values, (b) a limited self-diagnostic program to pinpoint problems, and (c) prompts to assist in transferring the data.

CONCLUSION

The use of automated traffic data collection procedures and equipment has increased rapidly as demand for data has grown while available resources have not. Recent developments in portable traffic sensor technology may be of use in improving the efficiency of acquiring these data. This paper has reviewed several aspects of possible technologies that may be applied to this need. The results of this paper are shown in Tables 1 and 2 as well as in Figures 7, 8, 9, and 10. Piezoelectric cable, infrared, and laser sensors were identified as having potential for increased use in temporary traffic data collection applications.

Performance requirements for portable sensors and traffic data collection equipment were developed based on a variety of sources. The need to consider standards for these devices is apparent and should be pursued to provide both users and vendors with guidelines.

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Multivariate Analysis of Pavement Dynaflect Deflection Data

JOHN G. ROHLF and RAMEY O. ROGNESS

ABSTRACT

Pavement management has become an area of great concern for highway departments. Pavement evaluation and research play an important role in the pavement management process. In this study, a relationship was developed between Dynaflect deflections and pavement temperature, subgrade moisture, and cumulative traffic loading for a number of different pavement sections. Dynaflect deflections and pavement surface temperatures were recorded for 76 flexible pavement sections. The data were collected over a 9-year period on a North Dakota State Highway Department test road. A subgrade moisture classification was developed and used as a surrogate measure of subgrade moisture. The 5-day mean air temperature, in addition to the surface temperature, was used to represent the overall pavement temperature. The five Dynaflect sensor readings were found to be highly correlated. As a result, multivariate analysis techniques were used to analyze the data. Season (moisture), pavement surface and mean air temperatures, and traffic were found to significantly affect pavement deflection. The effects of temperature were significantly different for the different seasons.

Pavement management has become an area of great concern for highway dependents. As available resources and funds decrease, and a majority of roadways reach a state of severe deterioration, highway departments are no longer able to manage their roadways based on experience alone.

PAVEMENT MANAGEMENT

It has become apparent that in order to maximize the benefits of limited budgets, highway departments must develop extensive pavement management systems. In recent years, highway departments have begun to realize the importance of pavement evaluation and research in the pavement management process. Many highway departments have established control or evaluation roadway sections. Data related to pavement performance are periodically measured and recorded in a data bank.

In general, the data collected through pavement evaluation activities can be classified into the following four groups (1):

1. Roughness (ride quality),
2. Surface distress (impending failure),

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3. Structural evaluation (surface deflection), and
4. Skid resistance (friction).

Although all four of the preceding data groups provide important pavement evaluation information, the data in this paper pertain to the analysis of structural evaluation data, in particular, the analysis of surface deflection data for flexible pavements as measured with a dynamic force generator and a deflection measuring system.

OBJECTIVE

Pavement deflections are highly affected by (a) the type and thickness of the pavement components, (b) the temperature of the pavement, (c) the moisture content of the subgrade, and (d) the amount of traffic that has passed over the roadway. The objective of this paper is to develop a relationship between dynamic deflection and pavement temperature, subgrade moisture, and traffic loading for a number of different pavement cross sections. This relationship can then be used to standardize dynamic deflections to some reference temperatures. This relationship enables the different pavement sections to be compared at various moisture and traffic combinations.

PAVEMENT DEFLECTIONS

In the past, the Benkelman Beam was the deflectometer most commonly used by the highway departments. Since the early 1970's, the use of dynamic deflection devices has increased in popularity. The main advantage of dynamic deflection devices is that deflections are simultaneously measured at several points rather than just at the point of load. The resulting deflection basin can be used to determine structural information about the entire pavement system.

Five parameters, which have been associated with the strength properties of the pavement and subgrade, are defined as functions of the sensor deflections. These parameters are as follows:

1. Dynaflect Maximum Deflection (DMD),
2. Surface Curvature Index (SCI),
3. Base Curvature Index (BCI),
4. Spreadability (SP%), and
5. Fifth Sensor Deflection (W5).

Figure 1 shows the layout of the Dynaflect sensors and the resulting pavement deflection basin.

The Dynaflect deflection parameters are indicators of various characteristics of the pavement layers. These deflection parameters are used in the structural evaluation and rehabilitation of pavements. The uses of the deflection parameters are as follows (2-4):

1. DMD. The Dynaflect Maximum Deflection is an indication of the pavement's overall structural condition. A high DMD is usually an indication of low subgrade support. Low-strength base and surface layers could also result in a high DMD.
2. SCI. The Surface Curvature Index is an indication of the structural properties of the pavement surface layer. The SCI is also directly proportional to the stresses and strains experienced at the bottom of the pavement surface layer.
3. BCI. The Base Curvature Index is an indication of the base and subgrade support conditions. Majidzadeh (2) indicated that under certain conditions, the BCI could possibly be used to predict the modulus of subgrade support.

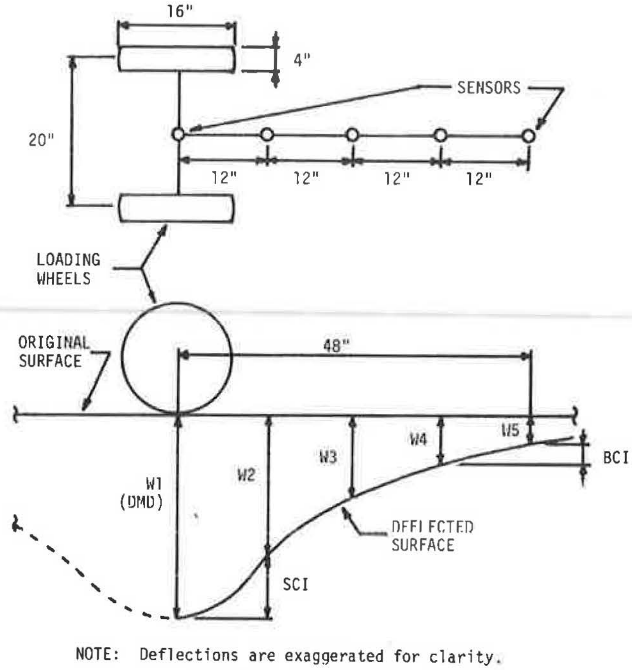

FIGURE 1 Dynaflect deflection basin.

4. SP%. The Spreadability is an indication of the pavement's stiffness and load-carrying ability. The SP% is not an indicator of the overall pavement strength; but rather, it is an indication of the ratio of the surface layer to support layer strengths.
5. W5. The fifth sensor reading is an indication of the modulus of the subgrade.

In addition to indicating the overall structural condition of a pavement, Dynaflect deflections provide information on the structural properties of the various pavement layers.

PAVEMENT TEMPERATURES

The temperature of flexible pavements at the time when deflection measurements are made has a substantial effect on the deflection. This temperature effect is a result of the temperature dependency of the stiffness of the asphalt components.

Before the effects of temperature can be considered, the temperature of the pavement must be determined. Although the temperature of the pavement surface can be easily measured, it does not necessarily represent the temperature throughout the pavement. A method to estimate the pavement temperature at various depths based on the surface temperature was developed by Southgate and Deen (5).

Southgate and Deen based their pavement temperature distribution on the surface temperature of the pavement and the previous 5-day mean air temperature. The addition of the mean air temperature to the model provides information that accounts for the effects of daily weather conditions on surface temperatures. For example, the mean air temperature enables the model to distinguish between two equal surface temperatures: one that was taken in the summer on an overcast day, and one that was taken in the spring or fall on a cool, sunny day.

The mean air temperatures were computed as the average of the daily high and low temperatures. Although this method does not result in the true mean air temperature, these data are available for each U.S. Weather Bureau reporting station. The mean air temperature for only the previous 5 days was used because Southgate and Deen found that beyond the 5-day point, the increase in accuracy was not significant.

Southgate and Deen (5) used data that were collected by the Asphalt Institute from a test site at San Diego, California, to verify their pavement temperature distribution method. They found that the estimated temperatures, using their method, were within two standard deviations of the actual temperatures, as measured with thermocouples embedded in the pavement. Hines (6) found that the estimated temperatures, using Southgate and Deen's method, were slightly lower than the actual temperatures.

The pavement temperature distribution method developed by Southgate and Deen (5) has been used by the Kentucky Department of Highways (5), the Colorado Department of Highways (6), and the Utah Department of Transportation (7).

Once the mean pavement temperature has been determined, a relationship between pavement temperature and deflection can then be developed. Deflection adjustment factor curves that relate deflections at various temperatures to corresponding deflections at 60°F were developed by Southgate and Deen (5).

Although the temperature adjustment factor curves developed by Southgate and Deen have been commonly used (5-7) for dynamic deflections, these curves were developed for Benkelman Beam data. A report by Hoffman and Thompson (8) indicates that there is some question as to the correlation between Benkelman Beam deflection and dynamic deflection.

CLIMATE AND TEMPERATURE

The deflection of flexible pavements is dependent on the subgrade strength. Because the strength of the subgrade is moisture-dependent, the moisture of the subgrade has a significant effect on the deflection of the pavement. Unfortunately, quantitative measures of moisture content are generally not available for most situations. Also, as reported by Jorgenson (3), attempts to measure subgrade moisture are not always successful.

It is well documented (1,4,6,9-13) that spring thaw has an adverse effect on pavement performance. Because actual moisture data are not always available, a common method used to account for subgrade moisture is to classify the months of the year into groups with similar subgrade moisture content (6,9).

Colorado (6) developed a "critical factor" that is used to adjust deflection readings made throughout the year to corresponding spring thaw deflections. The critical factors were developed for various time periods and regional factor combinations. The regional factors were based on annual precipitation, elevation, drainage, frost, and other special conditions.

Utah (9) reported on how spring weight limits could be developed based on dynamic deflections. They indicated how monthly variations in climate variables corresponded to changes in deflection. The monthly climate variables considered were average air temperature, precipitation, the number of days above freezing, and the number of days below freezing.

TRAFFIC EFFECT

The traditional method of designing flexible pavements is based on the number of equivalent 18,000-lb loads that the pavement will have to carry (14). Hardcastle (15) reported that an interaction does exist between traffic loadings and the subgrade strength of the pavement at the time of the loading.

Several points should be considered in the analysis of Dynaflect deflection data including the following:

1. The pavement surface temperature alone does not accurately represent the temperature throughout the pavement. As Southgate and Deen (5) indicated, the previous 5-day mean air temperature is useful in estimating the temperature throughout the pavement.
2. When actual moisture data are not available, part of the variability of deflection attributed to moisture can be accounted for by dividing the year into wet, dry, and frozen seasons.
3. Hardcastle (15) indicated that the effect of traffic on deflection varies with the subgrade moisture at the time of application. Introduction of the traffic data into the model, in such a way that the subgrade moisture at the time of application is considered, may improve the model.

DYNAFLECT DATA

The data used for this project were collected by the North Dakota State Highway Department (NDSHD) as part of their Lakota Test Road project. The Lakota Test Road was constructed in 1973.

The test road is a portion of United States Highway 2 (U.S. 2) and is located in the northeastern part of the state, just to the east of Lakota, North Dakota. U.S. 2 is a primary highway that runs east and west across the northern part of North Dakota and is 2 lanes wide in the area of the test road. The test road consists of 76 different test sections. Each test section is 500-ft long and 1-lane wide. Thirty-eight of the test sections are part of the eastbound (south) lane of U.S. 2 and the other 38 test sections are part of the westbound (north) lane.

TEST SECTIONS

The 76 test sections were constructed using two types of bituminous surface layers and five different base types. One-half of the test sections were asphalt cement (AC), 120-150 bituminous pavement. The other half were slow-curing (SC), 3000 bituminous pavement. The different bases consist of gravel, treated soil, treated aggregate, bituminous stabilized aggregate, and portland cement concrete mix. Table 1 gives the surface and base materials used in the test road.

The test road sections also consist of four different surface and base thickness combinations. Surface thicknesses of 2 1/4 in. are combined with base thicknesses of 4 and 6 in. The compositions of the various test sections are given in Table 2 (south lane) and Table 3 (north lane).

NDSHD personnel collected data on the test road periodically each year from 1974 through 1982. Data were collected frequently the first 4 years, and only once a year the last 5 years.

The pavement Dynaflect deflections were measured along the outside wheel path at 50-ft intervals for each test section. This resulted in 10 deflection observations per test section per collection date. In all, approximately 38,000 deflection observations were made and recorded.

SAMPLING PLAN

Because the number of deflection observations was so large, the amount of computer storage space required

TABLE 1 Materials Used in Test Road (3)

Material	Description
Surface	
AC	120-150 bituminous pavement
SC	3000 bituminous pavement
Base	
Gravel	National standard gradation
Soil treatment	Soil + 8% cement
	Soil + 2% lime + 4% cement (with 4-in. base)
	Soil + 3% lime + 5% cement (with 6-in. base)
Aggregate treatment	
	Aggregate + 7% cement
	Aggregate + 2% lime + 17% fly ash
Bituminous	
	Aggregate + 6.4% AC 120-150
	Aggregate + 6.6% AC 120-150
	Aggregate + 6.5% emulsified asphalt
Portland cement concrete	
	Aggregate + 4.5 bags of cement/yd^3
	Aggregate + 6.0 bags of cement/yd^3

Note: AC = asphalt cement and SC = slow curing.

for the analysis would be excessive. Thus, it was computationally impractical to analyze the entire data set as a whole. An alternative to using the entire data set was to use a random sample to represent the data set. The use of a random sample to represent a large data file is an accepted practice in data analysis.

To select a random sample, a random number function generator in the Statistical Analysis System, (SAS), (16) was used. A deviate from a standardized

TABLE 2 Composition of Test Sections: South Lane (3)

Test Section Number	Station	Base[a] T	Base[a] Type	Surface[a] T	Surface[a] Type
15	35-40	4	4A	2	2
11	40-45	4	2A	2	2
8	45-50	4	5B	2	1
16	50-55	4	4B	2	2
14	55-60	4	4C	2	2
4	60-65	4	2B	2	1
10	65-70	4	3A	2	2
6	70-75	4	4A	2	1
9	75-80	4	5A	2	1
29	80-85	6	3A	2	2
35	85-90	6	4B	2	2
28	90-95	6	1	2	1
23	95-100	6	4C	2	1
26	100-105	6	5B	2	1
34	105-110	6	4A	2	2
38	110-115	6	1	2	2
19	115-120	6	3A	2	1
20	120-125	6	2A	2	1
33	125-130	6	4C	2	2
42	130-135	4	2B	4	1
50	135-140	4	3B	4	2
51	140-145	4	2B	4	2
44	145-150	4	4A	4	1
45	150-155	4	4B	4	1
43	155-160	4	4C	4	1
54	160-165	4	4B	4	2
52	165-170	4	4C	4	2
53	170-175	4	4A	4	2
63	175-180	6	4B	4	1
60	180-185	6	2C	4	1
68	185-190	6	2A	4	2
74	190-195	6	5B	4	2
72	195-200	6	4A	4	2
75	200-205	6	5A	4	2
76	205-210	6	1	4	2
69	210-215	6	3B	4	2
71	215-220	6	4C	4	2
61	220-225	6	4C	4	1

[a]Base and surface types as listed in Table 1.

TABLE 3 Composition of Test Sections: North Lane (3)

Test Section Number	Station	Base[a] T	Base[a] Type	Surface[a] T	Surface[a] Type
17	35-40	4	5B	2	2
13	40-45	4	2B	2	2
2	45-50	4	2A	2	1
7	50-55	4	4B	2	2
5	55-60	4	4C	2	2
3	60-65	4	3B	2	1
18	65-70	4	5A	2	2
12	70-75	4	3B	2	1
1	75-80	4	3A	2	1
24	80-85	6	4A	2	2
36	85-90	6	5B	2	2
30	90-95	6	2A	2	1
22	95-100	6	2C	2	1
32	100-105	6	2C	2	1
31	105-110	6	3B	2	2
21	110-115	6	3B	2	2
37	115-120	6	5A	2	1
27	120-125	6	5A	2	1
25	125-130	6	4B	2	2
49	130-135	4	2A	4	1
48	135-140	4	3A	4	2
47	140-145	4	5A	4	2
41	145-150	4	3B	4	1
40	150-155	4	2A	4	1
46	155-160	4	5B	4	1
55	160-165	4	5B	4	2
56	165-170	4	5A	4	2
39	170-175	4	3A	4	2
62	175-180	6	4A	4	1
65	180-185	6	5A	4	1
57	185-190	6	3A	4	2
66	190-195	6	1	4	2
58	195-200	6	2A	4	2
67	200-205	6	3A	4	2
59	205-210	6	3B	4	2
64	210-215	6	5B	4	2
70	215-220	6	2C	4	2
73	220-225	6	4B	4	1

[a]Base and surface types as given in Table 1.

normal distribution was generated for each observation. Observations that had a generated deviate equal to -1.28 or less were used for the 10 percent sample. The value of -1.28 corresponds to a tail area of 10 percent. (A 10 percent sample was used because it was small enough to be analyzed on the computer system available, yet large enough to represent the data set.)

TEMPERATURE AND MOISTURE

The temperature of the pavement was recorded when the deflection readings were made. The temperatures measured were partial depth mat temperatures. It was recognized that these temperatures were neither surface temperatures nor mat temperatures. It is felt that the pavement temperatures collected do not accurately represent the temperatures throughout the pavement. The 5-day mean air temperatures, in addition to the temperatures collected, would be more representative of the overall pavement temperatures.

Fourteen randomly selected test sections had tubes installed that could be used to measure the subgrade moisture. The tubes had sealed bottoms and moisture-proof covers. The moisture of the subgrade was measured using a Toxler Moisture Depth Probe Model 1255.

Several problems were encountered with the use of the moisture tubes. In his report, Jorgenson (3) stated the following problems with the tubes:

1. The moisture probe would not fit down the tube.

2. Moisture leaked into the tube through the sealed bottom.
3. The moisture-proof cover leaked as a result of subgrade and pavement movement.
4. The moisture-proof cover was removed.
5. The tube cover was covered with a pavement overlay.
6. The tube was removed by snowplows.

Because of these problems, the moisture data that were collected for the first several years of the study were not reliable. Moisture data were not collected in the latter years. Consequently, not enough reliable moisture data were available to be used in the deflection model directly.

Because sufficient moisture data were not available, the only alternative was to use some surrogate measure to represent moisture content. The moisture data collected were used, along with climatological data, to classify the months of the year into wet and dry subgrade moisture periods.

TRAFFIC

Traffic data for the test road were collected by the NDSHD. The traffic data were collected at an automatic traffic recording station (ATR), which is located on U.S. 2 approximately 2.5 mi east of Lakota, North Dakota.

The monthly axle counts in each direction were recorded. Vehicle classification counts were also made monthly. The classification counts, along with the equivalent load factors used by the NDSHD, were used to convert the monthly axle counts to equivalent 18-kip axle loads.

CLIMATE

Climatological data are required for the calculation of the 5-day mean air temperatures and for the subgrade moisture classification. Climatological data are recorded daily and reported monthly for weather stations throughout the country by the National Oceanic and Atmospheric Administration. The weather recording station nearest the Lakota Test Road is approximately 12 mi east of the test sections, at Petersburg, North Dakota.

The data required for the 5-day mean air temperature were the daily high and low temperatures for the 5 days preceding each collection date. The monthly mean air temperatures and the monthly normal precipitation throughout the study period were of interest for the moisture classification.

DATA PREPARATION

The NDSHD has a Dynaflect deflection data file stored on a computer tape. This was the data file from which the 10 percent random sample was generated, as discussed previously. The data file contained the following variables:

- The observation date (DATE);
- The pavement temperature (TEMP);
- The test section number (SEC);
- Eastbound or westbound lane (DIR);
- Observation location (STA); and
- The five sensor deflections (W1 through W5).

The data set used for this study was created using the sample generated from the Dynaflect deflection data file. Changes made to the data sample include (a) the addition of dummy variables to represent the different test sections; (b) the addition of climatological data (5-day mean temperature and seasonality); and (c) the addition of traffic data.

Although the test sections were assigned numbers, the variable SEC is not a continuous variable and could not be used in the analysis directly. Qualitative variables, such as SEC, could have been analyzed using one of two methods.

One possible method of analyzing test sections would be to divide the data into subsets and analyze each test section separately. Although this method would be the easiest computationally, it has two major drawbacks. One drawback to this method is that a separate regression model would be required for each test section. This would result in 76 independent regression models. Secondly, because the 76 regression models would be calculated independently, there would be no basis for comparing the different test sections.

The alternative to analyzing each test section separately is to use indicator variables (17), or dummy variables, to represent the test sections. This was accomplished by first breaking the test sections down into their basic components. Two of the components--the surface and base thicknesses--are continuous variables and two of the components--the surface and base materials--are qualitative variables.

The variables' surface and base thickness (ST and BT, respectively) were used in the analysis directly. Dummy variables were used to represent the 2 surface materials (SM) and the 11 base materials (B1 through B10). The values assigned to the dummy variables are given in Table 4. It should be noted that Base 5B is represented when variables B1 through B10 all equal zero.

TABLE 4 Test Section Components

Variable	Value	Represents[a]
SM	1	AC 120-150
	0	SC 3000
B1	1	Base 1
	0	(not Base 1)
B2	1	Base 2A
	0	(not Base 2A)
B3	1	Base 2B
	0	(not Base 2B)
B4	1	Base 2C
	0	(not Base 2C)
B5	1	Base 3A
	0	(not Base 3A)
B6	1	Base 3B
	0	(not Base 3B)
B7	1	Base 4A
	0	(not Base 4A)
B8	1	Base 4B
	0	(not Base 4B)
B9	1	Base 4C
	0	(not Base 4C)
B10	1	Base 5A
	0	(not Base 5A)

[a]Base types as given in Table 1.

By representing the test sections, as previously stated, it was possible to analyze all of the test sections simultaneously using one model. Also, using this method, it was possible to compare the various test sections and test the interaction between their components.

Climatological information, which was added to the data set included the 5-day mean air temperature (T5) and a dummy variable used to indicate season (SEAS). The 5-day mean air temperatures were calculated by averaging the daily high and low temperatures for the 5-days preceding the observation date. This was done based on the report by Southgate and Deen (5), as discussed earlier.

The dummy variable SEAS was added to the data set in an attempt to consider the effects of subgrade moisture on deflection. The first step in determining values for SEAS was to classify the months of the year into groups with similar subgrade moisture. The three classes used were wet, dry, and frozen subgrade.

The season classifications were based on the mean monthly air temperatures during the study period; the normal monthly precipitation; moisture data collected by the NDSHD, as reported by Jorgenson (3); and spring load-limit information obtained from the NDSHD.

The frozen season was determined primarily from the mean monthly air temperatures during the study period. December, January, February, and March were clearly identified as frozen months. The transition month, April, had a mean air temperature of 43.1°F. Also, April was typically the month in which the spring weight limits were imposed by the NDSHD. Thus, April was considered as a wet month. The mean air temperature for November, 28.3°F, was only slightly below freezing; consequently, November was classified as a dry month.

The cutoff point between the wet and dry classes was not so easily defined. The moisture data collected did not vary much from date to date and were not of much use in the season classification. The moisture content for April and May was anticipated to be high because of the spring thaw. In addition, the month of June has the highest normal precipitation. It was decided to consider April through June as wet months.

Although three season classes were determined, only data collected during the wet and dry classes were used in the analysis. Data collected during the frozen class were deleted because the material properties of the subgrade change when frozen. The values assigned to SEAS were 0 and 1, which represented the dry and wet classes, respectively.

It should be noted that SEAS was a general approximation of a moisture season classification. The actual moisture season classification may have varied from year to year. Because no quantitative measure of subgrade moisture was available, the use of a general approximation was the only method available that would consider the effects of moisture on deflection and would be a typical approach to prediction or planning analysis.

The total traffic that has passed over the pavement at the time of the deflection reading was of interest. A computer file was created that contained the accumulated traffic loads by months. It was determined, as described previously, that the traffic should be entered in the model in such a way that the subgrade moisture (SEAS) during the period of load application is considered. To consider the effect of SEAS, the monthly accumulated traffic loads were combined to form seasonal cumulative traffic loads for each month of the study period.

ANALYSIS

The development of a relationship between Dynaflect deflection and temperature, moisture, and traffic for various pavement cross sections was desired. One means of accomplishing this is the use of regression. Because Dynaflect deflections are measured using five sensors, regression equations must be developed for each of the five sensors.

The traditional approach to this type of problem is to develop a univariate regression model for each of the dependent variables (five sensors) individually. However, if a significant correlation exists between the dependent variables, the resulting univariate models may be biased by the data for the dependent variable being analyzed. The information contained in the other dependent variables may reinforce or contradict that of the variable being analyzed. Multivariate analysis techniques are more appropriate when the dependent variables are correlated (18). Multivariate techniques consider information contained in all of the dependent variables simultaneously.

Because of the physical orientation of the Dynaflect, it is apparent that the deflections at the five sensors are correlated. The first step of the analysis of the data was to calculate the correlation matrix of the five sensor deflections. The correlation matrix between W1 through W5 is given in Table 5. All of the correlations between the sensors are significant at a significance level of 1 percent. Because the five sensor deflections are highly correlated, with values ranging from 0.3600 to 0.9337, multivariate techniques should be used to analyze the deflection data.

TABLE 5 Correlation Between Sensor Readings

Sensor	W1	W2	W3	W4	W5
W1	1.0000	0.8516	0.5899	0.4095	0.3600
W2	0.8516	1.0000	0.8540	0.6366	0.6196
W3	0.5899	0.8540	1.0000	0.8980	0.8368
W4	0.4095	0.6366	0.8980	1.0000	0.9337
W5	0.3600	0.6196	0.8368	0.9337	1.0000

The regression coefficients and their standard errors are identical for both univariate and multivariate regression. The difference between multivariate and univariate regression arises in the test statistics used in hypothesis testing and in the confidence limits used to test significance of regression coefficient estimates.

The multivariate analysis of variance (MANOVA) table is given in Table 6. The MANOVA table is similar to a univariate analysis of variance table. In the MANOVA table, the total (T) sum of squares and cross products (SSCP) matrix is partitioned into the hypothesis (H) and error (E) SSCP matrices. The diagonals of the SSCP matrices are composed of the univariate sum of squares. In univariate analysis of variance, a function of the ratio of the hypothesis to the error sum of squares is used to test the significance of the model. The corresponding test in multivariate analysis is based on the $E^{-1}H$ matrix.

TABLE 6 MANOVA Table

Source Variation	df	SSCP Matrix	Wilk's Statistic
Regression	k	$H = \hat{\Gamma}X'Y - N\bar{y}\bar{y}'$	$\Lambda = \|E\|/(\|H + E\|)$
Error	$N - k - 1$	$E = Y'Y - \hat{\Gamma}X'Y$	
Total	$N - 1$	$T = H + E$	

Note: k = number of regression terms, N = number of observations, $\hat{\Gamma}$ = matrix of regression coefficient estimates, X = matrix of independent variables, Y = matrix of dependent variables, $\bar{y}$ = vector of dependent variable means, H = hypothesis sum of squares matrix, E = error sum of squares matrix, T = total sum of squares matrix, and df = degrees of freedom.

Because $E^{-1}H$ is a matrix, it is not suitable as a test statistic in itself. Test statistics based on the characteristic roots of the $E^{-1}H$ matrix have been developed (19). Wilk's statistic, as given in Table 6, is commonly used to test the significance of the regression model. Other test statistics based on functions of the characteristic roots of the $E^{-1}H$ matrix have been developed by Roy, Lawley and Hotelling, and Pillai. The test statistics and their corresponding table values are given in Table 7.

TABLE 7 Multivariate Test Statistics

Test Statistic	Equation	Criterion for Rejection of Ho
Wilk's Lambda	$\Lambda = \lvert E \rvert / \lvert H + E \rvert$	$< U^{\alpha}_{(p,k,N-k-1)}$
Roy's GCR	$\Theta = \lambda/(1 + \lambda)$	$> \Theta^{\alpha}_{(s,m,n)}$
Lawley-Hotelling	$U = \sum_{i=1}^{s} \lambda_i$	$> U^{\alpha}_{o(s,m,n)}$
Pillai's Trace	$V = \sum_{i=1}^{s} \lambda_i/(1 + \lambda_i)$	$> V^{\alpha}_{(s,m,n)}$

Note: Ho = null hypothesis ($\Gamma = 0$), α = significance level, N = number of observations, p = number of dependent variables, λ_i = characteristic roots of $E^{-1}H$, s = min(df_e,p), df_e = degrees of freedom for error, m = ($\lvert p - k \rvert$ - 1)/2, n = (N - k - p - 2)/2, k = number of independent variables, U^{α} = Wilk's Lambda Criterion, Θ^{α} = largest characteristic root distribution, U^{α}_{o} = Lawley-Hotelling Trace Criterion, and V^{α} = Pillai's Trace Criterion.

The four test statistics given in Table 7 generally produce the same results; however, this is not always true. Morrison (20) has stated under what conditions which test statistic has the most power.

In multivariate regression, simultaneous confidence limits are used to test the significance of the individual regression coefficients. The Roy-Bose simultaneous confidence limits (20) are calculated using the following expression:

$$\hat{B} + C_o \cdot \hat{\sigma}_{\hat{\beta}} \quad (1)$$

where

$\hat{B}$ = the regression coefficient estimate,
$\hat{\sigma}_{\hat{\beta}}$ = the estimated standard error of the regression coefficient estimate, and
$C_o = \{df_e \cdot [\theta^{\alpha}/(1 - \theta^{\alpha})]\}^{1/2}$

The simultaneous confidence intervals are wider than the individual confidence intervals used in univariate regression.

One reason why multivariate regression is typically not used when appropriate is that the statistical computer packages are not well developed in this topic area. Unlike univariate regression, there are no computer model-building procedures available for multivariate regression.

MULTIPLE REGRESSION MODEL

However, SAS (17-19) was used to perform many of the calculations required in the regression model development. The MANOVA option under SAS's General Linear Models (GLM) procedure was used to calculate the regression coefficient estimates, their estimated standard errors, and the error matrix (E). Using GLM, the hypothesis (H) matrix and the four test statistics were generated to test the significance of the independent variables. However, these tests are not partial tests.

Partial tests, for an independent variable, indicate whether or not the contribution of the variable significantly improves the model. The partial tests of the independent variables were performed using the Roy-Bose simultaneous confidence intervals. if the regression coefficient estimates for an independent variable were not significant for all of the dependent variables, that independent variable was eliminated from the model.

The first step in building the multivariate regression model was to test the significance of the variables that represent the test sections. The partial tests of the variables ST, BT, SM, B1, B2, B7, B8, and B9 were significant at alpha levels of 1 percent; therefore, these variables were left in the model. The alpha level, or significance level, is the probability of rejecting a true null hypothesis. The additions of B3, B4, B5, and B6 did not significantly improve the model, based on partial tests at levels of 1 percent significance. Consequently, these variables were excluded from the model.

Next, the climatological variables TEMP, T5, and SEAS were added to the model and tested for significance. These variables were significant at alpha levels of 1 percent and, therefore, were retained in the model. Interaction terms TEMP*T5 and T5*SEAS were also tested for significance. These interaction terms also improved the model, at 1 percent significance levels, and were also retained in the model.

The variables WET, DRY, and FROZ, which represent accumulated traffic by season, were then added to the model. The model improvements attributed to WET and DRY were significant at 1 percent; however, the improvement attributed to FROZ was not significant. WET and DRY were left in the model, although FROZ was deleted.

Other interaction terms between (a) base material and thickness, (b) surface material and thickness, (c) surface material and T5, (d) surface thickness and base thickness, and (e) base materials and T5 were also added to the model. None of the partial tests for these interaction terms was significant. These interactions did not significantly improve the model; consequently, they were deleted from the model.

The resulting model contained the following 15 independent terms: TEMP, T5, SEAS, SM, ST, BT, B1, B2, B7, B8, B9, WET, DRY, TEMP*T5, and SEAS*T5. The model, in matrix form, is represented by the following expression:

$$\underset{n\times5}{[W]} = \underset{n\times16}{(X)} \times \underset{16\times5}{[\Gamma]} + \underset{n\times5}{(\varepsilon)} \quad (2)$$

where

W = the matrix of sensor deflections,
Γ = the coefficient matrix,
X = the matrix of independent variables,
ε = the matrix of errors, and
n = the number of observations.

The errors of the ε matrix are assumed to be independent and normally distributed, with mean 0, and variance Σ. The matrix of independent variables contains 1's in the first column to represent the intercept. The matrix of regression coefficient estimates ($\hat{\Gamma}$) and the matrix of the estimated standard errors of the coefficient estimates ($\hat{\sigma}$) are given in Table 8.

Roy-Bose simultaneous confidence intervals are typically used to test the significance of each of the elements of the coefficient estimate matrix. Simultaneous intervals are used because they consider information contained in all of the dependent variables simultaneously. The equation for the Roy-Bose simultaneous confidence intervals was given earlier. For this model, with degrees of freedom for error equal to 3451 and theta equal to 0.02, the value of Co was 8.39. If 8.39 multiplied by the estimated

TABLE 8 Regression Coefficients and Standard Errors

$\hat{\Gamma}$	W1	W2	W3	W4	W5
INTERCEPT	0.10165	-0.07906	-0.11704	0.03805	0.11022
TEMP	0.02324[a]	0.01767[a]	0.01110[a]	0.00635[a]	0.00367[a]
T5	0.03329[a]	0.02652[a]	0.01576[a]	0.00837[a]	0.00460[a]
SEAS	-0.27352	-0.46012	-0.47327[a]	-0.38827[a]	-0.30897[a]
SM	-0.02511	-0.04965	-0.08908[a]	-0.06427[a]	-0.03768[a]
ST	-0.10038[a]	-0.03322	-0.00686	-0.00673	-0.00632
BT	-0.04136	0.01044	0.05094[a]	0.04189[a]	0.02954[a]
B1	0.40242[a]	-0.04755	-0.23621[a]	-0.19036[a]	-0.11557[a]
B2	0.31594[a]	0.07964	-0.05355	-0.05834	-0.04426
B7	0.03881	-0.07566	-0.13161[a]	-0.08833[a]	-0.04354[a]
B8	0.05188	-0.08071	-0.15520[a]	-0.11960[a]	-0.07634[a]
B9	0.30479[a]	-0.00881	-0.14729[a]	-0.12703[a]	-0.07732[a]
WET	3.29E-5[a]	1.88E-5[a]	1.29E-5[a]	1.40E-5[a]	9.95E-6[a]
DRY	-9.64E-6[a]	-4.99E-6	-3.18E-6	-3.91E-6[a]	-2.85E-6[a]
TEMP*T5	-0.00036[a]	-0.00030[a]	-0.00020[a]	-0.00012[a]	-7.14E-5[a]
T5*SEAS	0.00696	0.01038[a]	0.00965[a]	0.00761[a]	0.00562[a]
$\hat{\sigma}$					
INTERCEPT	0.12234	0.07334	0.04919	0.03612	0.02541
TEMP	0.00206	0.00123	0.00083	0.00061	0.00043
T5	0.00232	0.00139	0.00093	0.00068	0.00048
SEAS	0.09497	0.05693	0.03818	0.02804	0.01973
SM	0.01924	0.01153	0.00773	0.00568	0.00400
ST	0.00957	0.00574	0.00385	0.00283	0.00199
BT	0.00984	0.00590	0.00396	0.00290	0.00204
B1	0.04683	0.02807	0.01883	0.01387	0.00973
B2	0.03131	0.01877	0.01259	0.00924	0.00650
B7	0.03214	0.01927	0.01292	0.00949	0.00668
B8	0.03248	0.01944	0.01304	0.00958	0.00674
B9	0.03223	0.01932	0.01296	0.00952	0.00670
WET	3.11E-6	1.86E-6	1.25E-6	9.20E-7	6.50E-7
DRY	1.11E-6	6.70E-7	4.50E-7	3.30E-7	2.30E-7
TEMP*T5	3.49E-5	2.09E-5	1.40E-5	1.03E-5	7.25E-6
T5*SEAS	0.00174	0.00104	0.00070	0.00051	0.00036

[a]Coefficient estimates significant at one percent.

standard error of the coefficient estimate is greater than the absolute value of the hypothesized coefficients, then the coefficient estimate is not significantly different from zero. The elements that were significantly different from zero, at an alpha level of 1 percent, are indicated with an asterisk in Table 8.

The MANOVA table and the corresponding multivariate test statistics are given in Table 9. All four of the test statistics were significant. The MANOVA table supported the conclusion that the regression was significant, at an alpha level of 1 percent.

The univariate coefficient of determination (R-SQUARE) indicates what portion of the total variation is explained by a univariate model. However, the overall fit of a multivariate model is not as easily measured. The canonical correlation corresponding to the largest characteristic root is a relative measure of the fit of the model. Although the first canonical correlation does not directly measure the overall fit of the model, it is useful in measuring improvements made to the model. The corresponding univariate R-Square values for W1 through W5 are 0.3172, 0.3644, 0.4113, 0.3977, and 0.3713, respectively. Although these values are relatively low, they are for real data, which contain much variability.

TABLE 9 MANOVA Results

Source of Variation	Degrees of Freedom	SSCP Matrix
Regression	15	$H = \begin{bmatrix} 506.0 & 305.0 & 158.4 & 89.8 & 58.5 \\ 305.0 & 224.8 & 148.4 & 93.1 & 59.8 \\ 158.4 & 148.4 & 123.8 & 85.0 & 55.4 \\ 89.8 & 93.1 & 85.0 & 62.7 & 41.5 \\ 58.5 & 59.8 & 55.4 & 41.5 & 28.2 \end{bmatrix}$
Error	3451	$E = \begin{bmatrix} 1087.8 & 538.4 & 248.7 & 115.4 & 65.8 \\ 538.4 & 390.5 & 217.8 & 122.9 & 73.0 \\ 248.7 & 217.8 & 175.1 & 109.8 & 69.6 \\ 115.4 & 122.9 & 109.8 & 94.8 & 59.8 \\ 65.8 & 73.0 & 69.6 & 59.8 & 46.5 \end{bmatrix}$
Total	3466	$T = \begin{bmatrix} 1593.8 & 843.4 & 407.1 & 205.2 & 124.3 \\ 843.4 & 615.3 & 366.2 & 216.0 & 132.8 \\ 407.1 & 366.2 & 298.9 & 194.8 & 125.0 \\ 205.2 & 216.0 & 194.8 & 157.5 & 101.3 \\ 124.2 & 132.8 & 125.0 & 101.3 & 74.7 \end{bmatrix}$

Note: The tests of null hypothesis are expressed as Ho: $\Gamma = 0$, where Wilk's Lambda = 0.3108 < 0.9156 reject Ho, Lawley-Hotelling Trace = 1.4468 > 1.000 reject Ho, Pillai's Trace = 0.9658 > 0.2680 reject Ho, and Roy's GCR = 0.4240 > 0.0200 reject Ho.

MODEL VERIFICATION AND VALIDATION

To further check the aptness of the model, residual plots were made for each of the five sensor readings. These plots indicate that the model is adequate. None of the five residual (versus predicted) plots shows any systematic tendencies. The predicted versus actual plots are clustered around the 45-degree line. This indicates that the model predictions and the actual values tend to be equal (Figures 2 and 3).

To check the regression model, a second 10 percent random sample was generated from the data file. The coefficient estimate matrix ($\hat{\Gamma}$) from the first sample was applied to the second sample.

The residual versus predicted and the predicted versus actual plots were made for each of the five sensor readings. As with the plots for the first sample, these plots indicate that the model is adequate. The residual plots did not show any systematic trends. The prediction versus actual plots,

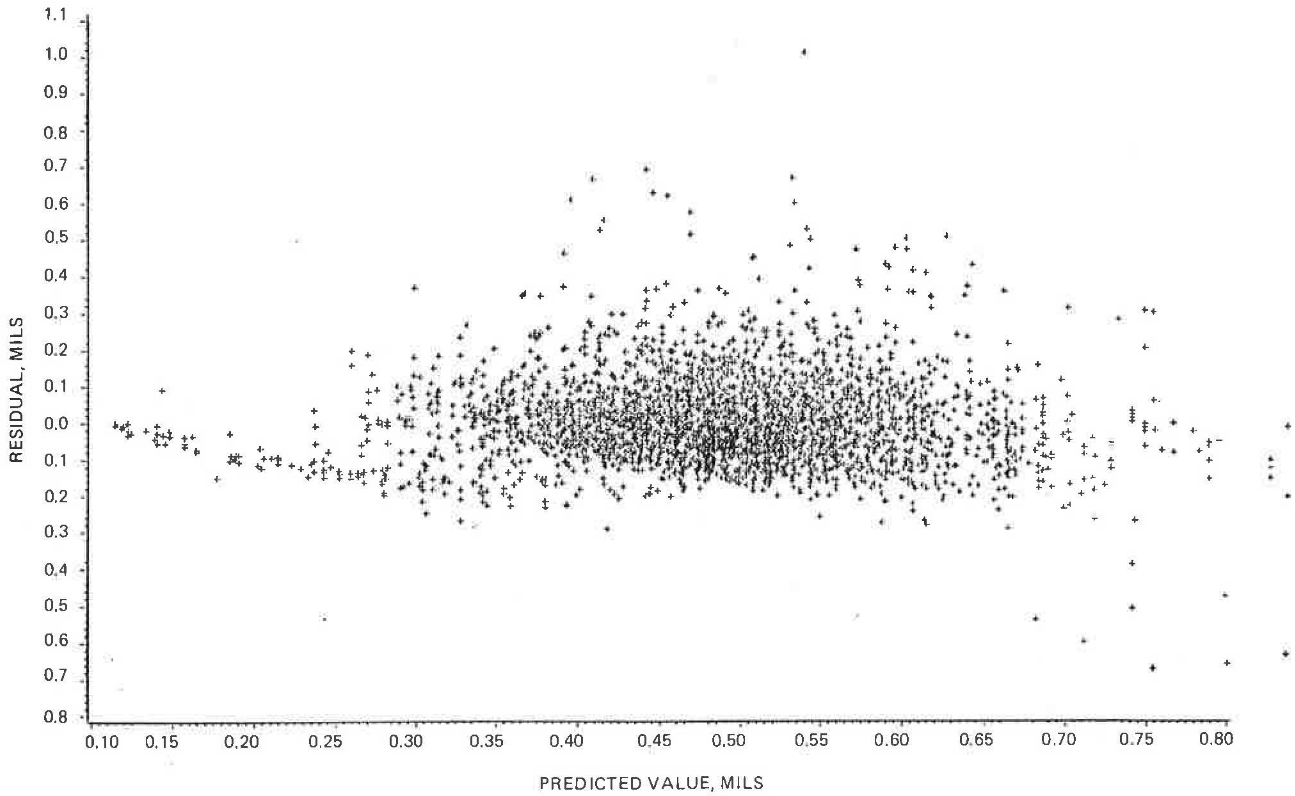

FIGURE 2 Residual versus predicted values—Sensor 5.

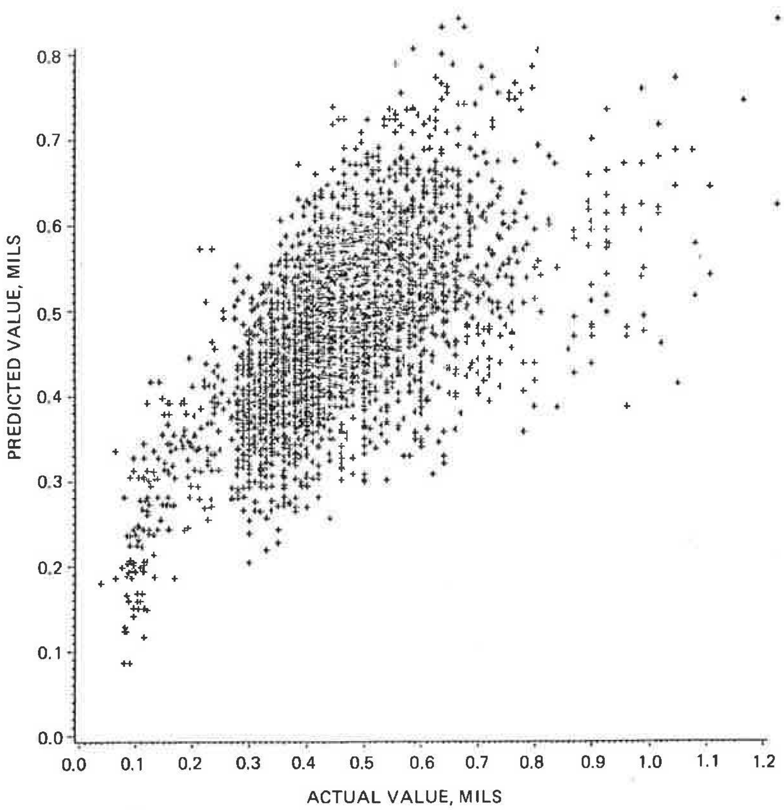

FIGURE 3 Predicted versus actual values—Sensor 5.

which are clustered around the 45-degree line, indicate that the predicted and actual values tend to be equal.

The results of mathematically based models often do not conform to real-life situations. To verify the model, the results were checked for areas that do not conform to the physical behavior of flexible pavements. This was done to ensure that the model developed was practical. As indicated, the predicted versus actual plots show that the predicted deflections are representative of the actual deflections. Also, the results of the model tend to agree with expected relationships.

MODEL INTERPRETATION

The interpretation of the model and the drawing of conclusions from the results is not a straightforward process. As often is the case with real data, the data set contains a large amount of unexplained variability.

The fact that data were collected over a 9-year period may have been a source of some of the variation. Over the collection period, the personnel collecting the data, the calibration of the Dynaflect, and the exact location of deflection readings may have varied. Other sources of variation may have also included inconsistencies in construction and maintenance.

Jorgenson (3) listed areas of the test road that had been patched or repaired. However, an adequate record was not kept as to whether or not deflection readings were taken on patched areas and included in the data file. Many of the test sections also experienced rutting. It is not known if the location of the deflection readings was moved from the outside wheel path in the areas where ruts had been filled.

It was also reported by Jorgenson (3) that most of the test sections constructed with the soil base required major repair. Three test sections 2, 13, and 70 (soil + lime base) failed within the first few years and were repaired, yet deflection readings were still taken on these sections.

BASE EFFECTS

In the following sections, the results of the model are discussed. All references to significance are based on multivariate tests at a 1 percent alpha level.

The thickness of the base did not significantly affect the deflections at sensors 1 and 2. This does not indicate that the thickness of the base in itself was nonsignificant, but rather that there was no significant difference between the 4- and 6-in. thicknesses.

The deflections at sensors 3 through 5 were directly related to the base thickness. This indicates that as the base thickness increases, the spreadability of the pavement also increases. Increases in both base thickness and spreadability are associated with a stronger pavement structure.

The variables B3, B4, B5, and B6 did not significantly affect the regression model. Therefore, the five sensor deflections for the following base materials were not significantly different than those for Base 5B (aggregate + 6.0 bag cement) as shown in the following table:

Base	Description
2A,2B	soil + lime + cement
3A	aggregate + cement
3B	aggregate + lime + flyash
5A	aggregate + 4.5 bag cement

The weaker soil base materials were probably included in this group as a result of the extreme amount of repair and maintenance they received throughout the study period. The repair and maintenance received by the soil-based sections improved their structural characteristics to a level similar to that of the stronger bases.

The deflections for Base 1 (gravel); Base 2A (soil + cement); Bases 4A and 4B (aggregate + asphaltic cement); and Base 4C (aggregate + emulsified asphalt) were significantly different than those for Base 5B (aggregate + 6.0 bag cement). However, not all of the five sensor deflections for these bases were significantly different.

The first sensor deflections for Bases 1, 2A, and 4C were significantly larger than those for Base 5B. A larger deflection for sensor 1 (DMD) was expected for these weaker bases. Bases 4A and 4B had first sensor deflections that were not significant; thus, indicating that there was no significant difference in overall strength between the asphaltic cement and 6.0 bag cement-aggregate treatments.

The deflections for the second sensor were not significant for these five bases. It should be noted, however, that the second sensor deflection was not significant for any of the bases. The third, fourth, and fifth sensor deflections were significantly lower for Bases 1, 4A, 4B, and 4C than those for Base 5B. This resulted in a lower spreadability for these bases, which indicates a lower base strength. The deflections at sensors 3 through 5 were not significant for Base 2A. However, primarily because of its larger deflection at sensor 1, Base 2A also had a lower spreadability than Base 5B.

SURFACE EFFECTS

The surface thickness was only significant for the first sensor deflections. The deflections at sensor 1 (DMD) were inversely related to the surface thickness. This indicates that the overall strength of the pavement structure increases as the surface thickness increases. As with the base thickness, the surface thickness only indicates whether or not the difference between the two surface thicknesses was significant.

The surface material did not significantly affect the deflection at sensors 1 and 2. However, the deflections at sensors 3 through 5 were significantly lower for the SC 3000 bituminous than for the AC 120-150 bituminous pavement. This resulted in the SC 3000 pavement having a lower spreadability and less ability to carry a load, which is expected.

CLIMATOLOGICAL EFFECTS

The pavement surface temperature (TEMP), the 5-day mean air temperature (T5), and their interaction term (TEMP*T5) were significant for all five sensor readings. The sensor deflections were directly affected by both the surface temperature and the mean air temperature. As expected, because of the dependency of the stiffness of asphaltic material on temperature, an increase in the temperature resulted in an increase in pavement deflection.

The sensor deflections were inversely related to the TEMP*T5 interaction. This indicates that as one of the temperatures increases, the effect of the other temperature decreases. It should be noted that the pavement surface temperature and the 5-day mean air temperature were related. At lower mean air temperatures, the surface temperature had a lower value, and at higher mean air temperatures, the surface temperature had a higher value.

The T5*SEAS interaction was significant for sensors 2 through 5. The effect of the 5-day mean air temperature was significantly higher for sensors 2 through 5 during the wet season. At 5-day mean air temperatures below approximately 50°F, the deflections at sensors 3 through 5 were lower during the wet season. This resulted in a lower spreadability during the wet season, which indicated weaker support conditions. At mean air temperatures above approximately 50°F, the effects of the mean air temperature were significantly higher during the wet season.

TRAFFIC EFFECTS

The effects of traffic varied with the season during which the loads were applied. Traffic loads applied during the frozen season (FROZ) did not significantly affect the deflections. The traffic loads applied during the wet season (WET) had the greatest effect on the sensor deflections. The sensor deflections were directly related to the accumulated traffic loads applied during the wet season.

The model indicates that the deflections were inversely related to the traffic applied during the dry season (DRY); however, this indication is misleading. If the variable WET is removed from the model, the deflections were directly related to DRY. Under the traffic loading combinations applied to the test road, the net result is a direct relationship between deflection and accumulated traffic.

CONCLUSIONS

The following are major conclusions that can be drawn from the analysis of the Dynaflect data and the interpretation of the regression model.

1. Dynaflect deflections for the five sensors were highly correlated; therefore, multivariate analysis techniques should be used to analyze Dynaflect data.
2. The base thicknesses and materials used for the various test sections were similar in structural strength. The resulting model did not show a significant difference between the routinely maintained soil, the aggregate, and the portland cement base treatments.
3. The surface thicknesses and surface material had significant effects on the sensor deflections. The first sensor deflection was directly related to the surface thickness. The AC 120-150 bituminous pavement was significantly stronger than the SC 3000 bituminous pavement.
4. Both surface temperature and mean air temperature significantly affected the pavement deflections.
5. The season of the year had a significant effect on pavement deflection as the effects of temperature on deflection were significantly different for wet and dry seasons.
6. Pavement deflections were significantly affected by the amount of traffic that had passed over the pavement. The effect of traffic varied with the season in which it was applied. Traffic applied during the wet season had the greatest effect on deflection. Traffic applied during the frozen season did not significantly affect deflection.
7. The regression model developed between Dynaflect deflections and pavement materials properties, temperature, moisture season, and traffic can be used to explain some of the variability in deflection data. As a result, data collected over various conditions can be compared on a more equivalent basis.

RECOMMENDATIONS

The following recommendations are made on how future test road studies could be improved.

1. The number of different pavement compositions studied should be reduced.
2. Base thicknesses and materials used should cover a wider range and the strength of the pavements studied should be more dispersed. Pavement structures with insufficient strength, however, should be avoided.
3. More precise records should be kept on pavement maintenance and repair. Deflection readings should not be included for areas that have received sufficient repair to significantly alter their strength.
4. Deflection readings should be taken at uniform time intervals throughout the study period. However, the total number of readings taken for the study could be reduced.
5. Alternate methods of collecting moisture data should be investigated.

If the study is to be performed as a part of a statewide pavement management program, these additional recommendations are made.

1. The test road should be constructed on a roadway that has typical traffic volumes for the state. U.S. 2 has considerably higher traffic volumes than a majority of North Dakota's roadways.
2. North Dakota falls into two climate zones. Similar test roads should be constructed in each climate zone.

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