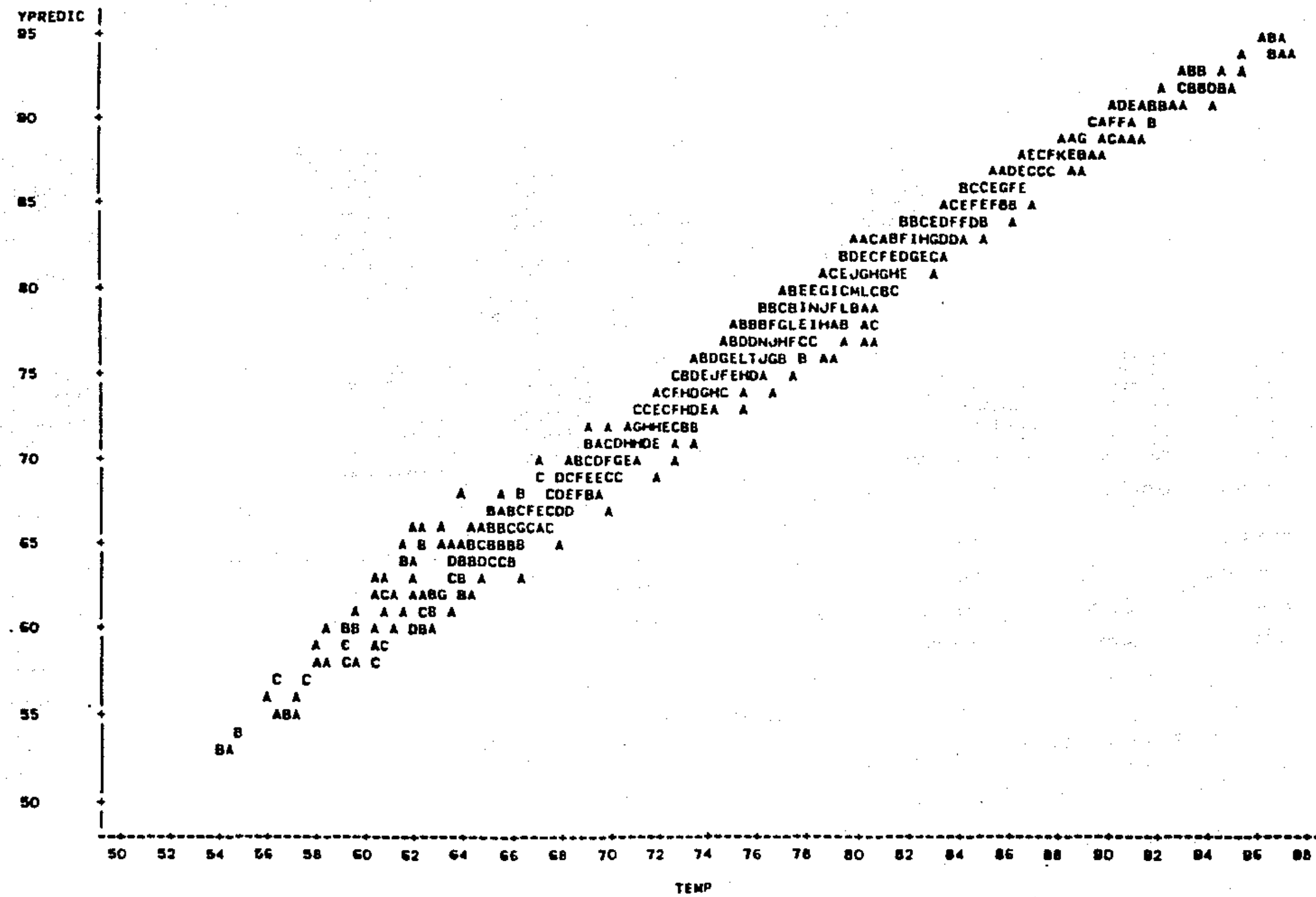
DEPENDENT VARIABLE: TEMP

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	7	82560.40912504	11794.34416072	8925.85	0.0001	0.983301	1.4236
ERROR	1180	1402.12955373	1.18824538		ROOT MSE		TEMP MEAN
CORRECTED TOTAL	1187	83962.53867877			1.09006669		76.56968013

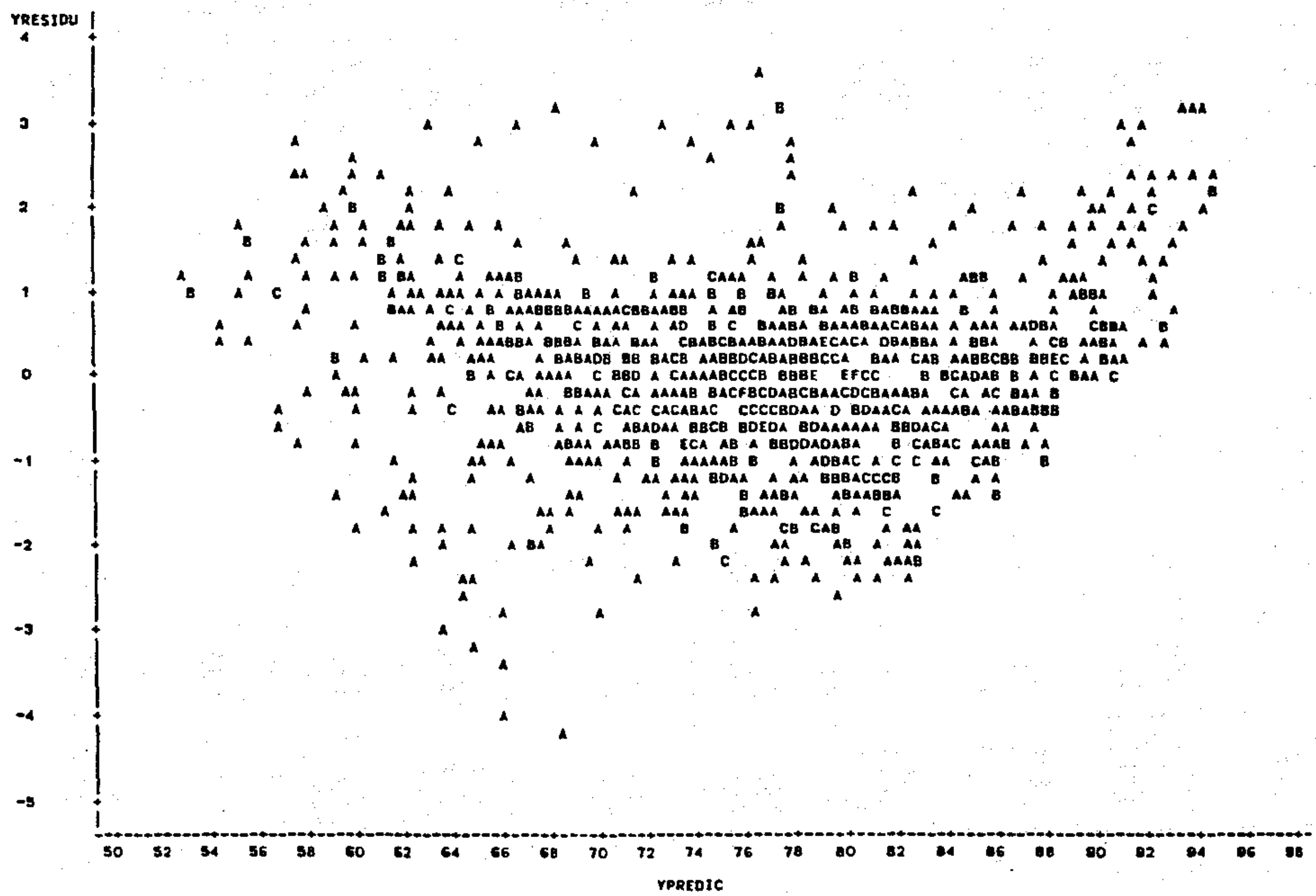
SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
DATE	1	4875.92921973	4103.47	0.0001	1	37585.42385364	31631.03	0.0001
TIME	1	16180.50912705	13617.14	0.0001	1	947.80030270	797.65	0.0001
LAYER	1	4600.83463649	3871.96	0.0001	1	4600.83463649	3871.96	0.0001
DATE*DATE	1	47258.63928237	39771.78	0.0001	1	47258.63928237	39771.78	0.0001
TIME*TIME	1	519.14961366	436.90	0.0001	1	663.25258910	558.18	0.0001
TIME*TIME*TIME	1	8916.02579882	7503.52	0.0001	1	388.98644742	327.36	0.0001
TIME*TIME*TIME*TIME	1	209.32144690	176.16	0.0001	1	209.32144690	176.16	0.0001

PARAMETER	ESTIMATE	T FOR H0: PARAMETER=0	PR > |T|	STD ERROR OF ESTIMATE
INTERCEPT	62.66070339	260.84	0.0001	0.24022340
DATE	2.22547650	177.85	0.0001	0.01251314
TIME	-4.51637367	-28.24	0.0001	0.15991327
LAYER	2.41021465	62.23	0.0001	0.03873383
DATE*DATE	-0.06541879	-199.43	0.0001	0.00032803
TIME*TIME	0.80313852	23.63	0.0001	0.03399414
TIME*TIME*TIME	-0.03855661	-18.09	0.0001	0.00218628
TIME*TIME*TIME*TIME	0.00057167	13.27	0.0001	0.00004307

PLOT OF YPREDIC*TEMP LEGEND: A = 1 OBS, B = 2 OBS, ETC.



PLOT OF YRESIDU*YPREDIC LEGEND: A = 1 OBS, B = 2 OBS, ETC.



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VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LAYER=1 RANGE=1									
DATE	222	21.12612613	13.20846919	1.00000000	36.00000000	0.88649441	4690.00000	174.46366	62.522
TIME	222	9.12612613	8.45067361	1.00000000	24.00000000	0.56717208	2026.00000	71.41388	92.599
PROFILE	222	492.15315315	318.09428860	1.00000000	864.00000000	21.34909079	109258.00000	101183.97644	64.633
TEMP	222	68.02202703	5.21991262	54.10000000	74.98000000	0.35033760	15100.89000	27.24749	7.674
LAYER=1 RANGE=2									
DATE	222	18.21621622	8.94417620	1.00000000	36.00000000	0.60029380	4044.000000	79.998288	49.100
TIME	222	13.25675676	8.60820530	1.00000000	24.00000000	0.57774491	2943.000000	74.101198	64.934
PROFILE	222	426.44594595	214.71478347	8.00000000	857.00000000	14.41071271	94671.000000	46102.438241	50.350
TEMP	222	79.34783784	2.95011539	75.04000000	84.80000000	0.19799878	17615.220000	8.703181	3.718
LAYER=1 RANGE=3									
DATE	129	19.04651163	10.40572293	1.00000000	36.00000000	0.91617282	2457.000000	108.279070	54.633
TIME	129	14.25581395	5.24147980	7.00000000	22.00000000	0.46148656	1839.000000	27.473110	36.767
PROFILE	129	447.37209302	249.81521514	10.00000000	855.00000000	21.99500326	57711.000000	62407.641715	55.841
TEMP	129	89.75007752	2.83808570	85.20000000	94.95000000	0.24987951	11577.760000	8.054730	3.162
LAYER=1 RANGE=4									
DATE	127	16.37007874	10.47430958	1.00000000	33.00000000	0.92944468	2079.000000	109.711161	63.984
TIME	127	13.70866142	3.49400901	8.00000000	19.00000000	0.31004316	1741.000000	12.208099	25.488
PROFILE	127	382.59055118	251.39535531	12.00000000	783.00000000	22.30773050	48589.000000	63199.624672	65.709
TEMP	127	100.02511811	3.08173675	95.00000000	104.98000000	0.27345992	12703.190000	9.497101	3.081
LAYER=1 RANGE=5									
DATE	105	16.09523810	7.36092047	4.00000000	29.00000000	0.71835228	1690.000000	54.183150	45.734
TIME	105	13.57142857	2.40934536	10.00000000	18.00000000	0.23512803	1425.000000	5.804945	17.753
PROFILE	105	375.85714286	176.60965370	86.00000000	686.00000000	17.23533739	39465.000000	31190.969780	46.989
TEMP	105	109.98266667	2.72379588	105.10000000	114.74000000	0.26581526	11548.180000	7.419064	2.477
LAYER=1 RANGE=6									
DATE	59	17.35593220	3.80001230	11.00000000	25.00000000	0.49471946	1024.000000	14.4400935	21.895
TIME	59	14.00000000	1.25944706	12.00000000	16.00000000	0.16396604	826.000000	1.5862069	8.996
PROFILE	59	406.54237288	91.20899117	253.00000000	590.00000000	11.87439923	23986.000000	8319.0800701	22.435
TEMP	59	117.62779661	1.66300421	115.13000000	121.29000000	0.21650471	6940.040000	2.7655830	1.414
LAYER=2 RANGE=1									
DATE	222	21.12612613	13.20846919	1.00000000	36.00000000	0.88649441	4690.00000	174.46366	62.522
TIME	222	9.12612613	8.45067361	1.00000000	24.00000000	0.56717208	2026.00000	71.41388	92.599
PROFILE	222	492.15315315	318.09428860	1.00000000	864.00000000	21.34909079	109258.00000	101183.97644	64.633
TEMP	222	70.05594595	5.44692447	56.15000000	78.13000000	0.36557363	15552.42000	29.66899	7.775
LAYER=2 RANGE=2									
DATE	222	18.21621622	8.94417620	1.00000000	36.00000000	0.60029380	4044.000000	79.998288	49.100
TIME	222	13.25675676	8.60820530	1.00000000	24.00000000	0.57774491	2943.000000	74.101198	64.934
PROFILE	222	426.44594595	214.71478347	8.00000000	857.00000000	14.41071271	94671.000000	46102.438241	50.350
TEMP	222	80.99815315	3.72174176	70.45000000	88.47000000	0.24978695	17981.590000	13.851362	4.595

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VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
LAYER=2 RANGE=3									
DATE	129	19.04651163	10.40572293	1.00000000	36.00000000	0.91617282	2457.000000	108.279070	54.633
TIME	129	14.25581395	5.24147980	7.00000000	22.00000000	0.46148656	1839.000000	27.473110	36.767
PROFILE	129	447.37209302	249.81521514	10.00000000	855.00000000	21.99500326	57711.000000	62407.641715	55.841
TEMP	129	88.69054264	4.39956768	79.42000000	98.53000000	0.38736034	11441.080000	19.356196	4.961
LAYER=2 RANGE=4									
DATE	127	16.37007874	10.47430958	1.00000000	33.00000000	0.92944468	2079.000000	109.711161	63.984
TIME	127	13.70866142	3.49400901	8.00000000	19.00000000	0.31004316	1741.000000	12.208099	25.488
PROFILE	127	382.59055118	251.39535531	12.00000000	783.00000000	22.30773050	48589.000000	63199.624672	65.709
TEMP	127	96.76015748	4.37253876	88.51000000	106.42000000	0.38800007	12288.540000	19.119095	4.519
LAYER=2 RANGE=5									
DATE	105	16.09523810	7.36092047	4.00000000	28.00000000	0.71835228	1690.000000	54.183150	45.734
TIME	105	13.57142857	2.40934536	10.00000000	18.00000000	0.23512803	1425.000000	5.804945	17.753
PROFILE	105	375.85714286	176.60965370	86.00000000	686.00000000	17.23533739	39465.000000	31190.969780	46.989
TEMP	105	105.23638095	3.45943752	98.79000000	111.45000000	0.33760653	11049.820000	11.967708	3.287
LAYER=2 RANGE=6									
DATE	59	17.35593220	3.80001230	11.00000000	25.00000000	0.49471946	1024.000000	14.4400935	21.895
TIME	59	14.00000000	1.25944706	12.00000000	16.00000000	0.16396604	826.000000	1.5862069	8.996
PROFILE	59	406.54237288	91.20899117	253.00000000	590.00000000	11.87439923	23986.000000	8319.0800701	22.435
TEMP	59	112.26847458	1.92175280	109.07000000	115.73000000	0.25019090	6623.840000	3.6931338	1.712
LAYER=3 RANGE=1									
DATE	222	21.12612613	13.20846919	1.00000000	36.00000000	0.88649441	4690.00000	174.46366	62.522
TIME	222	9.12612613	8.45067361	1.00000000	24.00000000	0.56717208	2026.00000	71.41388	92.599
PROFILE	222	492.15315315	318.09428860	1.00000000	864.00000000	21.34909079	109258.00000	101183.97644	64.633
TEMP	222	71.90617117	5.74419638	57.80000000	80.77000000	0.38552522	15963.17000	32.99579	7.988
LAYER=3 RANGE=2									
DATE	222	18.21621622	8.94417620	1.00000000	36.00000000	0.60029380	4044.000000	79.998288	49.100
TIME	222	13.25675676	8.60820530	1.00000000	24.00000000	0.57774491	2943.000000	74.101198	64.934
PROFILE	222	426.44594595	214.71478347	8.00000000	857.00000000	14.41071271	94671.000000	46102.438241	50.350
TEMP	222	82.45184685	4.92693959	67.13000000	91.26000000	0.33067453	18304.310000	24.274734	5.976
LAYER=3 RANGE=3									
DATE	129	19.04651163	10.40572293	1.00000000	36.00000000	0.91617282	2457.000000	108.279070	54.633
TIME	129	14.25581395	5.24147980	7.00000000	22.00000000	0.46148656	1839.000000	27.473110	36.767
PROFILE	129	447.37209302	249.81521514	10.00000000	855.00000000	21.99500326	57711.000000	62407.641715	55.841
TEMP	129	87.69961240	6.65060751	74.77000000	100.06000000	0.58555334	11313.250000	44.230580	7.583
LAYER=3 RANGE=4									
DATE	127	16.37007874	10.47430958	1.00000000	33.00000000	0.92944468	2079.000000	109.711161	63.984
TIME	127	13.70866142	3.49400901	8.00000000	19.00000000	0.31004316	1741.000000	12.208099	25.488
PROFILE	127	382.59055118	251.39535531	12.00000000	783.00000000	22.30773050	48589.000000	63199.624672	65.709
TEMP	127	93.64275591	6.08689402	82.88000000	106.20000000	0.54012450	11892.630000	37.050279	6.500

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LAYER=3 RANGE=5

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
DATE	105	16.09523810	7.36092047	4.00000000	29.00000000	0.71835228	1690.000000	54.183150	45.734
TIME	105	13.57142857	2.40934536	10.00000000	18.00000000	0.23512803	1425.000000	5.804945	17.753
PROFILE	105	375.85714286	176.60965370	86.00000000	686.00000000	17.23533739	39465.000000	31190.969780	46.989
TEMP	105	100.84590476	4.43448694	93.35000000	109.47000000	0.43276161	10588.820000	19.664674	4.397

LAYER=3 RANGE=6

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
DATE	59	17.35593220	3.80001230	11.00000000	25.00000000	0.49471946	1024.000000	14.4400935	21.895
TIME	59	14.00000000	1.25944706	12.00000000	16.00000000	0.16396604	826.000000	1.5862069	8.996
PROFILE	59	406.54237288	91.20899117	253.00000000	590.00000000	11.87439923	23986.000000	8319.0800701	22.435
TEMP	59	107.21728814	2.44662881	103.20000000	111.07000000	0.31852394	6325.820000	5.9859925	2.282

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TABLE OF RANGE BY LAYER

RANGE	LAYER: FREQUENCY / PERCENT / ROW PCT / COL PCT	1	2	3	TOTAL
PROFILE 1	FREQUENCY	222	222	222	666
	PERCENT	8.56	8.56	8.56	25.69
	ROW PCT	33.33	33.33	33.33	
	COL PCT	25.69	25.69	25.69	
PROFILE 2	FREQUENCY	222	222	222	666
	PERCENT	8.56	8.56	8.56	25.69
	ROW PCT	33.33	33.33	33.33	
	COL PCT	25.69	25.69	25.69	
PROFILE 3	FREQUENCY	129	129	129	387
	PERCENT	4.98	4.98	4.98	14.93
	ROW PCT	33.33	33.33	33.33	
	COL PCT	14.93	14.93	14.93	
PROFILE 4	FREQUENCY	127	127	127	381
	PERCENT	4.90	4.90	4.90	14.70
	ROW PCT	33.33	33.33	33.33	
	COL PCT	14.70	14.70	14.70	
PROFILE 5	FREQUENCY	105	105	105	315
	PERCENT	4.05	4.05	4.05	12.15
	ROW PCT	33.33	33.33	33.33	
	COL PCT	12.15	12.15	12.15	
PROFILE 6	FREQUENCY	59	59	59	177
	PERCENT	2.28	2.28	2.28	6.83
	ROW PCT	33.33	33.33	33.33	
	COL PCT	6.83	6.83	6.83	
TOTAL		864	864	864	2592
		33.33	33.33	33.33	100.00