NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **76**

DETECTING SEASONAL CHANGES IN LOAD-CARRYING CAPABILITIES OF FLEXIBLE PAVEMENTS

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NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

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DETECTING SEASONAL CHANGES IN LOAD-CARRYING CAPABILITIES OF FLEXIBLE PAVEMENTS

FRANK H. SCRIVNER, RUDELL PEOHL,
W. M. MOORE, AND M. B. PHILLIPS
TEXAS A&M UNIVERSITY
COLLEGE STATION, TEXAS

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION
OF STATE HIGHWAY OFFICIALS IN COOPERATION
WITH THE BUREAU OF PUBLIC ROADS

SUBJECT CLASSIFICATION:

- PAVEMENT DESIGN
- PAVEMENT PERFORMANCE
- MAINTENANCE, GENERAL
- FOUNDATIONS (SOILS)
- MECHANICS (EARTH MASS)

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway Officials.

This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

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FOREWORD

By Staff

Highway Research Board

This report describes procedures for determining the load-carrying capabilities of existing flexible pavements in areas subjected to frost action. The findings are based on field studies conducted primarily with Dynaflect equipment that measures responses to impulse or dynamic loading. Some correlations have also been made with curvature meter, Benkelman Beam deflection, and plate bearing test data. The warrants for an axle-load restriction policy will be particularly useful to maintenance and other highway engineers who must impose load restrictions during the spring thaw to minimize the detrimental effect of overloading during this critical period. The information collected during the field studies adds to existing knowledge in the field of pavement design and performance and should be of value to engineers with this area of interest.

Seasonal load restrictions must be placed on thousands of miles of secondary roads to prevent serious damage during spring thaws when bearing capacity of subgrade soils is reduced. The time for application of these restrictions, extent of axle-load reductions and duration of the imposed restrictions are usually based on engineering judgment. A need exists for a rapid, simple, nondestructive, and accurate method that will indicate the relative load-carrying capacity of pavements during this period of weakness. The results of previous research, published as *NCHRP Report 21,* "Detecting Variations in Load-Carrying Capacity of Flexible Pavements," indicated the feasibility of the application of impulse testing techniques to the solution of this problem.

The objectives of the phase of the study reported herein were (1) to evaluate existing procedures, including those utilizing impulse techniques; (2) to select the most promising method for determining the load-carrying capabilities of flexible pavements during the spring thaw period; and (3) to develop guidelines for field use of the selected method. The Texas Transportation Institute's initial evaluation of existing methods resulted in selection of the Dynaflect instrument for further field study and the ultimate development of warrants for imposing load restrictions. The field study involved collection and interpretation of deflection, temperature and other data at 24 test sections of existing road in Illinois and Minnesota. Coverage was given to a wide range of soil, climate, and pavement design conditions, and data were collected over almost a full year to include all seasonal variations.

The over-all efficiency of the Dynaflect, and other procedures included in the investigation, was judged primarily on the basis of accuracy, economy, and nondestructive nature of the testing. In this regard, it should be recognized that the relative economy of any procedures will need to be determined by each highway agency for any given situation, as influenced by such factors as availability of instrumentation and cost of labor.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was conducted under NCHRP Project 1-5(2) by the Texas Transportation Institute, Texas A&M University, with F. H. Scrivner and W. M. Moore as co-principal investigators.

Sincere gratitude is expressed to all personnel of the Illinois Division of Highways and the Minnesota Department of Highways who participated in this research. These men helped in the selection of test sections, supplied section design information from the construction records, provided personnel and equipment for the installation of the thermocouples and for the static load tests discussed in Chapter Two, and provided flagmen when necessary for the protection of the Texas crew. Special thanks are due the following and the numerous other state personnel who assisted in the research:

Illinois Division of Highways

Virden E. Staff, Chief Highway Engineer
John E. Burke, Engineer of Research and Development
Donald R. Schwartz, Assistant Engineer of Research and Development
Philip G. Dierstein, Engineer of Pavement Research

Minnesota Department of Highways

John R. Jamieson, formerly Commissioner of Highways (presently Deputy Federal Highway Administrator, Federal Highway Administration)
C. K. Preus, Research Coordination Engineer
F. C. Fredrickson, Materials Engineer
Paul A. Jenson, Research Engineer
Paul Diethelm, Materials Engineer, District 6
John Allen, Materials Engineer, District 1

Appreciation is also expressed to Eugene E. Skok, Instructor, Department of Civil Engineering, University of Minnesota, for his advice and assistance.

The following Texas A&M University personnel are due special thanks: Mrs. Judy Davis, who handled the fiscal affairs of the project; Neil K. Holley and Charles E. Schlieker, who participated in the field work; and M. B. Phillips, who assisted in the preparation of the report.

DETECTING SEASONAL CHANGES IN LOAD-CARRYING CAPABILITIES OF FLEXIBLE PAVEMENTS

SUMMARY

The main effort of this research was directed toward (1) finding an instrument capable of measuring—with speed, accuracy, and economy—seasonal changes in the strength of flexible pavements, and (2) showing how it could be used in a program to protect pavements from overloading during critical periods.

The instrument selected was the Dynaflect, a trailer-mounted device that loads the pavement dynamically and indicates the corresponding deflection at several points on the surface. One-man operated and towed by a passenger car, the Dynaflect appears to meet the requirements for the job.

Tests were made with the Dynaflect on pavements at locations ranging from Springfield, Illinois, northward to Duluth, Minnesota. The tests revealed that the annual strength history of pavements in northern climates is divisible into four distinct periods—(1) a period of deep frost and high strength, (2) a period of rapid strength loss, (3) a period of rapid strength recovery, and (4) a period of slow strength recovery. The second and third periods together constitute the critical period for flexible pavements.

A series of correlation studies indicated that Dynaflect measurements could be used with reasonable accuracy to predict the results of plate bearing tests and Benkelman Beam deflection tests, as well as the curvature of the pavement in the vicinity of a heavy wheel load. Thus, the Dynaflect apparently could be substituted for other instruments being used to detect seasonal changes in strength. In addition, the Dynaflect—though not the most economical to operate—proved to be more sensitive than the other instruments to changes in strength.

The research resulted in suggested warrants, based on the use of the Dynaflect, for deciding when, where, and how long to impose reduced load limits. It appears that if these warrants were used to control the placement and removal of load restrictions, some reduction in the duration of the restricted period might result.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

The problem attacked in this report was phrased as follows in the project statement prepared by the Highway Research Board:

> Load-carrying capabilities of flexible pavements vary throughout the year due to such effects as frost, temperature, moisture, and other environmental factors. In recognition of these factors, some authorities have invoked load restrictions on pavements during spring thaw periods. Thus, on a local level at least, methods exist which permit an assessment of relative load-carrying capability of pavements under the influence of seasonal variations. Existing procedures, as presently used, appear to be limited in applicability, criteria for general use, and convenience. A need exists for an evaluation of existing, or new, methods and the development of a method which will indicate the load-carrying capabilities of flexible pavements as affected by these environmental factors. From a practical standpoint, the procedure should be nondestructive and be both simple and rapid in operation.

An obviously necessary step in the search for a solution of the problem was the selection of areas of the country where significant seasonal changes in load-carrying capability could be observed and the ability of instruments to detect these changes could be tested. Another necessary step was the selection of the most promising instrument or instruments to be field tested. The final necessary step was the testing of one or more of these instruments over a full weather cycle, the selection of the best of the instruments tested, and the development of a recommended procedure for its use. It was assumed from the beginning that the ultimate use of the instrument and associated procedure would be in assisting highway administrators to decide when and where to impose or remove axle load restrictions during critical seasons of the year, and what the reduced load limits should be.

TECHNIQUES CONSIDERED—INSTRUMENTS SELECTED FOR FIELD TESTING

The use of non-destructive techniques stemming mainly from seismology for detecting changes in the strength or condition of highway pavements has been reported by Jones (*3*), Nijboer and Metcalf (*4*), Phelps and Cantor (*5*), Isada (*6*), Scrivner and Moore (*7*), Atwell (*8*), and others.

The work of Atwell at Texas Transportation Institute (Fig. 1) and Isada at Cornell Aeronautical Laboratory (Fig. 2) indicated that techniques dependent upon the measurement of a time lapse between the application of an impulse load and the arrival of the wave front at a distant point showed little promise of meeting the criteria specified for this project. On the other hand, Isada's alternate method, based on measuring the deflection at a nearby point resulting from an impulse load, was successful, but further development of the instrumentation would have been required before this technique could have been field tested. The methods based on inducing steady-state vibration and measuring the resulting wavelength (Figs. 3 and 4) as described by Jones, Nijboer and Metcalf, Scrivner and Moore, and others have proved to be slow, cumbersome, and difficult of interpretation. However, this technique is still under investigation at the Texas Transportation Institute.

None of the foregoing instrumentation or techniques was field tested in this project for the reasons stated. However, three others were tested, but on a limited scale. These were the plate bearing test, as performed by the Minnesota Department of Highways (Fig. 5); a test involving use of an instrument designed to measure the curvature of the pavement surface in the vicinity of a 9,000-lb wheel load (Fig. 6); and the well-known Benkelman Beam deflection test, performed by both the Minnesota Department of Highways and the Illinois Division of Highways (Fig. 7). The detailed procedures used in these tests are given in Appendix A.

Figure 1. Standard seismic techniques were employed by Atwell of Texas Transportation Institute, who measured velocity of shock wave caused by hammer blow.

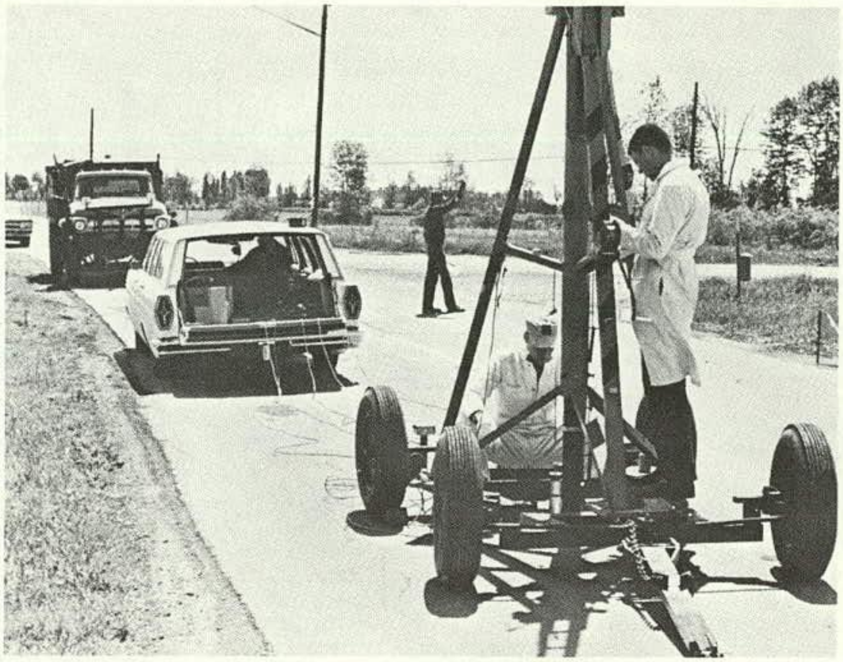

Figure 2. Device developed by Isada of Cornell Aeronautical Laboratory dropped 500-lb weight on a 15-in. diameter plate, measured resulting deflection of pavement 9 in. from center of impact.

None of the three methods described was considered to meet all of the specifications mentioned in the problem statement. All require a heavy truck for loading (a disadvantage when testing lightly designed pavements weakened by the spring thaw), and none was believed to be as sensitive as the Dynaflect to changes in strength. Nevertheless, all have a background of use in highway research, and a series of correlation studies was conducted in this project for the purpose of showing that all, including the Dynaflect, apparently respond to much the same properties of the pavement structure, and that the Dynaflect—although apparently not the most economical—is the most sensitive of the instruments tested.

THE DYNAFLECT

Although a number of instruments were investigated in the first stages of the research, and four were selected for field testing, the instrument that appeared from the start to have

Figure 3. The Shell Vibrator System, developed by Shell Oil Co., forces road structure to vibrate at selected frequencies, measures length of resulting waves in surface of pavement.

Figure 4. Shell Vibrator System in use on highway. Phone connects motion sensor operator in background with oscilloscope operator in van.

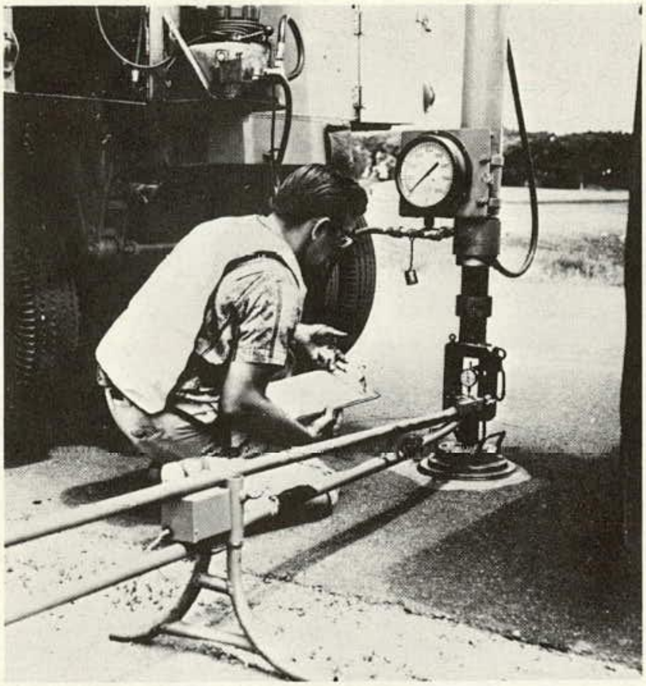

Figure 5. Plate bearing test equipment used by Minnesota Department of Highways. Truck and trailer supply load on 12-in. diameter plate.

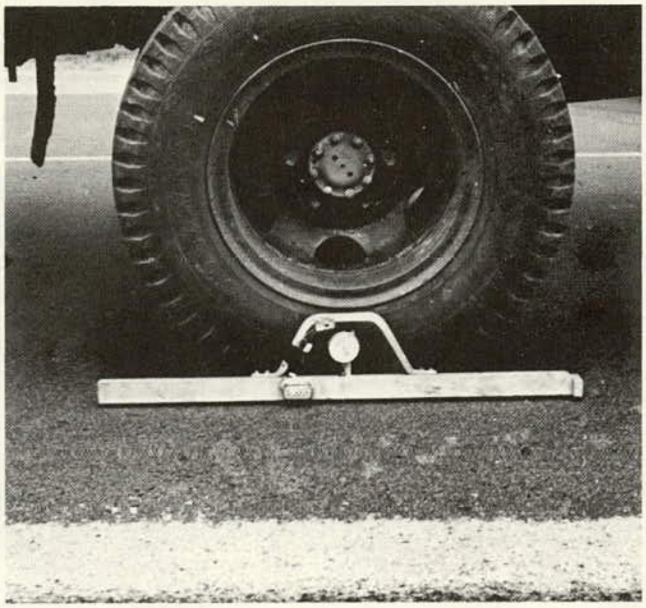

Figure 6. Curvature meter, designed by McCullough of the Texas Highway Department, was patterned after original device developed by Dehlen of South Africa.

Figure 7. The Benkelman Beam, developed by A. C. Benkelman at the WASHO Road Test, is here used by the Minnesota Department of Highways.

the greatest potential was the Dynaflect (*8*), a device available commercially on a rental basis, and thoroughly field tested by the Texas Transportation Institute prior to the beginning of this project for reliability, reproducibility, and correlation with Benkelman Beam measurements.

The Dynaflect is mounted on a small two-wheel trailer (Fig. 8) usually towed behind a passenger car. Between test sections it travels on pneumatic tires at normal highway speeds. On arrival at a test section (Fig. 9), a pair of steel load wheels are lowered to the pavement, lifting the travel wheels and transmitting to the pavement an oscillating load generated by eccentric weights rotating eight revolutions per sec (Fig. 10). When a testing point is reached, the Dynaflect is stopped over the point (Fig. 11), five motion sensors are lowered to the pavement surface, and the voltage output of the sensors is read on a meter directly in milli-in. of vertical deflection of the pavement surface (Fig. 12).

The detailed procedure for calibrating and operating the Dynaflect is given in Appendix A. Experience indicates that this instrument has the degree of reliability and ruggedness, as well as of simplicity and economy of operation, sought in this research.

The relative positions on the pavement of the Dynaflect load wheels and five sensors are shown in Figure 13. A typical deflection basin reconstructed from Dynaflect readings is shown in Figure 14 by the smooth curve drawn through the plotted points representing the sensor readings. The line AB in Figure 14 is the same as the line AB in Figure 13.

Figure 8. Key instrument in the research was the Dynaflect, here shown ready for travel between sections.

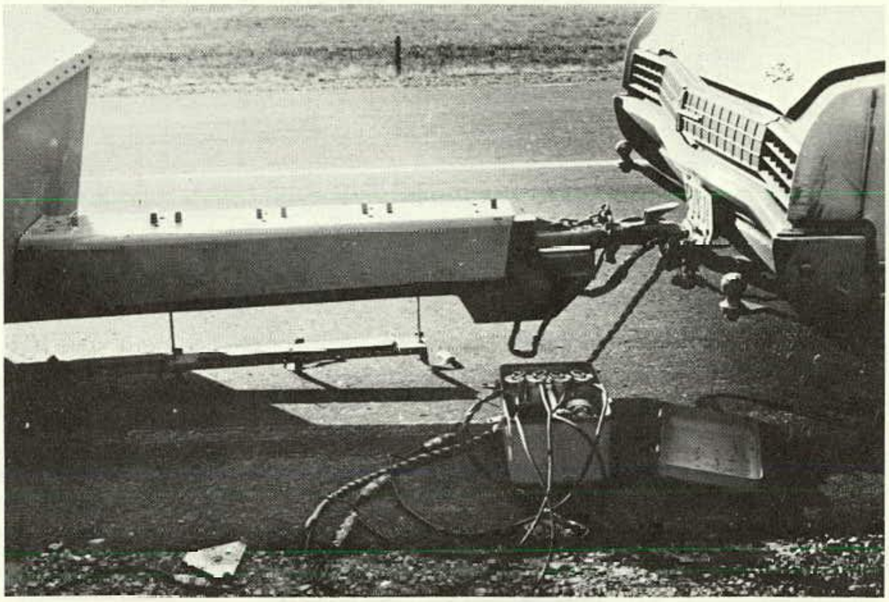

Figure 9. Upon arrival at section to be tested, deflection sensors of the Dynaflect are checked for proper calibration.

Figure 10. Between test points within a test section Dynaflect travels on its load wheels, with sensors lifted.

Figure 11. The towing vehicle has been stopped with Dynaflect over test point, and the five sensors lowered to the pavement. Cyclic load is applied and removed eight times per second.

Conventionally hereafter the reading of sensor No. 1 is represented by the symbol w_1, the reading of sensor No. 2 by w_2, etc. The term "deflection basin depth" (or simply "deflection") means the reading of sensor No. 1, whereas the term "surface curvature index" (or simply "surface curvature") means the difference between w_1 and w_2 (that is, $w_1 - w_2$).

The term "surface curvature index" (SCI) deserves some further explanation, because it is used later in this report in an analysis of the results. It can be shown that the curvature (used now in the mathematical sense) at the point C in Figure 14 can be approximated by the derivative d^2w/dx^2, where x is measured parallel to the line AB and w is measured parallel to the line AC. Assuming symmetry of the basin, the derivative, d^2w/dx^2, can in turn be approximated by the difference equation

$$\frac{d^2w}{dx^2} \approx \frac{2(w_1 - w_2)}{1{,}000\,a^2} \qquad (1)$$

or

$$\frac{d^2w}{dx^2} \approx \frac{\text{SCI}}{500a^2} \qquad (2)$$

where a is the distance between sensor No. 1 and sensor No. 2 in inches, and the number 1,000 in Eq. 1 converts the unit of measurement from milli-in. to in. The physical significance of the derivative, d^2w/dx^2, is attributed to the fact that its reciprocal is approximately equal to the radius of curvature (in in.) of the surface at the point C. The significance of this fact, in turn, will be appreciated by engineers accustomed to dealing with stresses and strains.

Figure 12. Operation of Dynaflect is controlled from driver's seat in towing vehicle.

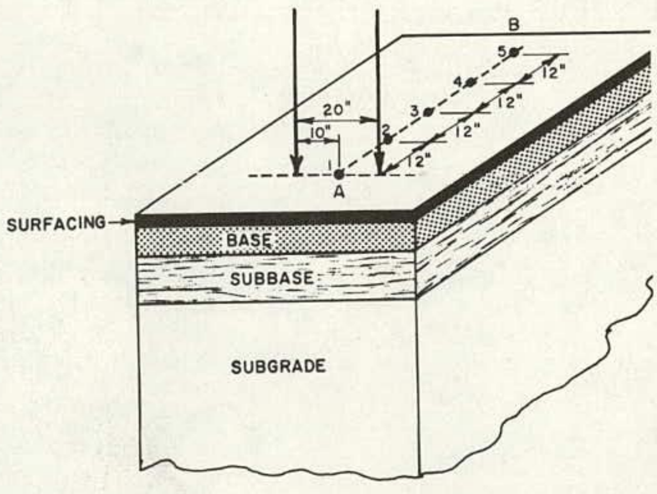

Figure 13. Position of Dynaflect sensors and load wheels during test. Vertical arrows represent load wheels. Points 1 through 5 indicate location of sensors.

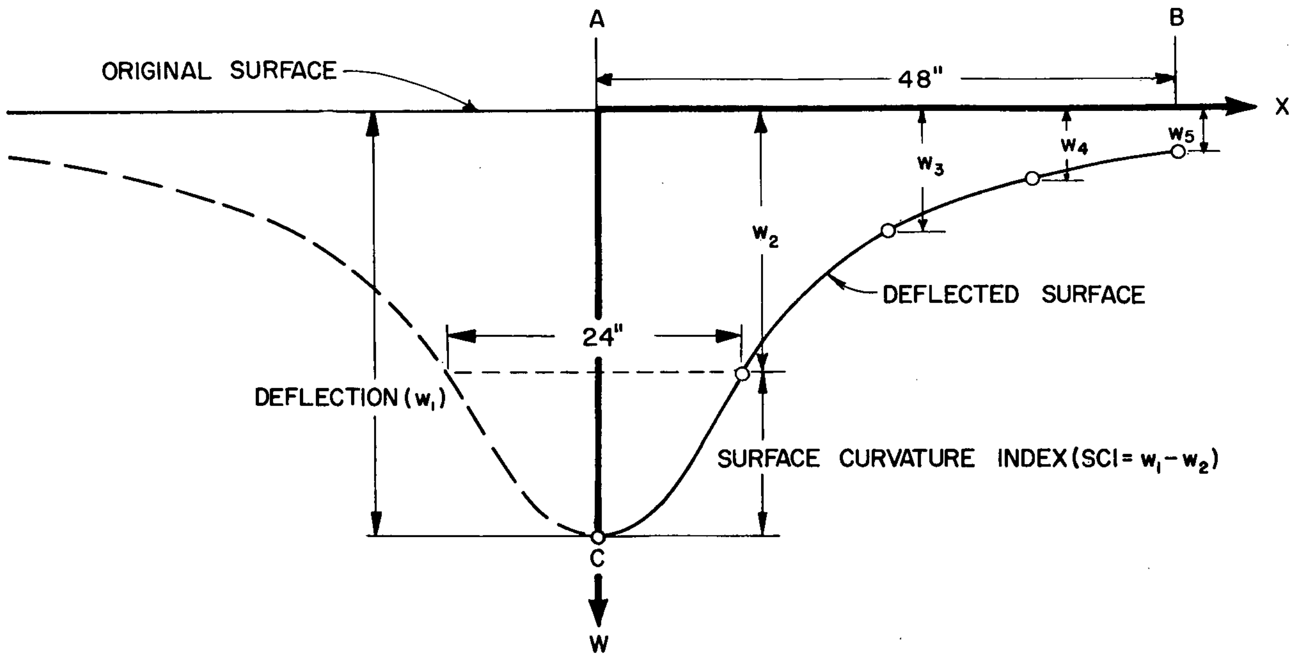

Figure 14. Typical deflection basin reconstructed from Dynaflect readings. Only one-half of basin is measured.

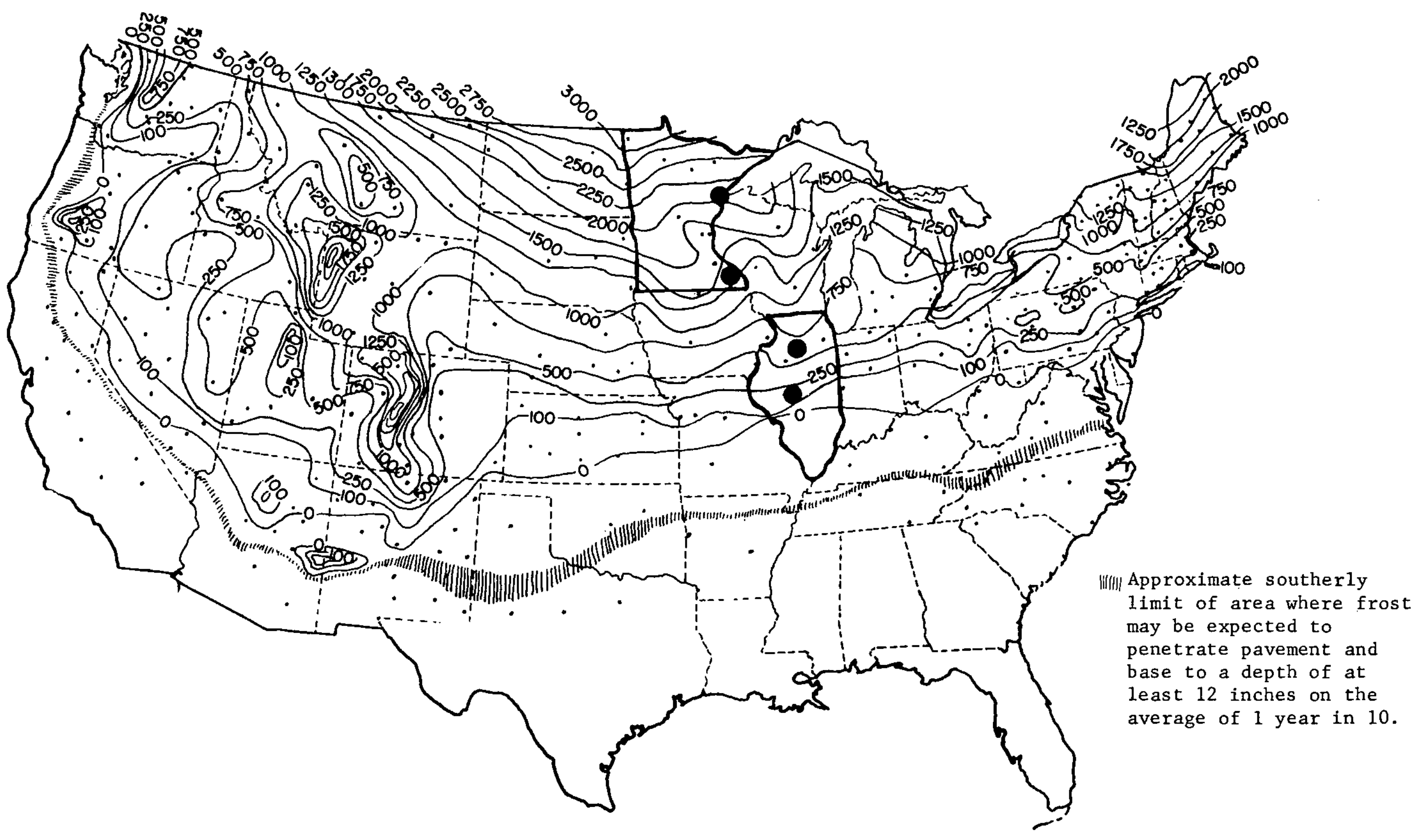

Figure 15. Distribution of mean freezing index values in continental U. S. Large dots show location of areas chosen for study.

It is recognized that the SCI does not represent the greatest surface curvature imposed by the Dynaflect; the true maximum probably occurs beneath the load wheels. However, the SCI is probably proportional to the maximum curvature and is therefore a meaningful quantity. Of greater significance is the probable similarity of the Dynaflect basin to that produced by the dual wheels of a truck.

SELECTION OF AREAS AND TEST SECTIONS

The most commonly observed change in the load-carrying capacity of flexible pavements is the well-known "spring breakup" that occurs annually as winter frost leaves the ground in the northern U.S. Although severe damage is usually confined to secondary highways and county roads, even pavements composed of frost-resistant materials and designed to carry heavy traffic suffer a loss in strength during this period. With these facts in mind, it was decided to select study sections located within the very large region of the United States where highways are known to be vulnerable to freeze damage.

It was believed desirable, however, to locate the study areas so that a wide range in frost penetration could be observed. The areas selected, therefore, ranged in location from as far south as Springfield, Illinois, to as far north as Duluth, Minnesota. Four areas were selected as shown in Figure 15 on a map with contours of the "mean freezing index" taken from the U.S. Corps of Engineers' *Airfield Pavement Design Manual* (*9*). The freezing index, a cumulative temperature-time statistic, has been correlated with observed depths of frost penetration by the Corps of Engineers. Large values of the index are associated with large depths of frost penetration. Thus, shallow frost penetration would be expected in the Springfield area, where the mean freezing index is about 100, and deep frost in the Duluth area where the index is near 2,100.

The study areas selected are also shown on a map of somewhat larger scale (Fig. 16). With the cooperation and assistance of the state engineers concerned, six test sections were selected in each of the four areas, as indicated on the map. In each area two of the six sections were located on highways presumably designed to carry relatively heavy traffic, whereas four were on state highways or county roads designed for light traffic. Table 1 gives the location of the 24 test sections; Table 2 gives their nominal design.

It can be seen from Table 3, which gives the frost penetration predicted from the mean freezing index, as well as the average penetration actually observed, that frost penetration during the field research activity ranged from 14 in. at Springfield to 67 in. at Duluth. Thus, the desired range in frost penetration was achieved.

The test sections were 1,000 ft in length, with thermocouples installed at two locations within each section (Figs. 17 and 18). Ten test points were permanently marked in the outer wheel path, as shown in Figure 19, so that the deflection and other tests (described later in detail) could be made at the same points on successive visits of the testing crew.

Observations of frost penetration were made by means of the thermocouple installations shown in Figure 20. Thermocouples were installed at depths ranging up to 6.5 ft; the spacing of individual thermocouples is shown on the sketch. A junction box was placed in the shoulder opposite each installation, as shown in Figure 21. The measuring system was calibrated and the thermocouples were read inside a passenger car (Fig. 22). The measurement procedure is described in Appendix A.

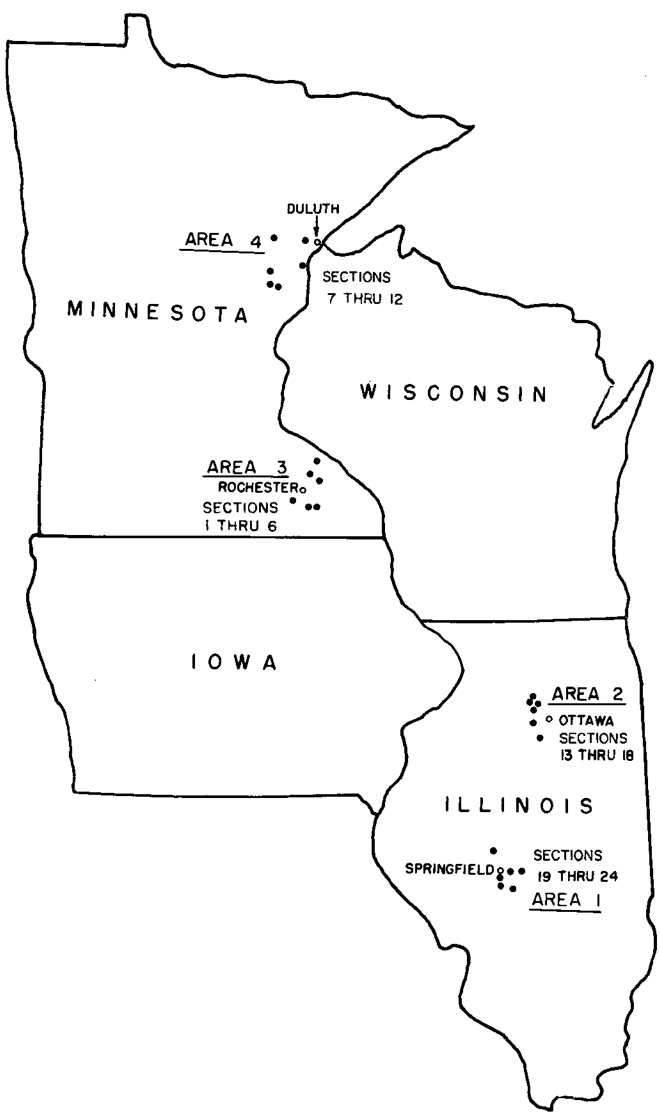

Figure 16. Four areas selected for investigation; solid circles indicate approximate location of six sections chosen in each area.

TABLE 1

LOCATION AND NOMINAL DESIGN CLASSIFICATION OF TEST SECTIONS

AREA NO.	SEC. NO.	DESIGN CLASS.[a]	HWY.	LOCATION	TRAFFIC DIR.
1	19	1	US 66 W Frontage Rd.	0.5 mi N IH 55	North
1	20	2	IH 55 W Frontage Rd.	1.0 mi S Bus. 66	North
1	21	1	Lake Dr.	2.1 mi E of US 66	East
1	22	1	Co. 630	0.5 mi E of US 36	East
1	23	1	Co. 563	0.5 mi S of US 36	North
1	24	2	SH 29	0.2 mi S of SH 124	South
2	13	1	Co. 1365	150 ft W of Co. 174	West
2	14	1	Co. 260	1.6 mi N of Troy Grove	North
2	15	1	Co. 270	150 ft E of Co. 260	East
2	16	1	Co. 254	2.0 mi E of US 51	West
2	17	2	US 351	0.4 mi N of Illinois R.	South
2	18	1[b]	Co. 260	0.2 mi N of IH 80	North
3	1	1	SH 30	6.7 mi W of US 52	West
3	2	1	SH 30	9.0 mi W of US 52	East
3	3	1	SH 30	2.5 mi W of US 63	East
3	4	1	SH 247	3.6 mi E of US 63	West
3	5	2	US 63	6.6 mi N of SH 247	North
3	6	2	US 63	9.0 mi N of SH 60	North
4	7	1	SH 23	2.5 mi S of Nemadji R.	South
4	8	2	US 2	3.1 mi SE of SH 194	SE
4	9	1	SH 73	8.0 mi S of US 2	South
4	10	1	SH 73	9.0 mi N of SH 27	South
4	11	1	SH 27	2.1 mi W of SH 73	West
4	12	2	IH 35	4.0 mi S of Moose Lake	North

[a] 1—Design for light traffic. 2—Design to carry relatively heavy traffic.
[b] Originally given a Design 2 classification. This section was later changed after pavement was drilled. See Table 2.

TABLE 2

NOMINAL DESIGN OF TEST SECTIONS

AREA	SEC. NO.	DESIGN CLASS.[a]	THICKNESS (INCHES)			MATERIAL TYPE			
			SURFACE	BASE	SUBBASE	SURFACE	BASE	SUBBASE	SUBGRADE
1	19	1	1[b]	7	—	S.T.	Gran. matl.	—	Silty clay
1	20	2	4.5	8	6	A.C.	Cr. stone	Cr. stone	Silty clay
1	21	1	2.5[b]	6.5	—	S.T.	Cr. stone	—	Silty clay
1	22	1	4.3[b]	6	—	S.T.	Gravel	—	Silty clay
1	23	1	2[b]	7	—	S.T.	Cr. stone	—	Silty clay
1	24	2	4.5	9	6	A.C.	Cr. stone	Gravel	Silty clay
2	13	1	0.5[b]	8	—	S.T.	Gravel	—	Silty clay
2	14	1	0.5[b]	4	4	S.T.	NaCl stab. gr.	Gravel	Silty clay
2	15	1	2	8	—	A.C.	Gravel	—	Clay till (some gravel)
2	16	1	0.5[b]	4	4	S.T.	Gravel	Gravel	Silty clay
2	17	2	3	10	—	A.C.	Cr. stone	—	Sand fill
2	18	1	2[b]	7[b]	—	A.C.	Gravel	—	Silty clay
3	1	1	3	3	9	A.C.	Cr. rock	Sand-gravel	Silty clay loam
3	2	1	4	16.5	—	A.C.	Gravel	—	Silty clay loam
3	3	1	2	3	9	A.C.	Cr. rock	Sand-gravel	Organic loam
3	4	1	1.5	9	—	A.C.	Gravel	—	Organic loam
3	5	2	3	6	12	A.C.	Cr. rock	Sand-gravel	Silty loam
3	6	2	6	4.5	12	A.C.	Gravel	Sand-gravel	Clay till (some gravel)
4	7	1	6	13	—	A.C.	Gravel	—	A-7-5 clay
4	8	2	6	16.5	—	A.C.	Gravel	—	Gravel fill on sandy loam
4	9	1	4	3	9	A.C.	Gravel	Gravel	Gray and red clay
4	10	1	4	9	—	A.C.	Sand-gravel	—	Clay loam
4	11	1	3	3	9	A.C.	Gravel	Sand-gravel	A-6 clay to A-4 sandy loam
4	12	2	8	4	12	A.C.	Bit. treat. gr.	Gravel	Sand fill

[a] 1—Design for light traffic. 2—Design to carry relatively heavy traffic.
[b] Thickness determined by drilling.

TABLE 3

PREDICTED AND MEASURED FROST PENETRATION IN THE FOUR STUDY AREAS

AREA NO.	AREA	MEAN FREEZING INDEX	FROST PENETRATION (IN.) ESTIMATED FROM M.F.I.	AVG. OF MEASUREMENTS MADE IN 1967
1	Springfield, Ill.	100	18	14
2	Ottawa, Ill.	600	35	33
3	Rochester, Minn.	1300	49	52
4	Duluth, Minn.	2100	64	67

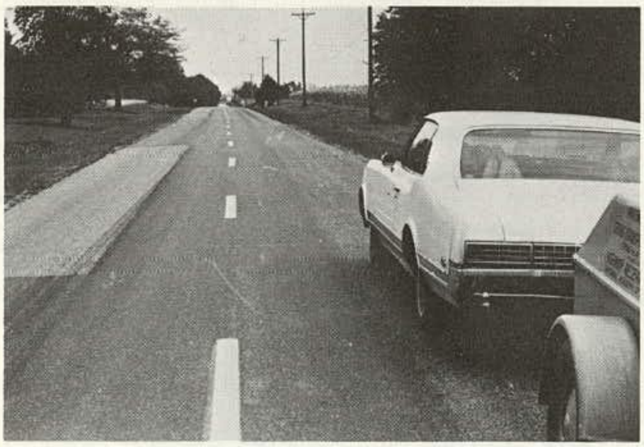

Figure 17. Typical of the four sections of relatively light design selected in each area is this one on Lake Drive in suburban Springfield, Ill.

Figure 18. A study section of relatively heavy design is this one on Interstate Highway 35, 50 miles south of Duluth, Minn. Two sections of heavy design were selected in each area.

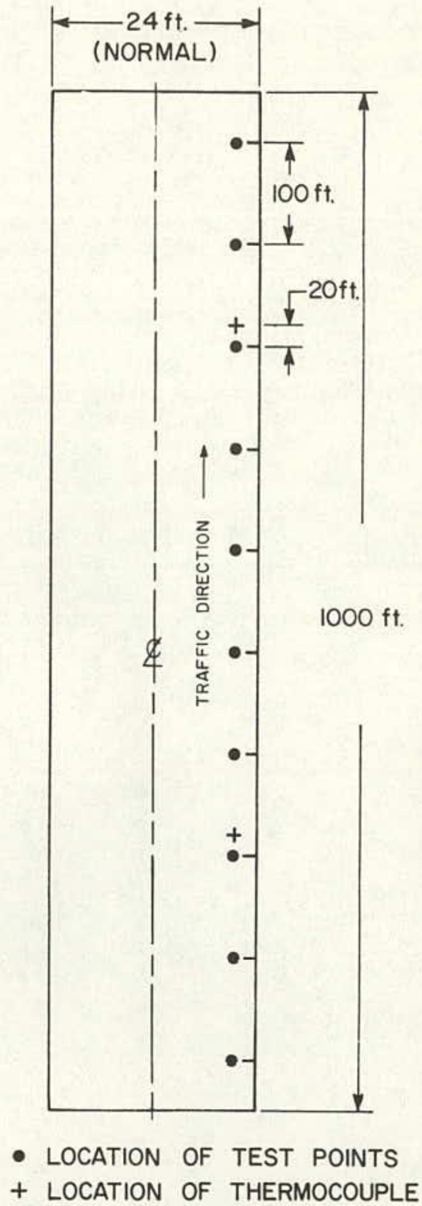

Figure 19. Typical test section layout. Deflections were measured at ten points. Ground temperatures were measured by thermocouples installed at depths ranging up to 6.5 ft.

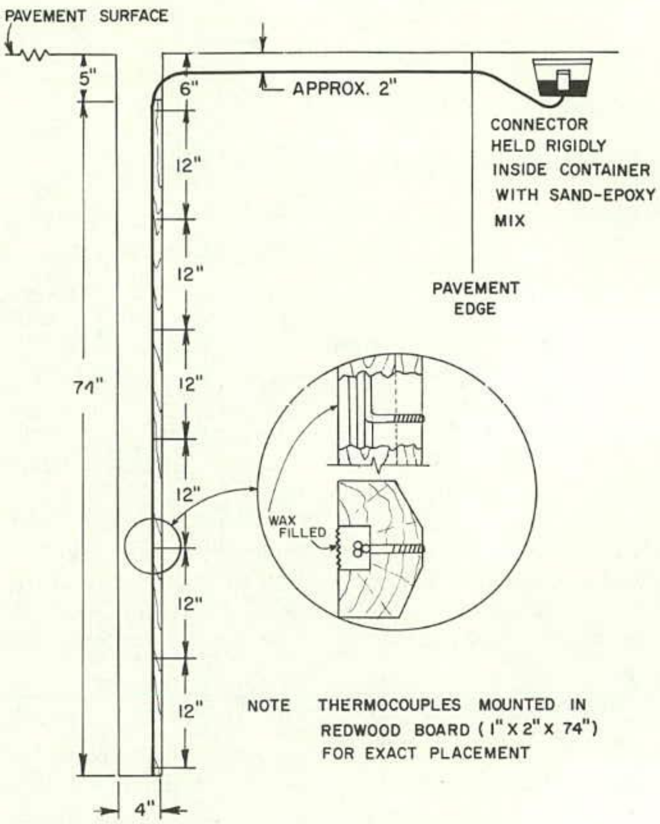

Figure 20. Typical thermocouple installation.

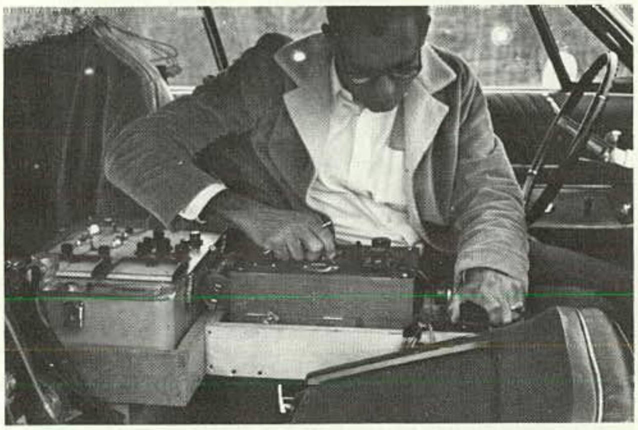

Figure 22. Thermocouples were read from inside vehicle.

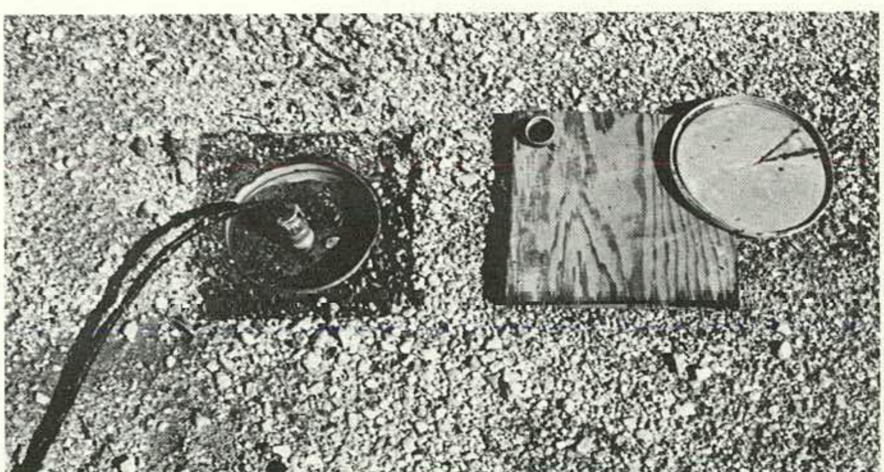

Figure 21. Thermocouple junction box installed outside pavement edge and covered with shoulder material when not in use.

CHAPTER TWO

FINDINGS

A two-man testing crew, with headquarters at College Station, Texas, gathered all Dynaflect and ground temperature data on the test sections. Benkelman Beam tests were performed by personnel of the Illinois Division of Highways in Study Area 2. Plate bearing and Benkelman Beam tests were performed by personnel of the Minnesota Department of Highways in Study Areas 3 and 4. Tests made with the curvature meter were performed by the Texas crew in cooperation with personnel of the other two states which provided the load vehicles and drivers. The Illinois and Minnesota organizations also supplied flagmen throughout the program wherever protection from traffic was required by the Texas crew, whose testing schedule is given in Table 4. The field testing program began in December, 1966, and ended in October, 1967. On all sections the deflections varied widely, from very low values in periods of deep frost to very high values during the spring thaw. Typical plots of the deflection basins observed in the fall, the winter, and the spring are shown in Figure 23 for a section of relatively light design in Area 3. In Figure 24 data from the same section are plotted against time. There is a rather abrupt rise of the deflection curve in mid-March coinciding with the disappearance of frost from the ground.

Typical data from a section of relatively heavy design are shown in Figure 25. By comparing this plot with the preceeding figure, it will be noted that there is a typical effect of design on deflection and surface curvature. It may also be seen from the two plots that local highway officials found it necessary to restrict axle loads in the case of the section having the higher deflection. Plots of the type shown in Figures 24 and 25 were made for all 24 sections and may be found in Appendix B.

THE FOUR STRENGTH PERIODS

A detailed study of all section plots like those in Figures 24 and 25 led to the division of the annual strength history of flexible pavements subjected to deep frost action (Study

TABLE 4

NUMBER OF VISITS TO EACH SECTION BY DYNAFLECT TESTING CREW

		1966	1967										
AREA	SEC.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	ALL
1	19	1	0	4	4	3	2	2	0	1	1	2	20
1	20	1	0	4	4	3	2	2	0	1	1	2	20
1	21	1	0	4	4	3	2	2	0	1	1	2	20
1	22	1	0	4	4	3	2	2	0	1	1	2	20
1	23	1	0	4	4	3	2	2	0	1	1	2	20
1	24	1	0	4	4	3	2	2	0	1	1	2	20
2	13	1	0	4	3	4	2	2	0	1	1	2	20
2	14	1	0	3	4	4	2	2	0	1	1	2	20
2	15	1	0	3	4	4	2	2	0	1	1	2	20
2	16	1	0	4	4	3	2	2	0	1	1	2	20
2	17	1	0	3	5	3	2	2	0	1	1	2	20
2	18	1	0	4	3	4	2	2	0	1	1	2	20
3	1	1	0	2	4	4	2	2	0	1	1	2	19
3	2	1	0	2	4	4	2	2	0	1	1	2	19
3	3	1	0	2	4	4	2	2	0	1	1	2	19
3	4	1	0	2	4	4	2	2	0	1	1	2	19
3	5	1	0	2	4	4	2	2	0	1	1	2	19
3	6	1	0	2	4	4	2	2	0	1	1	2	19
4	7	1	0	2	4	4	2	1	1	1	1	2	19
4	8	1	0	2	4	4	2	1	1	1	1	2	19
4	9	1	0	2	4	4	2	1	1	1	1	2	19
4	10	1	0	2	4	4	2	1	1	1	1	2	19
4	11	1	0	2	4	4	2	1	1	1	1	2	19
4	12	1	0	2	4	4	2	1	1	1	1	2	19
All	All	24	0	69	95	88	48	42	6	24	24	48	468

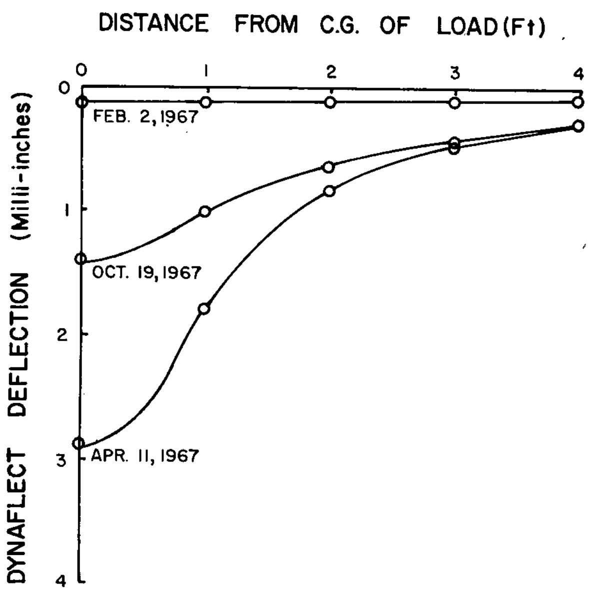

Figure 23. Typical seasonal variations in deflection basin. Data plotted are from Area 3, Section 1, near Rochester, Minn.

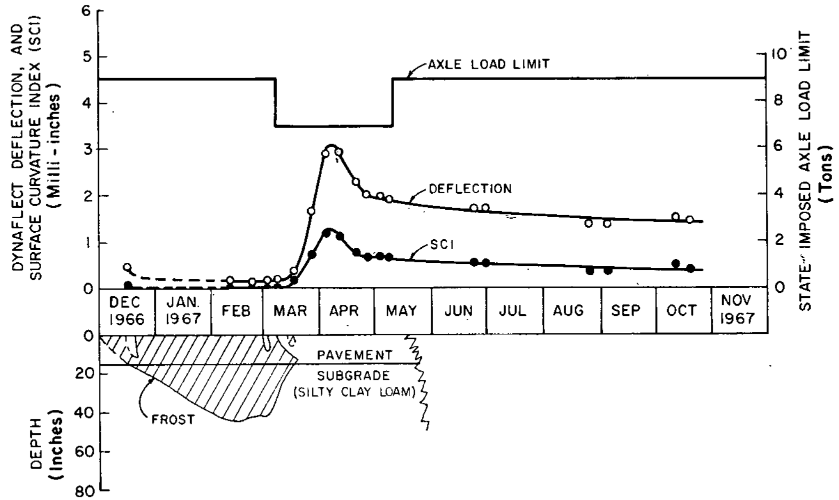

Figure 24. Typical deflection, surface curvature, frost penetration, and axle load restriction data plotted against time for a section of relatively light design. Data from Area 3, Section 1. Compare with Figure 23.

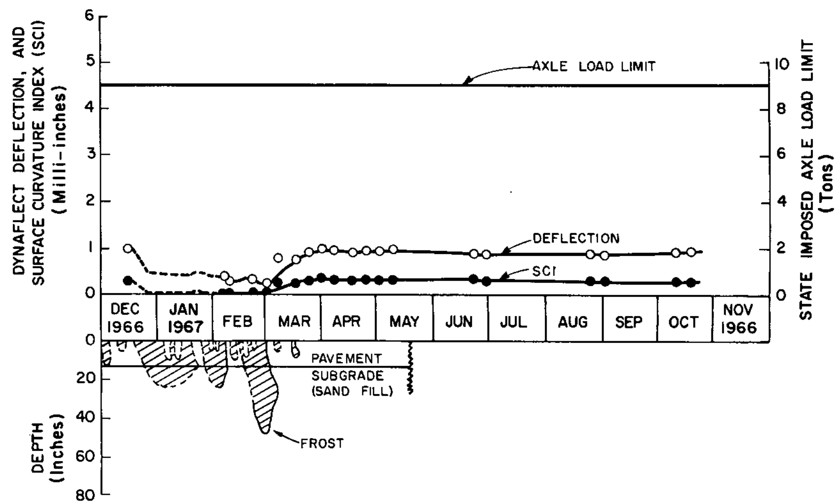

Figure 25. Typical data for a section of relatively heavy design. These data are from Area 2, Section 17. Compare with Figure 24.

Areas 2, 3, and 4) into four fairly well-defined periods (Fig. 26), as follows:

Period Designation	Description
A	Period of deep frost
B	Period of rapid strength loss
C	Period of rapid strength recovery
D	Period of slow strength recovery

Period A begins with the first appearance of deep frost in the late fall or winter. Period B begins with the abrupt upturn of the deflection curve coinciding with the disappearance of frost from the ground in the spring. Period C begins at the peak of the deflection curve. Period D begins at the point where the deflection curve levels off following the spring peak.

The period encompassing Periods B and C is referred to hereafter as the "critical period" during which restriction of axle loads may be desirable. (Suggested criteria for making this decision are given later.) Table 5A gives the duration of the critical period for each of the 18 sections in Study Areas 2, 3, and 4, as determined from the section deflection curve, and also the average duration for each study area.

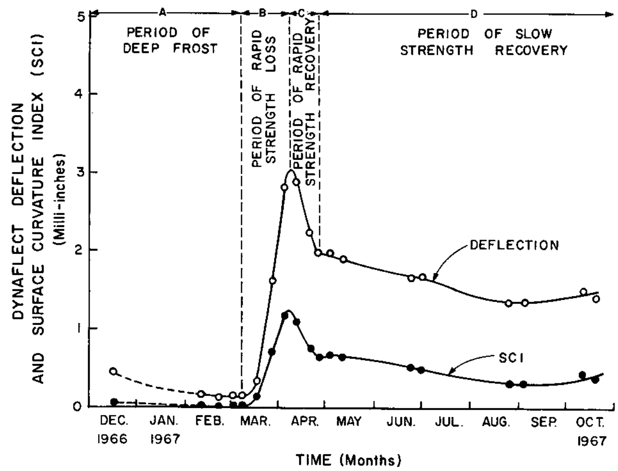

Figure 26. Typical seasonal variations in depth and curvature of the deflection basin. Note the four distinct periods—A (deep frost), B (rapid strength loss), C (rapid strength recovery), and D (slow strength recovery). Data from Area 3, Section 1.

TABLE 5

CRITICAL AND RESTRICTED PERIODS IN 1967, BY STUDY AREA

			A—CRITICAL PERIOD			B—RESTRICTED PERIOD		
AREA	SEC. NO.	DESIGN CLASS.	BEG. OF PERIOD B	END OF PERIOD C	DURATION (DAYS)	RESTRICT. IMPOSED	RESTRICT. REMOVED	DURATION (DAYS)
2	13	1	Mar. 2	Apr. 19	48	Feb. 14 [a]	Apr. 19	64
2	14	1	Mar. 5	Apr. 17	43	Feb. 14 [a]	Apr. 19	64
2	15	1	Mar. 5	Apr. 16	42	Feb. 14 [a]	Apr. 19	64
2	16	1	Mar. 1	Apr. 23	53	— [b]	— [b]	— [b]
2	17	2	Mar. 1	Apr. 17	47	— [b]	— [b]	— [b]
2	18	1	Mar. 6	Apr. 13	38	Feb. 14 [a]	Apr. 19	64
	Average		Mar. 3	Apr. 18	45.2	Feb. 14	Apr. 19	64
	Standard Deviation		2.3	3.3	5.3	0	0	0
	Coef. of Variation		—	—	11.7%	—	—	0%
3	1	1	Mar. 12	Apr. 26	45	Mar. 7	May 10	64
3	2	1	Mar. 10	Apr. 20	41	Mar. 7	May 10	64
3	3	1	Mar. 13	Apr. 20	38	Mar. 7	May 10	64
3	4	1	Mar. 16	Apr. 27	42	Mar. 7	May 10	64
3	5	2	Mar. 15	Apr. 24	40	— [b]	— [b]	— [b]
3	6	2	Mar. 14	Apr. 20	37	Mar. 7	May 10	64
	Average		Mar. 13	Apr. 23	40.5	Mar. 7	May 10	64
	Standard Deviation		2.2	3.3	2.9	0	0	0
	Coef. of Variation		—	—	7.2%	—	—	0%
4	7	1	Mar. 20	May 4	45	Mar. 14	May 10	57
4	8	2	Mar. 18	Apr. 28	41	— [b]	— [b]	— [b]
4	9	1	Mar. 20	Apr. 28	39	Mar. 16	May 17	62
4	10	1	Mar. 20	Apr. 30	41	Mar. 14	May 17	64
4	11	1	Mar. 20	May 4	45	Mar. 14	May 17	64
4	12	2	Mar. 18	May 4	47	— [b]	— [b]	— [b]
	Average		Mar. 19	May 1	43.0	Mar. 15	May 15	61.8
	Standard Deviation		1.0	3.0	3.1	1.0	3.5	3.3
	Coef. of Variation		—	—	7.2%	—	—	5.3%

[a] Dates are approximate. [b] These sections were not restricted.

As given in Table 5A, the critical period began about March 3 in the Ottawa area, about March 13 in the Rochester area, and about March 19 in the Duluth area, whereas the duration of the critical period ranged from 40 to 45 days. The duration of the critical period, unlike the beginning date, did not seem to be correlated with location. The average duration for the three areas was 43 days.

Axle load restrictions were imposed by the state on 13 of the 18 sections in Study Areas 2, 3, and 4. The dates these restrictions were imposed and the dates they were removed are given in Table 5B. There was a tendency, as indicated in the table, for the state to impose axle load restrictions a week or two before the beginning of the critical period and to remove them at some time up to three weeks after the period had ended. It is clear from the data presented that had the states concerned used deflection criteria for determining the critical period, the restrictions would have been imposed over periods of substantially shorter duration.

WARRANTS FOR IMPOSING REDUCED LOAD LIMITS

To establish a recommended criterion for separating highways that probably should be restricted during the critical period from those that probably should not, the test sections were listed in ascending order of normal surface curvature, as given in Table 6A. The normal surface curvature of a section is defined as the average value of the SCI (that is, the difference $w_1 - w_2$) observed on the section during the months of August, September, and October prior to the first freeze.

Table 6A also shows which of the sections were restricted by the state to light axle loads during the critical period, except in the case of the Springfield area (Study Area 1), where axle load restrictions are not placed as a matter of local policy.

In Table 6A a horizontal line has been drawn, below which are listed 12 sections that might, under local policy, have been restricted to light axle loads during the critical period. Of these 12 sections, for all of which the SCI was $\geqq$0.38, eleven were in fact restricted. Above the line are listed 6 other sections that might have been restricted under local policy. Of these 6 sections, for all of which the SCI was $\leqq$0.31, only 2 were actually restricted. To generalize, these findings can be restated as follows: In areas where local policy permits restricting highways to light axle loads during the critical period, only one road in three having normal SCI's $<$0.35 will be restricted based on local experience, but 11 out of 12 roads having normal SCI's $>$0.38 will be restricted based on local experience. In the table, the position of the line was selected to yield the best possible correlation with local experience.

Although the curvature of the deflection basin is a more reliable indication of pavement stress than the basin depth, the latter has been used for this purpose for some years in

TABLE 6

ORDERING OF SECTIONS BY NORMAL DEFLECTION AND NORMAL SURFACE CURVATURE INDEX

A—ORDERED BY NORMAL SCI

AREA NO.	SEC. NO.	DESIGN CLASS.	SCI, $W_1 - W_2$ NORM.	MIN.	MAX.	RESTRICT. IMPOSED
4	12	2	.09	.01	.09	No
3	6	2	.20	.00	.32	Yes
3	5	2	.28	.00	.51	No
3	2	1	.28	.01	.55	Yes
1	24	2	.28	.09	.50	[a]
4	8	2	.29	.00	.45	No
2	17	2	.31	.03	.35	No
1	20	2	.38	.02	.50	[a]
3	1	1	.38	.00	1.22	Yes
3	3	1	.45	.00	.76	Yes
1	22	1	.57	.06	1.15	[a]
4	7	1	.57	.01	.75	Yes
4	10	1	.59	.00	1.53	Yes
3	4	1	.61	.00	1.27	Yes
4	11	1	.65	.00	.95	Yes
4	9	1	.78	.00	1.44	Yes
1	21	1	.79	.11	1.98	[a]
2	18	1	.81	.02	1.38	Yes
1	23	1	.82	.07	1.78	[a]
2	16	1	.82	.03	1.73	No
2	15	1	.92	.02	1.80	Yes
2	14	1	.94	.02	2.00	Yes
1	19	1	1.09	.11	2.27	[a]
2	13	1	1.09	.03	2.26	Yes

B—ORDERED BY NORMAL DEFLECTION

AREA NO.	SEC. NO.	DESIGN CLASS.	DEFLECTION, W_1 NORM.	MIN.	MAX.	RESTRICT. IMPOSED
4	12	2	.60	.10	.62	No
3	6	2	.81	.08	1.15	Yes
2	17	2	.90	.22	.97	No
4	8	2	.90	.05	1.32	No
3	5	2	1.07	.14	1.62	No
3	2	1	1.14	.12	1.90	Yes
1	24	2	1.21	.74	1.72	[a]
3	3	1	1.26	.12	1.80	Yes
3	1	1	1.41	.13	3.05	Yes
4	10	1	1.64	.06	5.60	Yes
1	22	1	1.71	.67	2.70	[a]
3	4	1	1.85	.23	3.12	Yes
1	20	2	1.86	.53	2.30	[a]
4	11	1	1.96	.09	2.87	Yes
2	18	1	1.96	.33	3.30	Yes
4	9	1	2.19	.09	3.25	Yes
2	15	1	2.21	.25	4.05	Yes
1	21	1	2.24	.97	4.10	[a]
1	23	1	2.34	1.02	4.16	[a]
2	16	1	2.42	.56	4.20	No
4	7	1	2.49	.18	3.10	Yes
2	14	1	2.52	.33	4.42	Yes
1	19	1	2.76	.81	4.60	[a]
2	13	1	3.14	.43	5.20	Yes

[a] Located in the Springfield area where a restriction policy is not used.

pavement research. To examine deflection as a criterion for restricting a highway to reduced load limits during the critical period, an analysis, similar to that described, was made of normal deflections. As in the case of the normal SCI, the normal deflection is defined as the average deflection observed during the months of August, September, and October prior to the first freeze.

In Table 6B, the 24 test sections are listed in ascending order of normal deflection. Above the horizontal line drawn in this table are listed five sections that might have been restricted under local policy; only one was actually restricted. Below the line are listed 13 sections that might have been restricted under local policy; 12 of the 13 sections actually were restricted. Again generalizing, it may be stated that in areas where local policy permits restricting highways to light axle loads during the critical period, only 1 road in 5 having normal deflections <1.14 will be restricted based on local experience, but 12 out of 13 roads having normal deflections $\geqq 1.07$ will be restricted based on local experience.

In view of the foregoing, it appears that the chances of making a decision based on Dynaflect measurements that will accord with the judgment of local engineers are somewhat better if deflection, rather than surface curvature, is used as the criterion. However, if Table 6A is compared with 6B, it will be noted that there is a stronger tendency in Table 6A, in which the criterion is surface curvature, for the heavier designs to cluster near the top of the table where one would expect to find them. This fact was given some weight in attempting to judge which criterion—curvature or deflection—would in the long run prove the more reliable. The choice was surface curvature, after reflecting that repeated bending of the pavement—not its vertical motion—is responsible for its fatigue.

It appears from a study of 1967 air temperature data for the Springfield area that not one but several freeze-thaw cycles are likely to have occurred over an extended period of time in the late winter and early spring months. Unfortunately it was not feasible for the Dynaflect crew to remain in this area and gather deflection data during all of these freeze-thaw cycles; however, it may be assumed that deflections oscillated irregularly as the air temperature oscillated about 32°F. (See section data for Study Area 1, Appendix B.) In such areas there may be, therefore, not one distinct critical period, but several. Under these circumstances the imposition of reduced load limits on highways would seem to be impractical, and certainly not economical from the standpoint of the movement of goods over the highways.

On the other hand, further north in Study Areas 2, 3, and 4 the critical period was distinctly defined, appeared only once during the annual weather cycle, and averaged only 43 days in length. Under these circumstances instrument-controlled imposition of load restrictions seems practicable.

Based on the data and other considerations that have been presented, the following conclusions seem warranted:

1. In areas with a mean freezing index exceeding about 200 (the Springfield value was 100), a road should be restricted to light axle loads during the critical season if the average normal SCI measured during the previous fall exceeded 0.35. Pavements having SCI's less than that value need not be restricted provided, of course, that they are constructed of frost-resistant materials.

2. The restriction should be imposed not later than the beginning of Period B (the period of rapid strength loss) and removed not earlier than the beginning of Period D (the period of slow strength recovery), and the beginnings of these periods should be determined by frequent Dynaflect deflection measurements.

3. Imposing restrictions much later than the beginning of Period B would be hazardous because of the abrupt loss of strength starting at that time.

4. Maintaining restrictions long after the beginning of Period D would not be economical because of the typically slow rate of strength recovery characteristic of that period.

5. It appears that had the states concerned used deflection criteria for determining the critical period, the restrictions would have been imposed over periods of substantially shorter duration.

The first conclusion implies that the surface curvature measured in the fall of the year may be correlated with the peak curvature measured during the critical period. That such is indeed the case is indicated in Figure 27 where peak values of the SCI for all 24 sections are plotted against the normal values. The correlation coefficient was 0.95, and the standard deviation was 0.22. The equation for the regression line is shown in the figure. A similar correlation between normal and peak values of deflection was found, as shown in Figure 28.

An interesting phenomenon observed on all sections of Areas 2, 3, and 4 was the hysteresis loop shown in Figure 29. The data plotted in this figure indicate that for a given value of deflection, the corresponding surface curva-

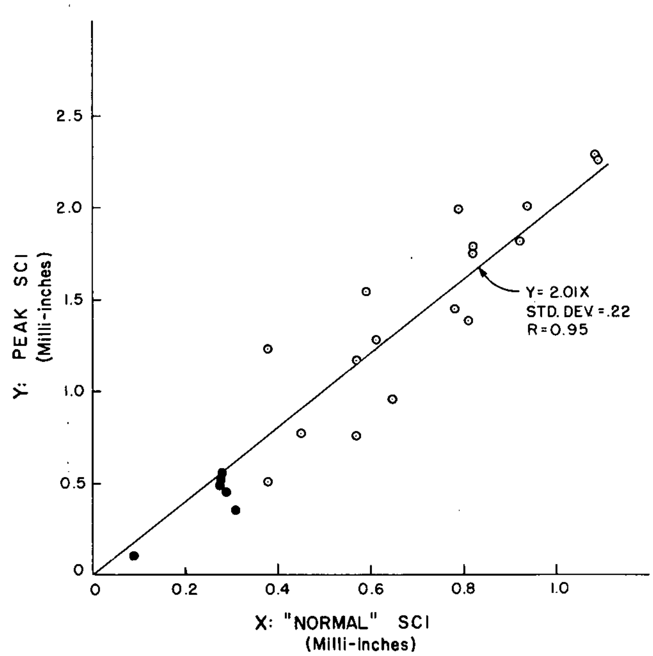

Figure 27. Relation of peak to "normal" surface curvature. Open circles represent light designs; solid circles, heavy designs.

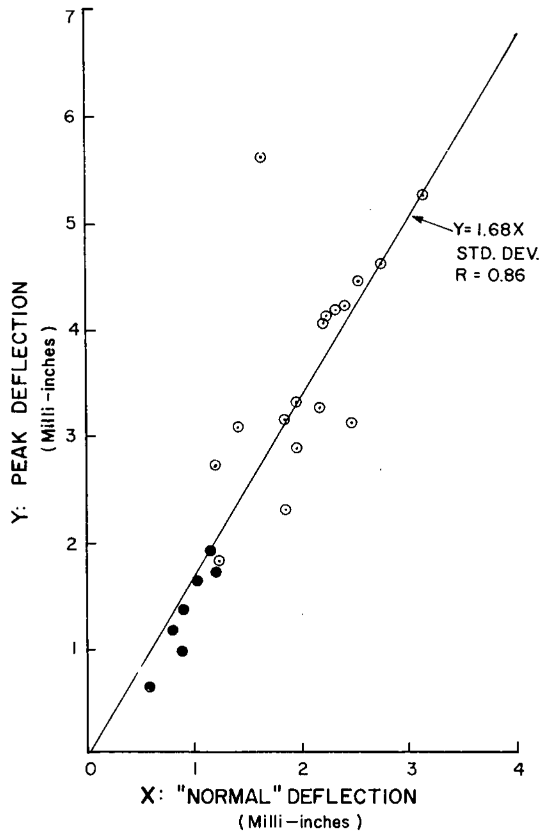

Figure 28. Relation of peak to "normal" deflections. Open circles represent light designs; solid circles, heavy designs.

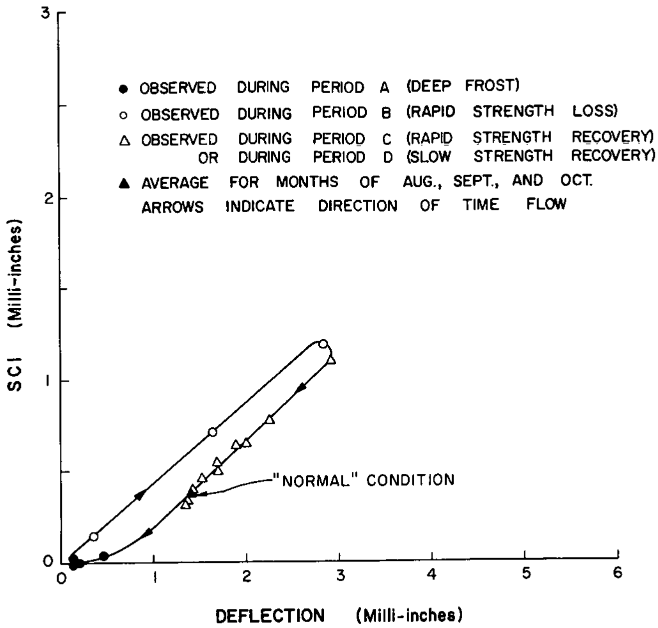

Figure 29. Effect of prevailing strength period on the curvature-deflection relationship, typical of Areas 2, 3, and 4, but not observed in Area 1. Data for Area 3, Section 1.

ture was greater during Period B—the period of rapid strength loss—than at any other time during the annual weather cycle, a fact that serves to reinforce the previously stated conclusion with respect to the hazard associated with this particular strength period. It is suggested that this phenomenon be further researched.

Conclusions 1 through 5 are concerned with determining where and when load restrictions should be placed, and when they should be removed. Of equal importance is the question of what the reduced load limit should be in a particular case. To answer this question with complete confidence, a much more comprehensive experimental design would be needed than could be implemented in this limited research project. However, until current research activities in the field of flexible pavements provide a better answer, the following simplified method is suggested for use—tempered by engineering judgment—in assigning axle load limits during the critical period.

The description of the method begins by proposing the following hypothesis based on the assumption that the surface curvature index is an indicator of a pavement's vulnerability to damage by traffic:

> The maximum safe axle load that can be applied to a given highway during the critical period is inversely proportional to the maximum surface curvature index measured during that period. The hypothesis may be stated in mathematical form as follows:

$$L_s = \frac{k}{\text{Maximum SCI}} \quad (3)$$

in which L_s is the maximum safe load that may be applied during the critical period, k is a constant, and the maximum SCI is as previously defined.

Now it may be inferred from Conclusion 1 that the maximum safe axle load that can be applied during the critical period on a highway with a normal SCI of 0.35 is the legal limit, 9 tons. The corresponding value of the maximum SCI can be estimated from the equation shown on Figure 27, and is, according to that equation, double the normal value, or 0.70. Thus, according to Eq. 3, $9 = k/0.70$, or $k = 6.3$.

By substituting 6.3 for k in Eq. 3, the following formula for estimating the maximum safe load from the maximum SCI is devised:

$$L_s = \frac{6.3}{\text{Maximum SCI}} \quad (4)$$

To provide at least a minimum of data to test the hypothesis, surface roughness measurements were made in June, 1968, on the sections in Areas 2, 3, and 4, by means of a newly developed instrument known as the Mays Road Meter after its inventor, Mr. Ivan K. Mays of the Texas Highway Department. Installed in an automobile, the device measures the accumulated displacement, in in., of the body of the car with respect to the rear axle. Roughness measurements are normally reported in in. per mi, as in the case of the Bureau of Public Roads' Roughometer. A more detailed description of the Mays Road Meter, which resembles in some respects the PCA Roadmeter (*10*), may be found in Appendix C.

The results of the roughness determinations are given in the last column of Table 7. Also given in this table are values of the maximum safe axle load for the critical period computed from Eq. 4, the load limit actually imposed by the state or county authorities, and the apparent safety factor, *F*, for the critical season, found by dividing the computed maximum safe load by the load limit actually imposed.

The 18 test sections in Table 7 have been divided into two groups, with Group 1 composed of sections with a maximum surface curvature index <0.70, and with Group 2 consisting of sections with greater values of maximum SCI. It will be seen from the table that the average roughness for sections in Group 1 was 69 while the average for Group 2 was 118 in. per mi, a difference which, according to an analysis of variance, is significant at the 1 percent level. This finding is offered to substantiate these researchers' opinion that the surface curvature index has an important engineering significance.

In Table 8 the 18 test sections are again divided into two groups. Group A consists of sections with an apparent safety factor ≧1.0, whereas Group B is composed of sections with a safety factor <1.0. If the hypothesis regarding the maximum safe load is valid, and assuming that the Group B sections were actually subjected to loads up to the imposed limit, the average roughness of the Group B sections would be expected to be greater than that of the Group A sections. This was actually the case; the average of Group A was 83, and the average of Group B was 126 in. per mi. The difference was statistically significant at the 2.5 percent level. It should be pointed out, however, that many other variables may have affected these results, such as the number and weight of the axle loads carried by the test sections during the past several critical periods, the length of time since the sections had last been resurfaced, etc. Nevertheless, the hypothesis, which was made on the basis of logic in advance of the roughness measurements, cannot be rejected on the basis of these data, and its use is recommended until further research provides a better one.

It will have occurred to the reader that a state or county about to embark on a program of axle load restrictions in accordance with these recommendations will wish to estimate the maximum surface curvature index in advance of the first critical period. The estimate may be made from a determination of the normal SCI made during the preceding fall by simply doubling the normal SCI (see Fig. 27). A graph for finding the maximum safe axle load from either the normal or the maximum value of the SCI is shown in Figure 30.

Because of the correlations found to exist between the Benkelman Beam, the Curvature Meter, and the Dynaflect, it would appear that either Curvature Meter or Benkelman Beam readings could be converted to values of SCI, and Figure 30 could then be used in conjunction with the

TABLE 7

APPARENT SAFETY FACTOR DURING CRITICAL PERIOD, AND SUBSEQUENT SURFACE ROUGHNESS (SECTIONS GROUPED BY MAXIMUM SURFACE CURVATURE INDEX)

GROUP	AREA NO.	SEC. NO.	DESIGN CLASS	HWY.	MAX. SCI	AXLE LOAD LIMIT (TONS) FOR CRITICAL PERIOD: COMPUTED FROM MAX. SCI	AXLE LOAD LIMIT (TONS) FOR CRITICAL PERIOD: ACTUALLY IMPOSED	APPARENT SAFETY FACTOR, F	ROUGHNESS (IN./MI)
1	4	12	2	IH 35	0.09	70.0	9	7.8	48
(Max. SCI <0.70)	3	6	2	US 63	0.32	19.7	7	2.8	52
	2	17	2	US 351	0.35	18.0	9	2.0	86
	4	8	2	US 2	0.45	14.0	9	1.6	90
	3	5	2	US 63	0.51	12.4	9	1.4	74
	3	2	1	SH 30	0.55	11.5	7	1.6	66
								Avg.	69.3
2	4	7	1	SH 23	0.75	8.4	6	1.4	97
(Max. SCI >0.70)	3	3	1	SH 30	0.76	8.3	6	1.4	117
	4	11	1	SH 27	0.95	6.6	4	1.7	95
	3	1	1	SH 30	1.22	5.2	7	0.74	126
	3	4	1	SH 247	1.27	5.0	6	0.83	120
	2	18	1	Co. 260	1.38	4.6	4.5	1.01	108
	4	9	1	SH 73	1.44	4.4	7	0.63	93
	4	10	1	SH 73	1.53	4.1	5	0.82	167
	2	16	1	Co. 254	1.73	3.6	9	0.40	207
	2	15	1	Co. 270	1.80	3.5	9	0.39	85
	2	14	1	Co. 260	2.00	3.2	4.5	0.70	[a]
	2	13	1	Co. 1365	2.26	2.8	4.5	0.62	85
								Avg.	118.2

[a] This section had been resurfaced between October 1967 and June 1968.

TABLE 8

APPARENT SAFETY FACTOR DURING CRITICAL PERIOD, AND SUBSEQUENT SURFACE ROUGHNESS (SECTIONS GROUPED BY APPARENT SAFETY FACTOR)

GROUP	AREA NO.	SEC. NO.	DESIGN CLASS	APPARENT SAFETY FACTOR, F	ROUGHNESS, R (IN./MI.)
A	4	12	2	7.8	48
(F>1)	3	6	2	2.8	52
	2	17	2	2.0	86
	4	11	1	1.7	95
	3	2	1	1.6	66
	4	8	2	1.6	90
	4	7	1	1.4	97
	3	3	1	1.4	117
	3	5	2	1.4	74
	2	18	1	1.0	108
				Avg.	83.3
B	3	4	1	0.83	120
(F<1)	4	10	1	0.82	167
	3	1	1	0.74	126
	2	14	1	0.70	[a]
	4	9	1	0.63	93
	2	13	1	0.62	85
	2	16	1	0.40	207
	2	15	1	0.39	85
				Avg.	126.1

[a] This section had been resurfaced between October 1967 and June 1968.

Benkelman Beam or the Curvature Meter to estimate the maximum safe axle load for the critical season. And indeed this could be done—but it would probably be inadvisable because of findings reported in the next section.

CORRELATION OF FOUR MEASUREMENTS SYSTEMS

In a previous section it was mentioned that a series of special tests was conducted to establish the degree of correlation between four non-destructive methods of testing highway pavements. These were the plate bearing test, a curvature meter test, the Benkelman Beam deflection test, and the Dynaflect test.

In February, immediately following one set of routine Dynaflect measurements, Benkelman Beam deflections were measured by the Illinois Highway Department on the ten test points on each of the six test sections in Area 2. At the same time, curvature meter measurements were made using the same load vehicle. In April, similar measurements were made by the Minnesota Highway Department in Area 3 and again in August in both Areas 3 and 4. At the same time in August the Minnesota Highway Department also made plate load tests at two of the test points on each of the 12 test sections in Areas 3 and 4. Thus, 240 direct comparisons were obtained between the Dynaflect, Benkelman Beam and the curvature meter; 24 of these comparisons also included plate bearing tests. The section averages of these data and the within-section standard deviations are given in Table 9. Analyses of variance performed on each of the five variables showed that the difference between sections was highly significant in each case.

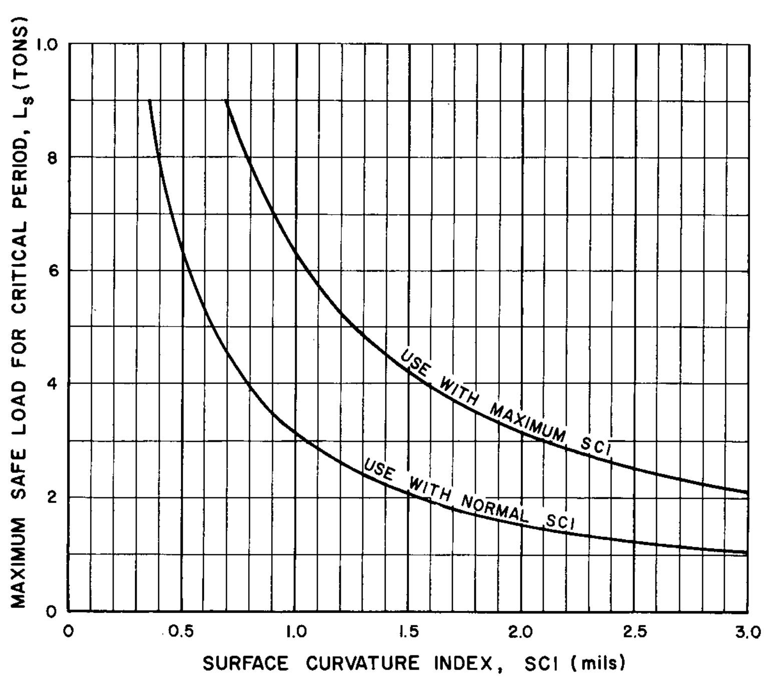

Figure 30. Graph for estimating maximum safe load to be applied during the critical season.

TABLE 9

SPECIAL TESTS SCHEDULE

AREA NO.	SEC. NO.	DATE	PERIOD	SECTION AVERAGES: BENKELMAN BEAM DEFL. (MILLI-IN.) (10 TESTS/SEC)	CURVATURE METER READING (MILLI-IN.) (10 TESTS/SEC)	LOAD ON A 12-IN. DIA. PLATE AT 0.2-IN. DEFL. (KIPS) (2 TESTS/SEC)	DYNAFLECT READINGS (MILLI-IN.) (10 TESTS/SEC): DEFL., W_1	SCI (W_1—W_2)
2	13	2-20-67	A	8[a]	2.0[a]	—	0.43	0.04
2	14	2-20-67	A	8[a]	1.5[a]	—	0.49	0.04
2	15	2-20-67	A	8[a]	4.3[a]	—	0.42	0.09
2	16	2-21-67	A	11[a]	2.5[a]	—	0.72	0.04
2	17	2-21-67	A	10[a]	2.1[a]	—	0.34	0.03
2	18	2-20-67	A	11[a]	4.8[a]	—	0.53	0.13
3	1	4-3-67	B	58	31.0	—	2.83	1.18
3	2	4-3-67	B	30	19.0	—	1.79	0.56
3	3	4-4-67	B	40	23.5	—	1.65	0.70
3	4	4-4-67	B	68	34.1	—	3.06	1.24
3	5	4-4-67	B	22	10.6	—	1.43	0.41
3	6	4-4-67	B	14	10.2	—	0.98	0.18
3	1	8-25-67	D	29	11.2	24.6	1.36	0.32
3	2	8-25-67	D	20	7.5	32.0	1.08	0.26
3	3	8-25-67	D	28	13.0	24.5	1.24	0.43
3	4	8-28-67	D	39	17.8	23.9	1.96	0.65
3	5	8-28-67	D	16	6.3	31.5	1.07	0.28
3	6	8-28-67	D	15	6.0	29.2	0.85	0.23
4	7	8-30-67	D	43	16.0	19.7	2.67	0.62
4	8	8-30-67	D	15	5.7	—[b]	0.89	0.27
4	9	8-29-67	D	60	30.3	19.0	2.47	0.94
4	10	8-29-67	D	37	16.5	25.7	1.79	0.70
4	11	8-29-67	D	44	21.5	18.6	2.16	0.77
4	12	8-29-67	D	10	4.2	—[b]	0.65	0.10
Within sets								
Std. deviation				7.9	4.3	2.4	0.22	0.10
F-ratio				53.1	53.4	8.5	139.4	133.4

[a] Data taken with vehicle rear axle load of 17.2 kips. Data have been linearly adjusted to 18 kips.
[b] Load required to deflect pavement 0.2 in. was not attained.

A plot of the 240 Dynaflect deflections versus the Benkelman Beam deflections is shown in Figure 31. Similarly, a plot of the curvature meter versus the Dynaflect SCI is shown in Figure 32. Also shown in these figures are lines representing linear regression analyses performed on the data, the equations for these lines, the correlation coefficients, and the standard deviations.

The results of 20 of the plate bearing tests are shown plotted versus the reciprocals of the Dynaflect deflections in Figure 33 (the pavements at four test points were too strong to permit attainment of the required load on the plate). The relationship between deflection and plate bearing tests—two highly dissimilar tests—is more complex than the relation between the similar measurements illustrated in Figures 31 and 32. However, if a pavement is assumed to obey elasticity theory, its composite modulus is inversely proportional to the deflection produced by a given load and directly proportional to the load required to produce a given deflection. One seemingly reasonable assumption leading to a relationship between these unlike measurements is the assumption that a pavement's composite modulus determined from deflection is proportional to the composite modulus determined from a plate bearing test. This assumption leads to the conclusion that the plate bearing values are inversely proportional to the Dynaflect deflection. As evidenced by the data shown in Figure 33, this assumption is not valid. However, the assumption that the deflection-determined composite modulus is linearly related to the plate bearing-determined composite modulus gives quite good agreement, as shown on the figure by the straight line determined by a linear regression analysis. Similarly, the assumption that the logarithm of the dynamic composite modulus is linearly related to the logarithm of the static composite modulus gives good agreement as shown on the figure by the curved line determined by a linear regression analysis of the logarithms of the variables. The latter assumption is probably more logical for extrapolation ouside of the range of measurements (especially for small plate load values or large deflections).

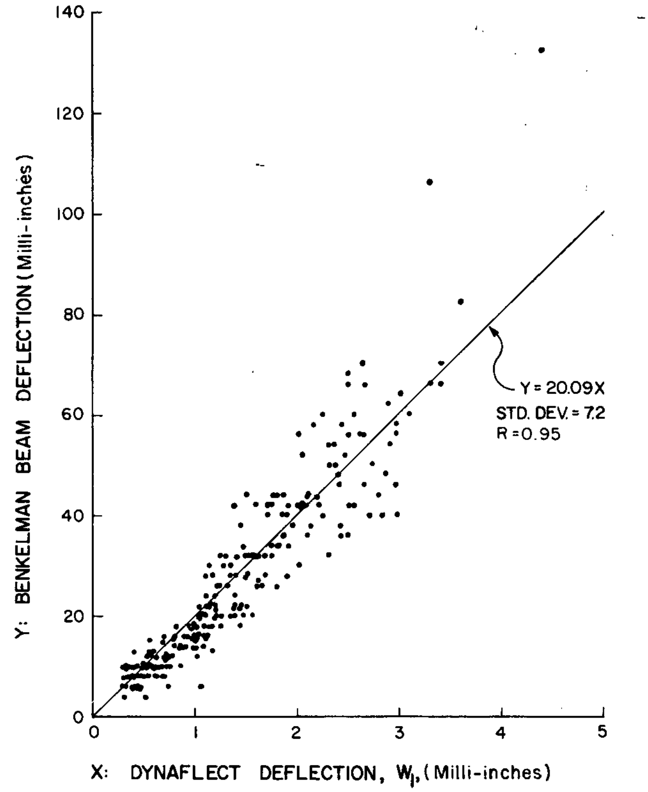

Figure 31. Relation of Benkelman Beam to Dynaflect deflection.

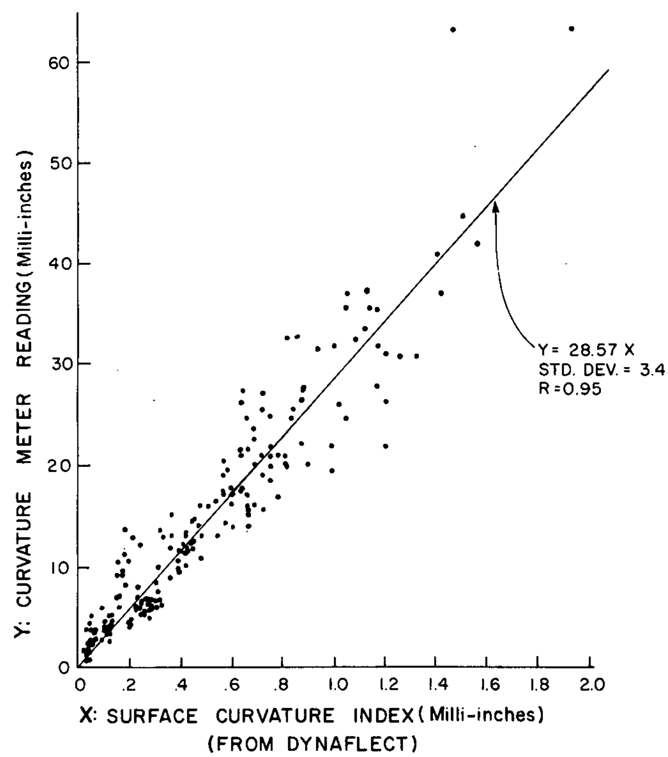

Figure 32. Relation of curvature meter reading to surface curvature index.

The results of the direct comparisons between the Dynaflect deflections and the standard static load response tests leads to one rather significant conclusion: Dynaflect deflections can be used to estimate the results of any of these standard static tests, and the estimates will be reasonably accurate. In fact, in all cases compared, the standard deviations of the estimating equations were in the same order of magnitude as the within-test section standard deviations. Because within-test section variations are due to both measurement errors and real variations in test sections, estimating errors are not solely indicative of measurement errors. No attempt was made in this research study to determine the magnitude of measurement errors, although they are believed to be smaller than errors stemming from variations within test sections.

A plot of the plate bearing values versus the reciprocal of the Benkelman Beam deflections is shown in Figure 34. The results are similar to those shown on the previous figure.

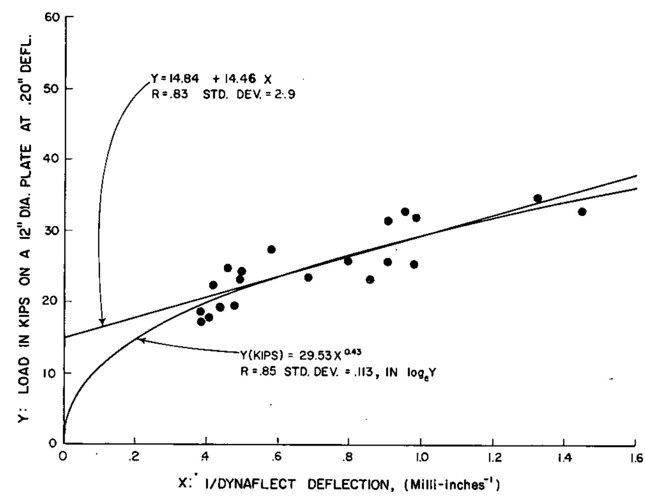

Figure 33. Relation of plate bearing value to reciprocal of Dynaflect deflection.

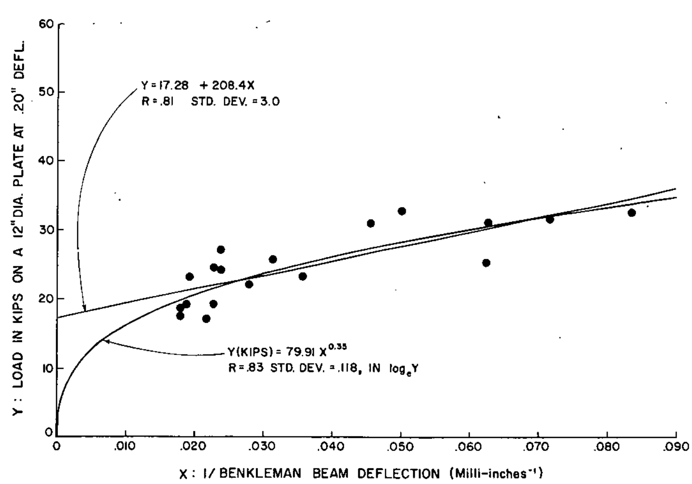

Figure 34. Relation of plate bearing value to reciprocal of Benkelman Beam deflection.

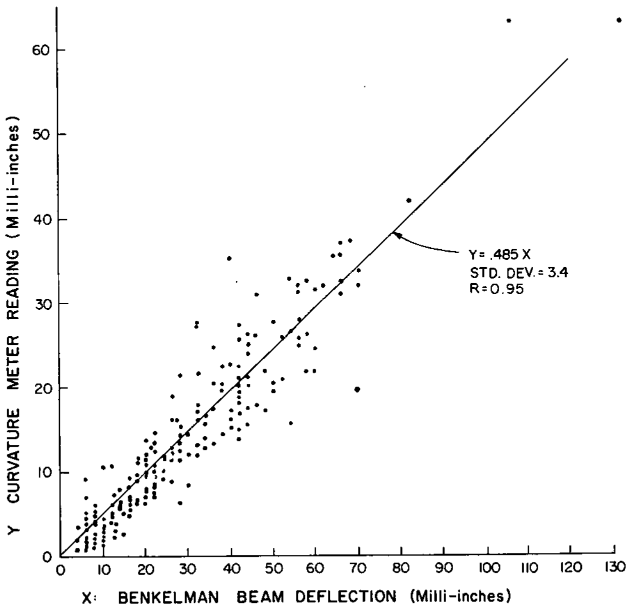

Figure 35. Relation of curvature meter reading to Benkelman Beam deflection.

Shown in Figure 35 is a plot of the Benkelman Beam deflections versus the curvature meter readings. The fact that curvature is strongly related to deflection is clearly demonstrated by this figure.

Based on the results of the correlation studies described, it appears that the sixth—and final—conclusion is warranted.

Dynaflect deflections can be used to estimate the results of Benkelman Beam, curvature meter, and plate bearing tests with reasonable accuracy, and, therefore, apparently could be substituted for those tests where they are being used to detect seasonal changes in the bearing capacity of flexible pavements.

RELATIVE QUALITY AND ECONOMY OF THE FOUR MEASUREMENTS SYSTEMS

It has been shown by correlation studies that each of the four instruments used in this research—the Dynaflect, the Benkelman Beam, the curvature meter, and the plate load-test—evidently respond to much the same properties of the pavement; in short, they all appear to measure the same thing. If this is true, the question naturally arises as to which instrument does the best job.

A method that can be used to arrive at a measure of the efficiency of any of the instruments under consideration is that of comparing its measurement of the variability *between* sets with its measurement of the variability *within* sets, where the word "set" again means a set of measurements made with a given instrument on a given section on a given day. If the measured variability between sets is large compared to the measured variability within the sets, then it can be said that the instrument is capable of performing its primary function of sensing changes in strength, and it can also be said that the greater the ratio of these variabilities, the greater is the sensitivity or efficiency of the instrument. The ratio of the between-set to the within-set variability is expressed by the quantity known in statistical science as the "*F*-ratio," and is routinely computed in an analysis of variance.

Because the *F*-ratio is dependent on the variability between and within sets—and these, in turn, are dependent in part upon physical differences between and within sections—it follows that a group of instruments can be ranked with complete fairness by their *F*-ratio only if (1) all instruments were used on the same group of sections, (2) all were used on the same test points within sections, (3) all were used on any given section on the same day, and (4) the variables analyzed were linearly correlated. These criteria of fairness are satisfied by all the test data for the Dynaflect, the Benkelman Beam, and the curvature meter that formed the averages in Table 10. Accordingly, these instruments have been ranked by their *F*-ratio in Table 11 and Appendix D, from which it can be seen that the Dynaflect is evidently a more sensitive instrument than either the curvature meter or the Benkelman Beam. The *F*-ratio of the plate bearing test is also given in Table 10, but its ranking in the table may not be valid because of the lesser volume of data available for analysis, and because the bearing power was not linearly correlated with the other variables analyzed.

Although the Dynaflect appears to be the most sensitive of the instruments under consideration, it is necessary before making a choice between instruments to consider also economy of operation. Table 11 gives an estimated cost comparison between the Dynaflect and the most promising of the remaining instruments, the curvature meter. It will be seen from these tables that an estimated 10 percent more work can be accomplished in a given time with the Dynaflect, but that its operation cost per

TABLE 10

COMPARISON OF INSTRUMENT SENSITIVITY BY ANALYSES OF VARIANCE (INSTRUMENTS RANKED IN DESCENDING ORDER OF SENSITIVITY)

INSTRUMENT OR TEST	NO. SETS	ORSERVATIONS PER SET	VARIABLE ANALYZED	F-RATIO
Dynaflect	24	10	w_1 (mils)	139.4
Dynaflect	24	10	SCI (mils)	133.4
Curvature meter	24	10	Curvature (mils)	53.4
Benkelman beam	24	10	Deflection (mils)	53.1
Plate load test	10	2	Bearing power (kips)	8.5[a]

[a] Not directly comparable with the other values of *F*-ratio because of the limited amount of data available for the plate load test.

TABLE 11

ECONOMIC ANALYSIS, DYNAFLECT AND CURVATURE METER (WORK UNIT: TESTING OF ONE SECTION PLUS 20 MILES TRAVEL TO NEXT SECTION)

A. CALCULATION OF WORK UNITS COMPLETED IN ONE 8-HR. DAY

DYNAFLECT	HR.	CURVATURE METER	HR.
Time on 1 section	0.25	Time on 1 section	0.25
Time to next section at 50 mph speed	0.40	Time to next section at 40 mph speed	0.50
Time per work unit	0.65	Time per work unit	0.75
Total calibration time per day (4 calibrations)	0.33	Total calibration time per day	0
Time from headquarters to first section (20 mi)	0.40	Time from headquarters to first section (20 mi.)	0.50
Fixed time charge per day	0.73	Fixed time charge per day	0.50
Let n=no. work units per day		Let n=no. work units per day	
Then, $0.73+0.65n=8$, or $n=11.18$ work units/day for an average day		Then, $0.50+0.75n=8$, or $n=10.00$ work units/day for an average day	

B. CALCULATION OF COST PER SECTION

DYNAFLECT (COST OF OPERATOR, CAR, PICK-UP, TWO FLAGMEN)	COST/DAY	CURVATURE METER (COST OF OPERATOR, LOADED TRUCK, TRUCK DRIVER, PICK-UP, TWO FLAGMEN)	COST/DAY
Car @ \$0.10/mile, $0.10\times 12.18\times 20$	\$ 24.36	Truck and driver @ \$7.50/hr, 7.50×8	\$ 60.00
Operator @ \$3/hr, 3×8	24.00	Operator @ \$3/hr, 3×8	24.00
Pick-up @ \$0.10/mile, $0.10\times 12.18\times 20$	24.36	Pick-up @ \$0.10/mile, $0.10\times 11.0\times 20$	22.00
Two flagmen @ \$3/hr. each, $2\times 3\times 8$	48.00	Two flagmen @ \$3/hr. each, $2\times 3\times 8$	48.00
Rental on Dynaflect @ \$1,500/mo.,[a] 1500/20	75.00		
	\$195.72		\$154.00
Cost per section= $\frac{195.72}{11.18}$=\$17.51		Cost per section= $\frac{154.00}{10.00}$=\$15.40	

[a] According to quotation dated July 3, 1968, received from Dresser Atlas, Division of Dresser Industries, Inc., P.O. Box 1407, Houston, Tex. 77001.

section is an estimated \$17.51, whereas the corresponding cost of the curvature meter is \$15.40 per section. The higher cost of the Dynaflect is justified by the higher sensitivity of that instrument and the lesser chance that its use will lead to a wrong conclusion regarding either the maximum safe load to be applied to a section during the critical season, or the proper time to impose or remove load restrictions.

CHAPTER THREE

EVALUATION AND APPLICATIONS

The findings discussed in detail in Chapter Two are summarized:

1. The plate bearing test (Fig. 5), a curvature meter test (Fig. 6), the Benkelman Beam deflection test (Fig. 7), and the Dynaflect deflection test (Figs. 8 through 13) were found to be capable of detecting seasonal changes in the load-carrying capacity of flexible pavements. The Dyna-

flect, an instrument available commercially on a rental basis, was best suited to the job. The conclusions that follow are based on the results of Dynaflect tests.

2. The annual strength history of flexible pavements subjected to deep frost action can be divided into four fairly well-defined periods (Figs. 24 and 25). These are designated in chronological order as Period A (period of deep frost), B (period of rapid strength loss), C (period of rapid strength recovery), and D (period of slow strength recovery). Period A begins with the first appearance of deep frost in the late fall or winter. Period B begins with the abrupt upturn of the deflection-time curve coinciding with the disappearance of frost from the ground in the spring. Period C begins at the peak of the deflection-time curve. Period D begins at the point where the deflection-time curve levels off following the spring peak. The period encompassing Periods B and C is the critical period during which restriction of axle loads may be desirable.

3. Warrants for an axle load restriction policy, based on Dynaflect deflection tests and correlated with actual practice in the states of Illinois and Minnesota, follow:

(a) In areas with a mean freezing index exceeding about 200 (see map, Fig. 15), a road should be restricted to light axle loads during the critical period if the average surface curvature index (Fig. 14), measured by Dynaflect during the previous fall, exceeded 0.35. Pavements having indexes less than that value need not be restricted provided, of course, that they are constructed of frost-resistant materials.

(b) The restriction should be imposed not later than the beginning of Period B (the period of rapid strength loss) and removed not earlier than the beginning of Period D (the period of slow strength recovery), and the beginnings of these periods should be determined by frequent Dynaflect deflection measurements.

(c) Imposing restrictions much later than the beginning of Period B would be hazardous because of the abrupt loss of strength starting at that time.

(d) Maintaining restrictions long after the beginning of Period D would not be economical because of the typically slow rate of strength recovery characteristic of that period.

(e) The use, tempered by engineering judgment, of the graph shown in Figure 30 is recommended for determining the maximum safe load to be permitted on a pavement during the critical period.

4. Use of the warrants given in item 3 would apparently result in somewhat shorter periods of restricted axle loads, at least in the areas studied in this research.

5. Dynaflect deflections can be used to estimate the results of Benkelman Beam, curvature meter, and plate bearing tests with reasonable accuracy; and, therefore, apparently could be substituted for those tests where they are being used to detect seasonal changes in the bearing capacity of flexible pavements (Figs. 31 and 32).

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APPENDIX A

TEST PROCEDURES

This appendix contains the procedures used for the measurements made on the individual test sections. It includes procedures for the following measurements:

1. Dynaflect deflections.
2. Temperature measurements.
3. Benkelman Beam deflections.
4. Curvature meter measurements.
5. Plate bearing test.

Ten test points, numbered from 1 to 10 in the direction of traffic flow, were permanently marked in the outer wheel path of each test section so that routine and comparison testing could be done at precisely the same points (see Fig. 19). These test points are often referenced in the procedures that follow.

DYNAFLECT OPERATING PROCEDURE

Described in this section is the procedure used to obtain the Dynaflect deflections used in this research study. It is divided into two parts: (1) the calibration procedure, and (2) test section measurements. Because test section locations were somewhat scattered, calibration was normally done after arriving at each test section. A more detailed operating procedure as well as the steps to be followed when malfunctions occur are contained in the manufacturer's operations manual (*10*).

A typical field data sheet is shown in Figure A-1. For analysis work, IBM cards were punched directly from this form.

Calibration Procedure

1. Connect the calibrator to control unit. Connect five sensors to their mating connectors and put sensors 1 through 4 in the calibrator.
2. Turn on power switch and allow control unit to warm up. Place frequency toggle switch in CALIBRATE position, sensor toggle switch in DOWN position, and deflection multiplier in CAL position. Adjust calibrator control frequency to 8 cps.
3. Place sensor selector switch to position 1 and adjust sensor 1 trim knob so that the deflection meter reads at the CAL position. Lock sensor 1 trim knob.
4. Place sensor selector switch to position 2. Adjust and lock sensor 2 trim knob. Similarly, adjust sensors 3 and 4. Turn off sensor selector switch.
5. Replace one of sensors in the calibrator with sensor 5 and adjust sensor 5 using the same procedure as used for sensors 1 through 4.
6. Recheck frequency meter and readings for the sensors in calibrator. Place sensor toggle switch in UP position.
7. Disconnect and stow the calibrator.

Test Section Measurements

1. Place identification of section, date, etc., on Dynaflect data sheet (see Fig. A-1).
2. Screw triangular bases on sensors and connect the sensors to the sensor carriage.
3. Place frequency toggle switch to OPERATE position and force toggle switch to DOWN position.
4. Pull onto pavement and center on outer wheel path.
5. Drive to first test point.
6. Place sensor switch in DOWN position and adjust frequency to 8 cps.
7. Place sensor selector switch in position 1 and adjust multiplier switch for maximum reading. Record deflection meter reading and multiplier switch setting on data sheet. Repeat procedure for sensors 2 through 5.
8. Place sensor switch in UP position.
9. Repeat steps 5 through 8 for test points 2 through 10.
10. Drive off pavement and place force switch in UP position.
11. Turn off power switch, and disconnect and stow sensors.

TEMPERATURE MEASUREMENT PROCEDURE

Described in this section is the procedure used to obtain sub-surface temperature measurements. Thermocouples were made with copper and constantan wires. Connection to thermocouples for measurement was made to a stationary connector located on the highway shoulder (see Fig. 20). A reference thermocouple was attached to the probe of a standard thermometer, which was inserted into a tube of grease located inside the vehicle to provide a relatively steady reference temperature during reading of thermocouples. The thermocouples were read with a Leeds and Northrup potentiometer.

Thermocouple temperature data are included on the Dynaflect field data sheet shown as Figure A-1.

1. Upon arrival at test point 3, plug thermocouple lead from potentiometer into connector on highway shoulder.
2. Place the surface thermocouple lead on the pavement with the surface probe in contact with the pavement.
3. Record air temperature, reference temperature, and reference junction potential (use standard copper-constantan potential table).
4. Read and record potential difference between reference junction and all thermocouples.
5. Algebraically add the reference junction potential and each thermocouple potential difference. Obtain temperatures from standard potential table and record.
6. Repeat steps 1 through 5 for test point 8.

Texas Transportation Institute
Pavement Design Department
November, 1966

DYNAFLECT DATA SHEET (Project 1-5(2))

Section 1 Area Rochester Hour 11:40 A.M. Day 11 Month Oct Year 67

Highway S.H. 30 Direction of Travel West Measured by R.P.

Subs. Code ________ (1=1 First; 2=2 First) Class. Code 1 (1=Light Design; 2=Heavy Design)

Station*	Sensor No. 1 Read	Mult	Def	Sensor No. 2 Read	Mult	Def	Sensor No. 3 Read	Mult	Def	Sensor No. 4 Read	Mult	Def	Sensor No. 5 Read	Mult	Def
1	3.7	.3	1.11	8.5	.1	.85	4.8	.1	.48	3.5	.1	.35	7.8	.03	.23
2	4.9	.3	1.47	3.6	.3	1.08	6.3	.1	.63	4.5	.1	.45	3.3	.1	.33
3	5.0	.3	1.50	3.2	.3	.96	4.3	.1	.43	9.8	.03	.29	6.4	.03	.19
4	4.3	.3	1.29	8.6	.1	.86	4.6	.1	.46	3.3	.1	.33	7.4	.03	.22
5	5.7	.3	1.71	3.6	.3	1.08	5.5	.1	.55	4.0	.1	.40	9.5	.03	.29
6	6.5	.3	1.95	4.4	.3	1.32	7.6	.1	.76	5.7	.1	.57	4.3	.1	.43
7	4.6	.3	1.38	3.3	.3	.99	5.9	.1	.59	4.2	.1	.42	9.8	.03	.29
8	5.0	.3	1.50	3.5	.3	1.05	5.8	.1	.58	4.0	.1	.40	8.8	.03	.26
9	4.3	.3	1.29	3.2	.3	.96	6.1	.1	.61	4.3	.1	.43	9.4	.03	.28
10	6.3	.3	1.89	4.5	.3	1.35	8.1	.1	.81	5.8	.1	.58	4.2	.1	.42

Average 1.509

	Ref. Temp	Ref. MV	1 Air	2 MV	2 Temp	3 MV	3 Temp	4 MV	4 Temp	5 MV	5 Temp	6 MV	6 Temp	7 MV	7 Temp	8 MV	8 Temp	9 MV	9 Temp
1	72	.88	39	.41	54	.40	54	.33	57	.21	63	.11	67	.06	69	.07	69	.08	69
2	74	.92	39	.42	55	.45	54	.36	58	.30	61	.16	67	.14	68	.15	67	.19	65

Sensor No.	Distance from Load	Temp	Distance below Surface	REMARKS:
1	0	1	Air	
2	1 ft.	2	0.0 ft.	
3	2 ft.	3	0.5 ft.	
4	3 ft.	4	1.5 ft.	
5	4 ft.	5	2.5 ft.	
		6	3.5 ft.	
		7	4.5 ft.	
		8	5.5 ft.	
		9	6.5 ft.	

*Numbered in direction of traffic.

Figure A-1. Typical Dynaflect data sheet.

BENKELMAN BEAM MEASUREMENT PROCEDURE

Described in this section is the procedure used to obtain Benkelman Beam measurements of the rebound deflection produced in a pavement by an 18-kip axle load. Within each section, measurements were made at 10 test points in the outer wheel path.

1. Place identification of section, date, etc., on Benkelman Beam data sheet.
2. Pull onto pavement aligning the right-hand wheels with the test points in the outer wheel path.
3. Stop the truck with the rear axle approximately 4.5 ft behind the first test point.
4. Insert the movable part of the Benkelman Beam between the dual wheels, resting the toe of the probe on the test point.
5. Adjust the legs so that the plunger of the beam is in contact with the stem of the dial gauge.
6. Switch on the stabilizing buzzer and make the initial reading.
7. Move the truck slowly forward, making the maximum reading as the rear wheels pass the Beam's toe of probe.
8. Make the final reading when the rear axle has passed the toe of the probe by at least a distance of 10 ft, and the rate of recovery of the pavement is ≦0.001 in./min.
9. Repeat steps 3 through 8 for test points 2 through 10.
10. The rebound deflections at each test point are twice the difference between the maximum and final readings expressed in milli-inches of probe rebound motion.

CURVATURE METER MEASUREMENT PROCEDURE

Described in this section is the procedure used to measure the curvature of the pavement surface adjacent to a 9-kip wheel load, by means of the curvature meter shown in Figure A-2. Within each section, measurements were made at 10 test points in the outer wheel path.

1. Place identification of section, date, etc., on curvature meter data sheet.
2. Pull onto pavement, aligning the right-hand wheels with the test points in the outer wheel path.
3. Stop the truck with the dual wheels centered on the first test point.
4. Place the curvature meter longitudinally approximately 1 in. from the side of the outer wheel with the dial centered on the axle hub.
5. Switch on the stabilizing buzzer and make the initial reading.
6. Move the truck slowly forward, making the final reading when the rear axle has moved at least 10 ft past the test point, and the recovery of the pavement is ≦0.001 in./min.
7. Repeat steps 3 through 6 for test points 2 through 10.
8. The curvature of each test point is the difference between the initial and final readings expressed in milli-inches.

PLATE BEARING TEST PROCEDURE

Described in this section is the procedure used to perform the plate bearing tests (load on a 12-in. diameter plate

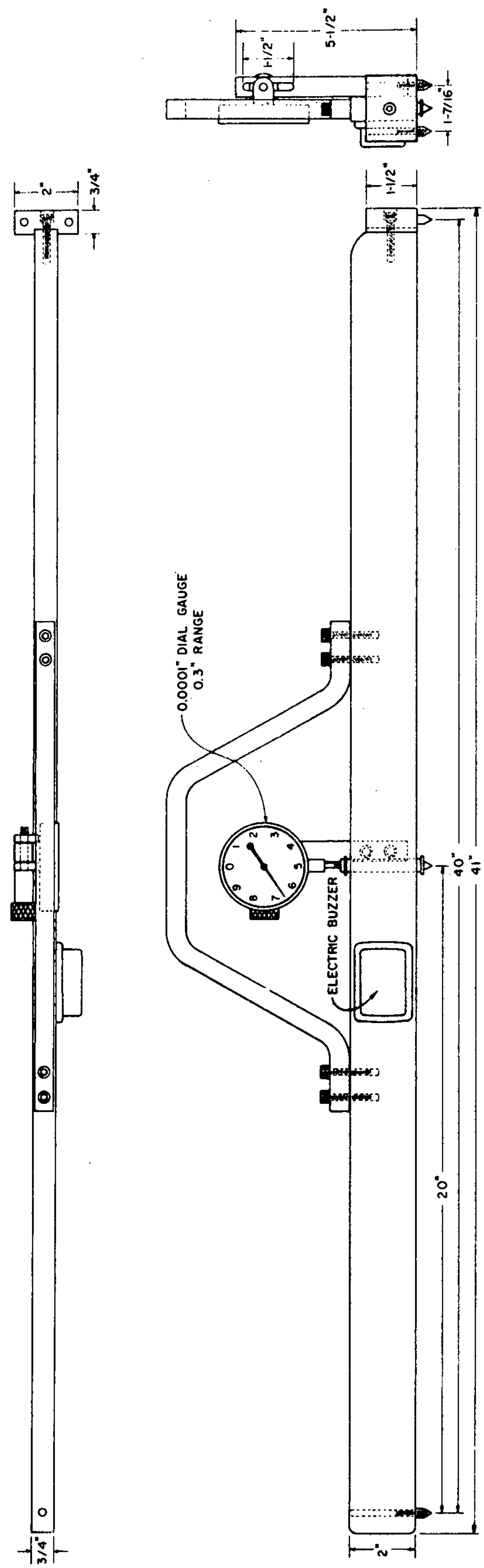

Figure A-2. Curvature meter designed by B. F. McCullough of the Texas Highway Department.

Rev. 8-30-62

Form 24162

MINNESOTA DEPARTMENT OF HIGHWAYS
MATERIALS AND RESEARCH SECTION

PLATE BEARING TEST SHEET

Depth	BORING DATA

S.S. No. or Inv. No. 300 DATE 25 Aug 67

S.P. ______ T.H. 30

T.P. Sec. 1 LOCATION Stewartville

12" PLATE ON mat

TEMPERATURE: MAT 86 AIR 78

SURF. COND. good

Test Pt. 8

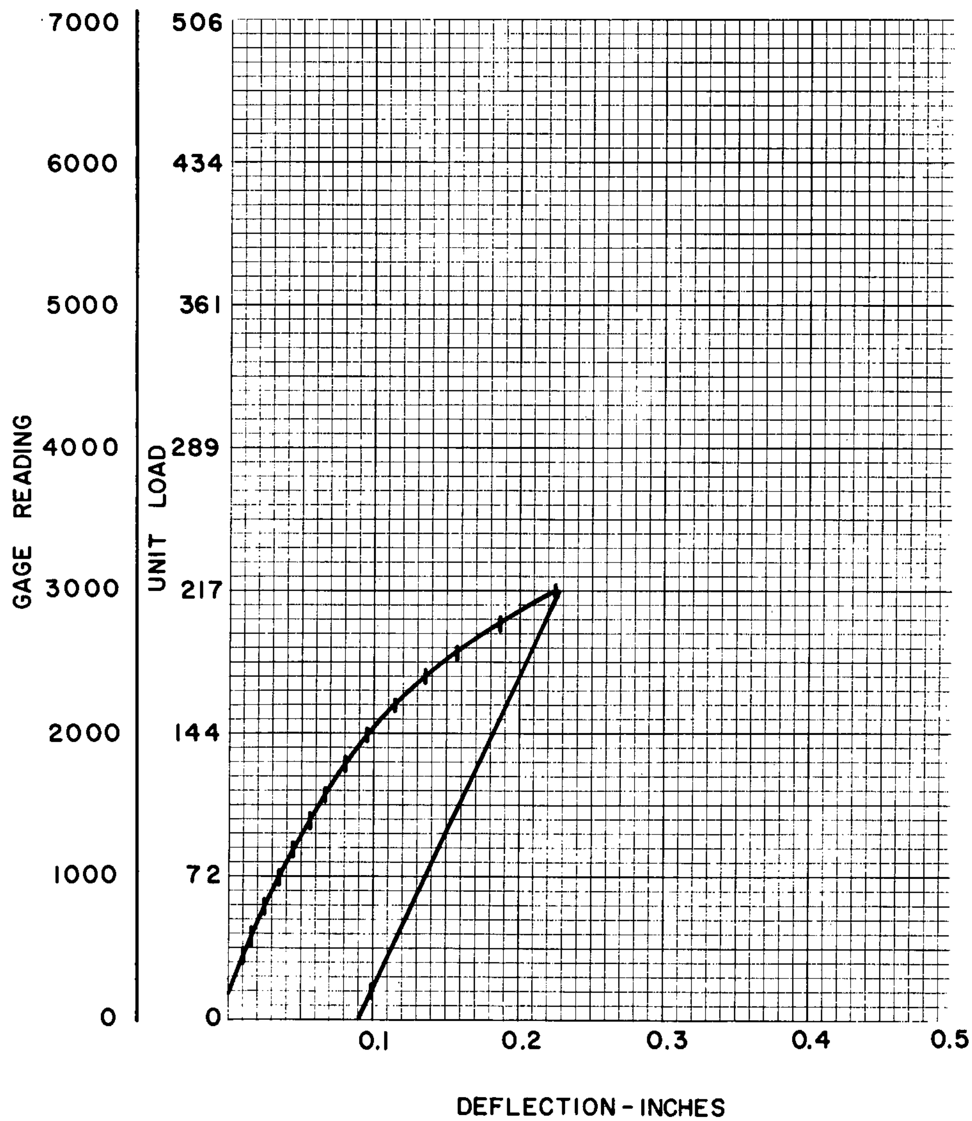

Figure A-3. Typical plate bearing data sheet.

required to deflect the pavement 0.2 in.). Measurements were made at 2 of the 10 test points in the outer wheel path of each test section. Figure A-3 is an example of a typical field data sheet. Each load gauge unit represents approximately 8.2 lb.

1. Place identification of section, date, etc., on the data sheet.
2. Pull the truck onto pavement and center on the outer wheel path.
3. Stop the truck with the hydraulic load jack centered on test point 3.
4. Seat the 12-in. diameter plate on the test point using silica sand.
5. Lower the load jack until it contacts the plate.
6. Place the deflection dial stand firmly on the highway shoulder so that deflection dial can be approximately positioned on the loading jack plunger.
7. Load the plate to a load gauge reading of 200 (approximately 1.6 kips); switch on the stabilizing buzzer; then zero the deflection dial.
8. Load the plate in increments of 200 units (approximately 1.6 kips) until a deflection dial reading of 0.2 in. is obtained; plot the load gauge reading versus the deflection dial reading on the data sheet after each load increment.
9. Repeat steps 3 through 8 for test point 8.
10. The plate bearing results at each test point is the total load required to produce a deflection dial reading of 0.200 in. (gauge dial reading times 8.175 lb for apparatus used here).

APPENDIX B

SECTION DATA

In the graphs which follow (Figs. B-1 through B-24) the following variables are shown plotted versus time:

1. Dynaflect deflection (w_1).
2. Surface Curvature Index ($w_1 - w_2$).
3. Depth of material found to be at a temperature of 32° F or less.
4. Prevailing single-axle load limit imposed by the state.

Each plotted point on the deflection and SCI curves is the average of ten observations made at the ten test points shown in Figure 19. The dashed portions of these two curves, and of the frost penetration curve, represent estimates made from air temperature data for periods during which the testing crew was absent from the section and the temperature oscillated above and below 32° F. This occurred principally in Study Area 1.

In Study Area 1 no restrictions were placed on axle loads; thus, the load-limit graphs for this area appear in the figures as a horizontal line. In Study Area 2 the gross load, rather than the axle load, was limited during the critical periods, and for this area the equivalent axle load limit was estimated at 75 percent of the gross load limit and plotted in the figures. In Study Areas 3 and 4 the restrictions imposed by the state were on axle load, and these are shown in the figures.

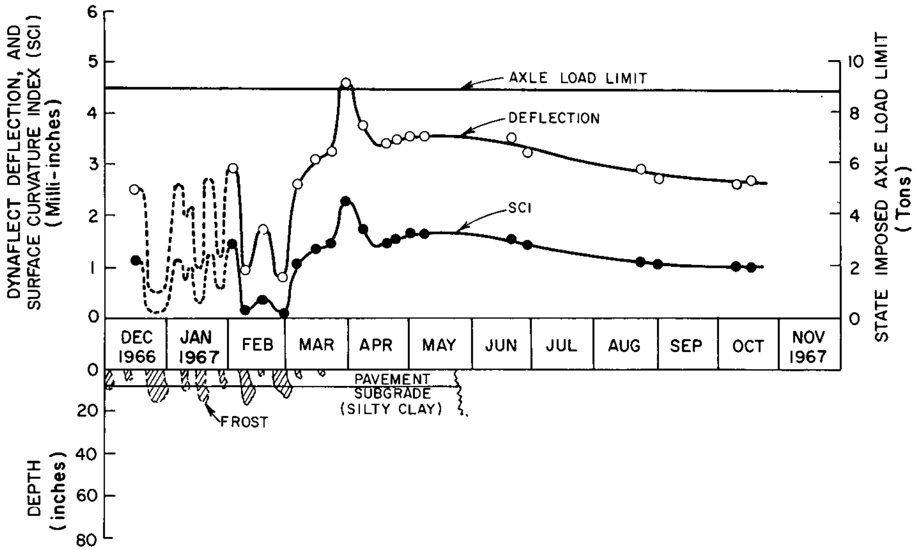

Figure B-1. Area 1, Section 19.

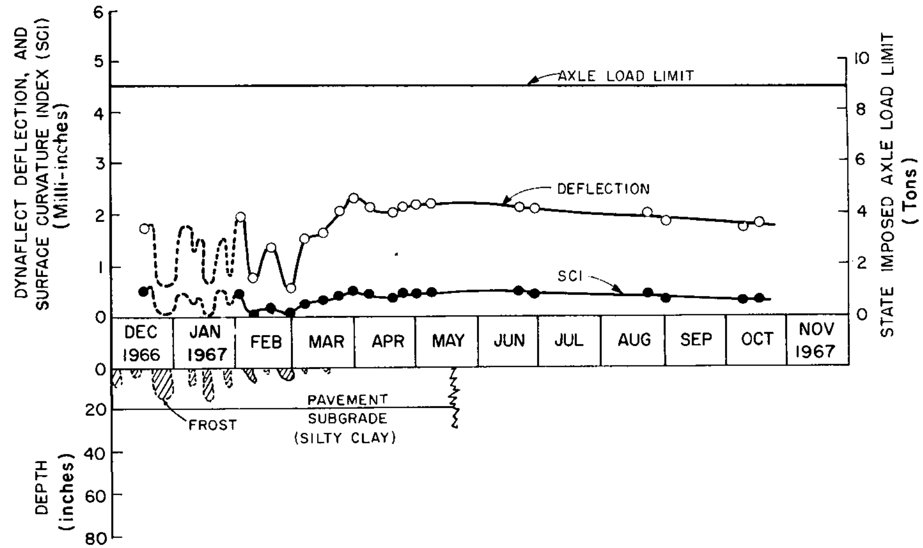

Figure B-2. Area 1, Section 20.

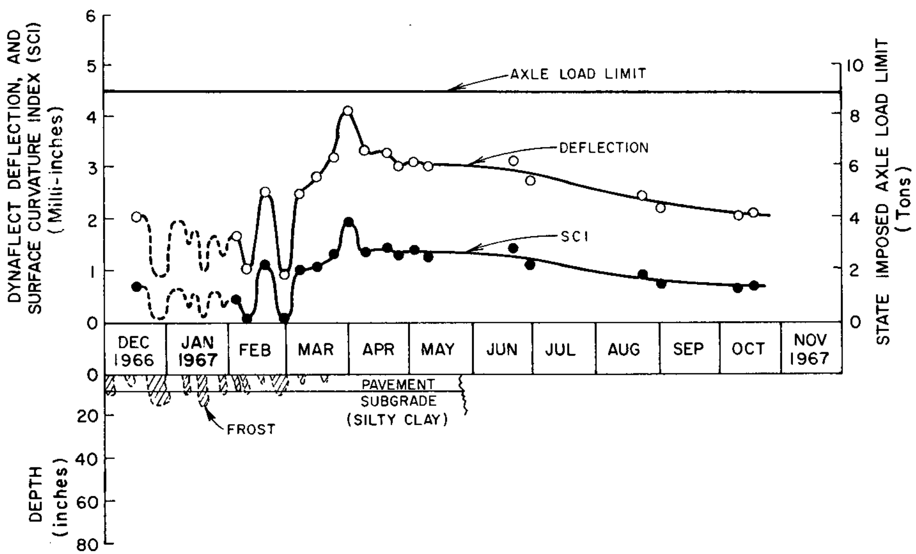

Figure B-3. Area 1, Section 21.

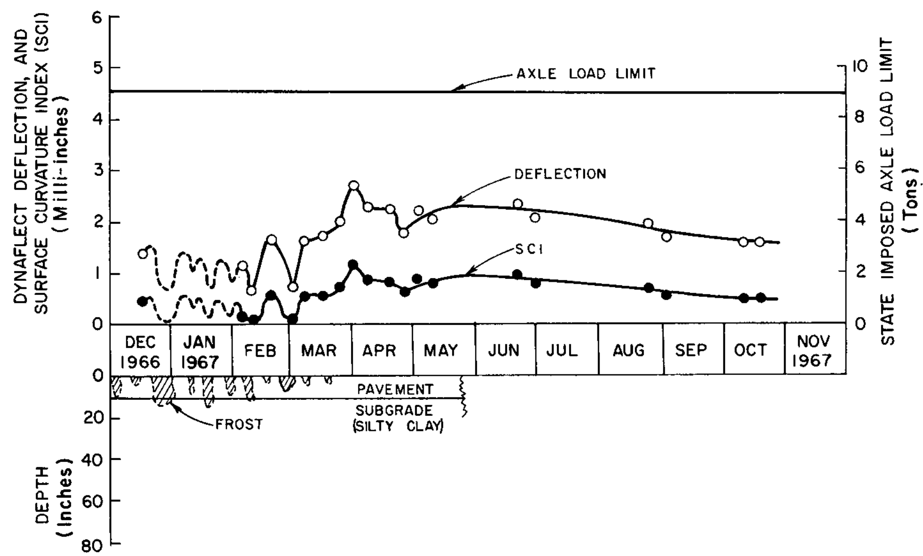

Figure B-4. Area 1, Section 22.

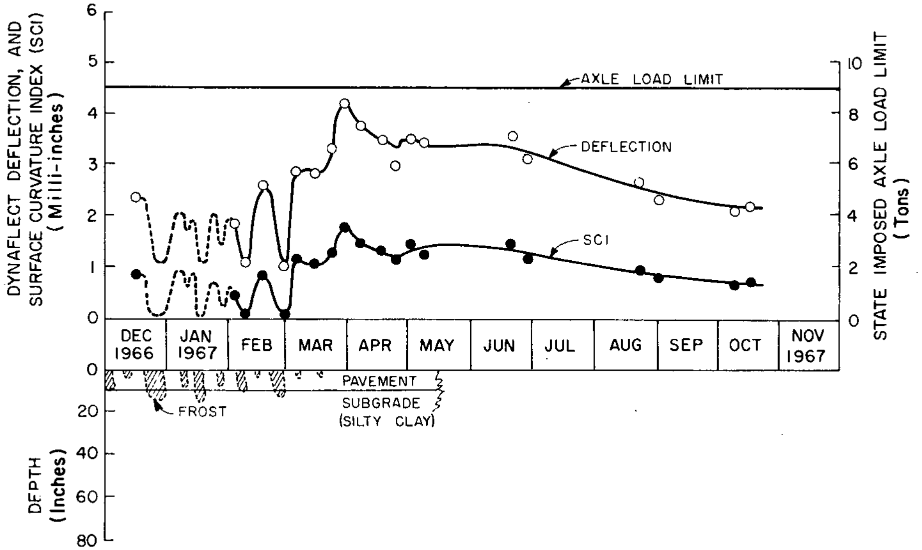

Figure B-5. Area 1, Section 23.

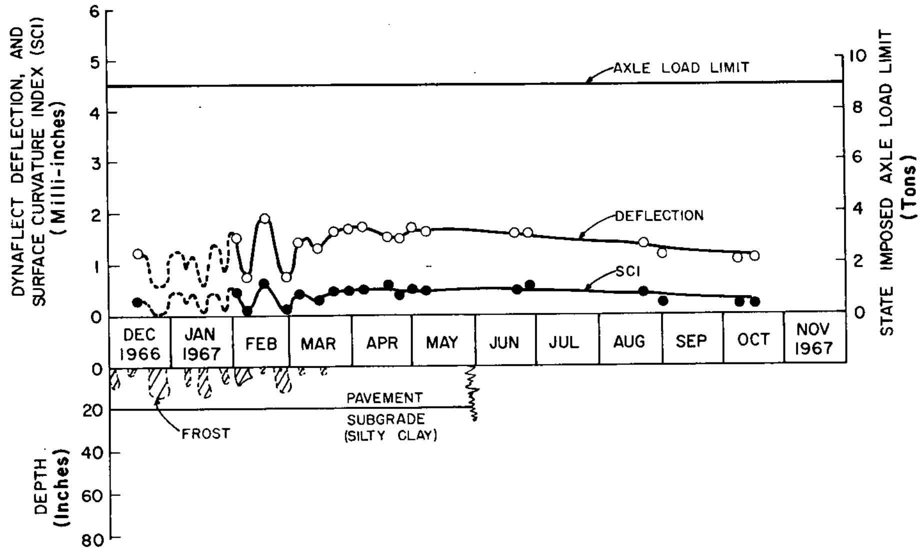

Figure B-6. Area 1, Section 24.

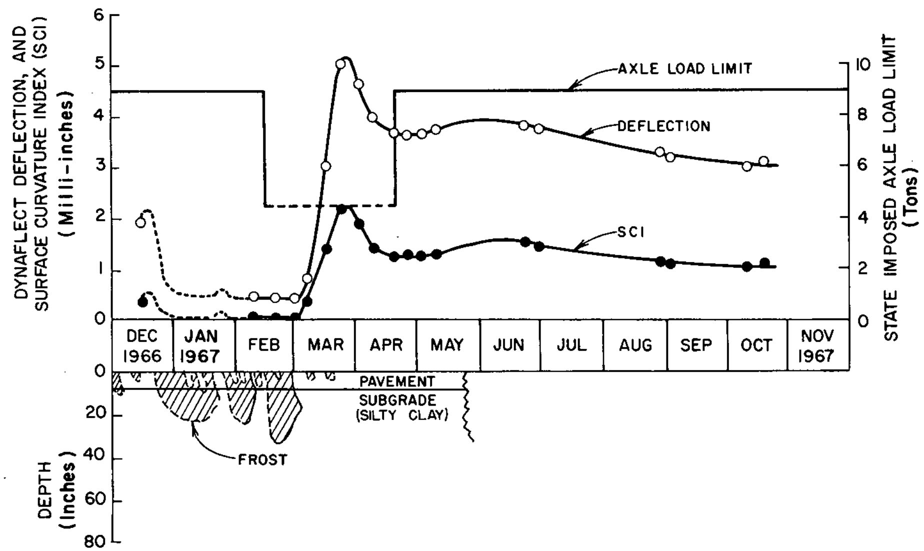

Figure B-7. Area 2, Section 13.

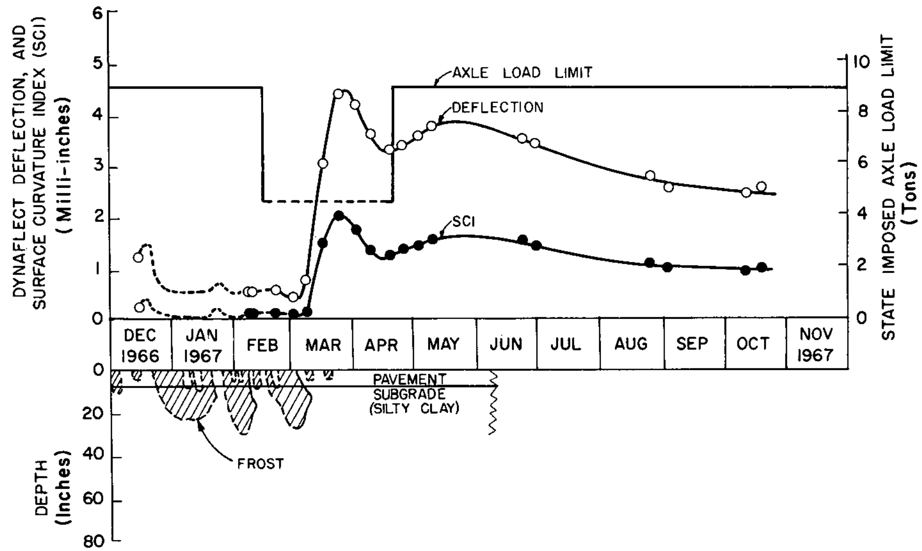

Figure B-8. Area 2, Section 14.

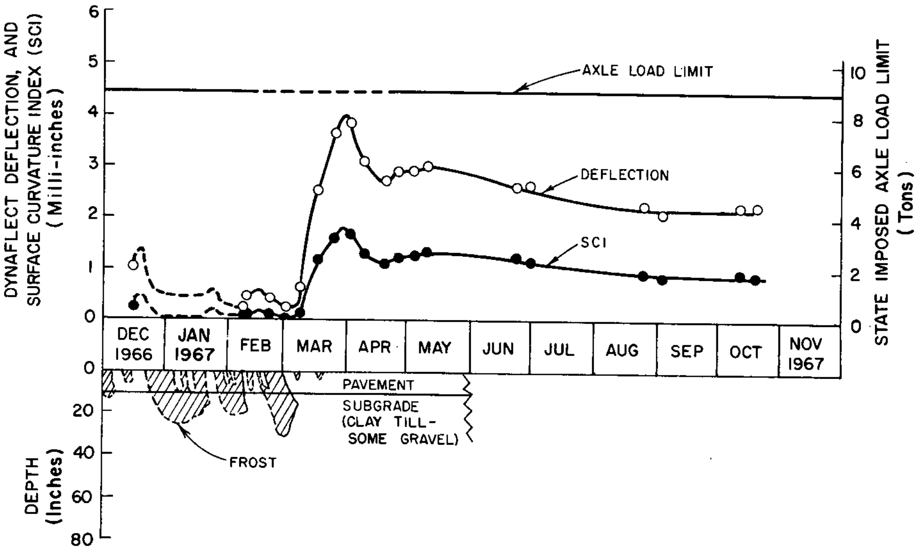

Figure B-9. Area 2, Section 15.

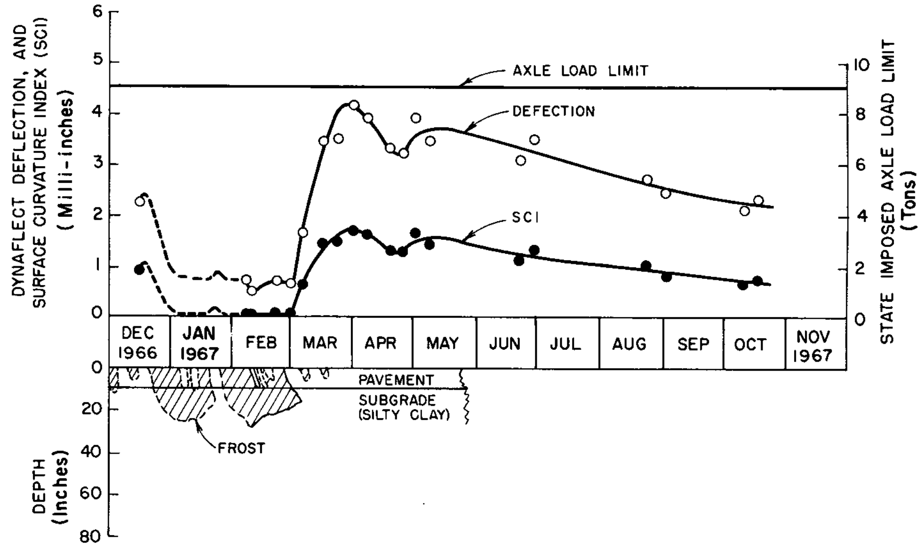

Figure B-10. Area 2, Section 16.

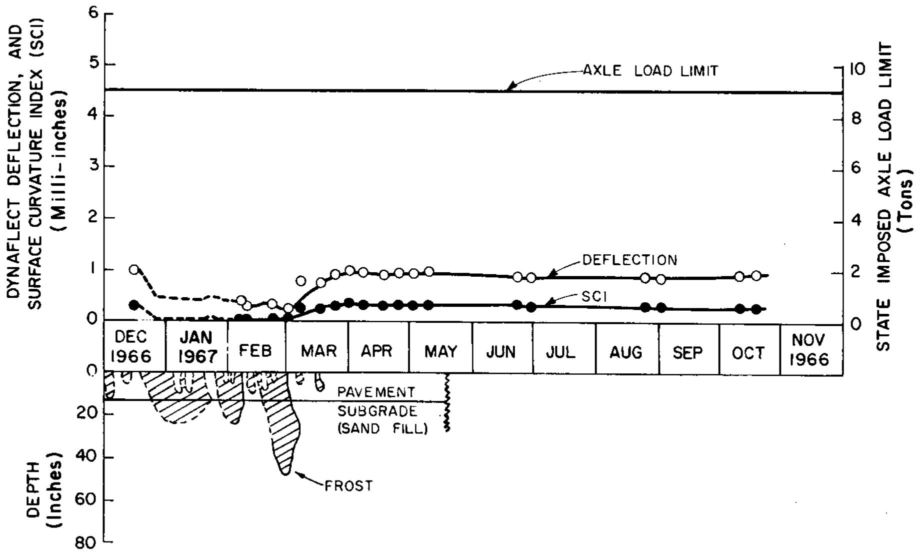

Figure B-11. Area 2, Section 17.

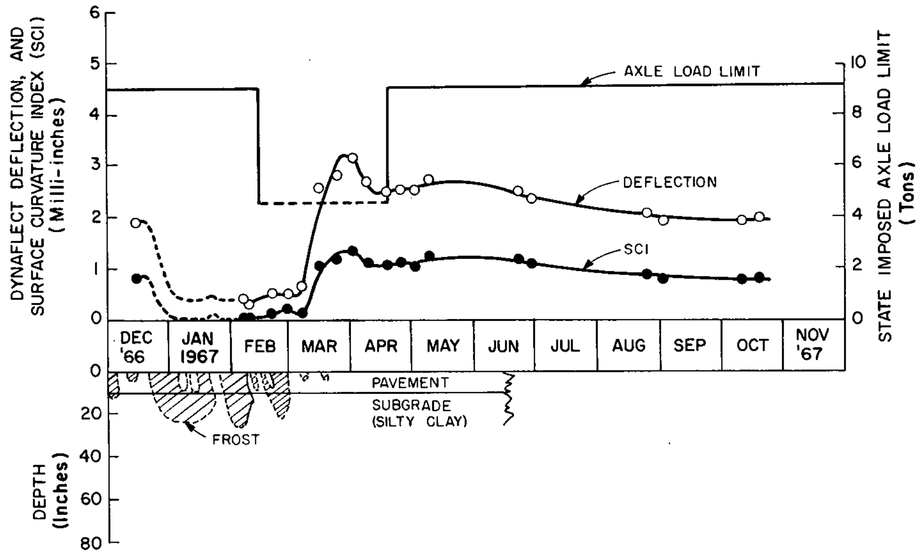

Figure B-12. Area 2, Section 18.

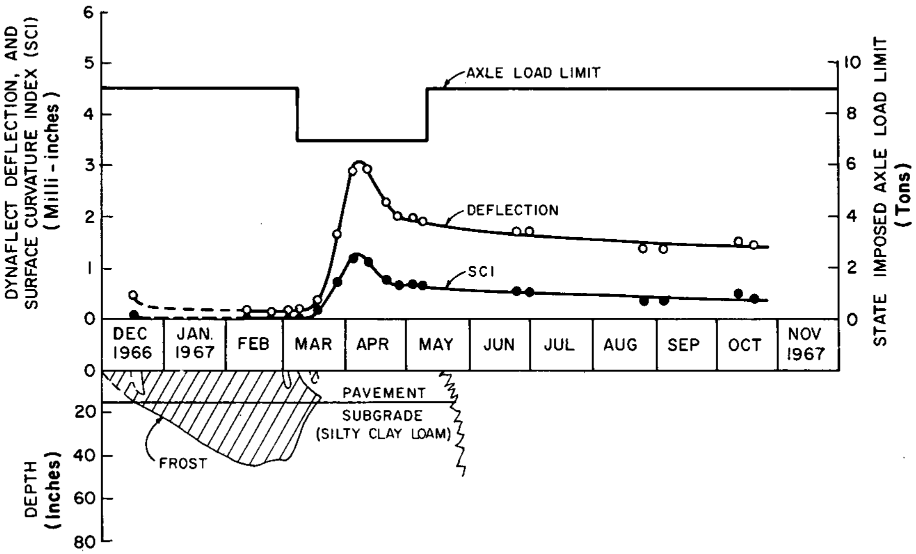

Figure B-13. Area 3, Section 1.

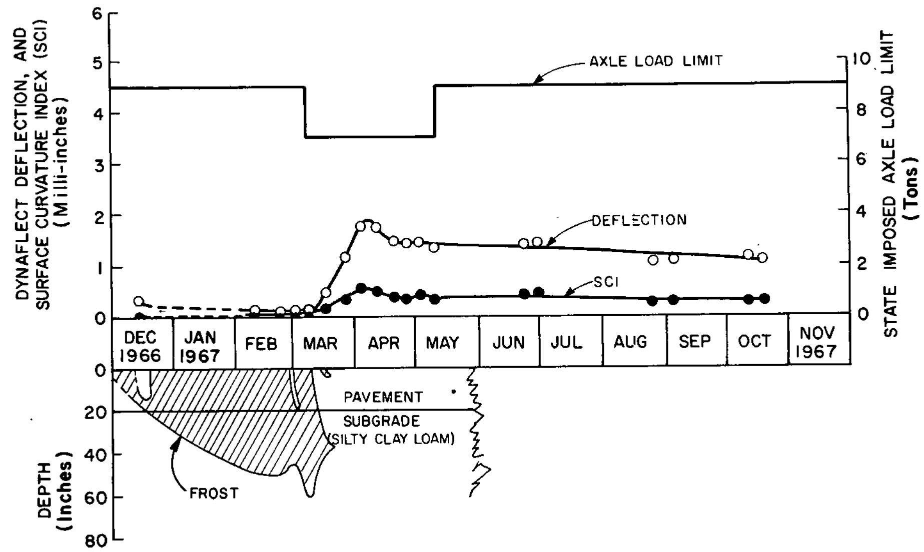

Figure B-14. Area 3, Section 2.

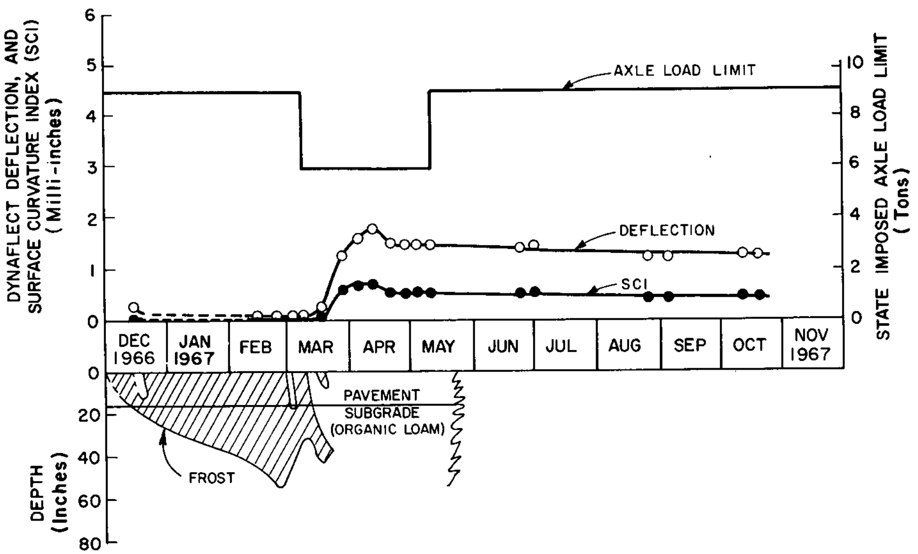

Figure B-15. Area 3, Section 3.

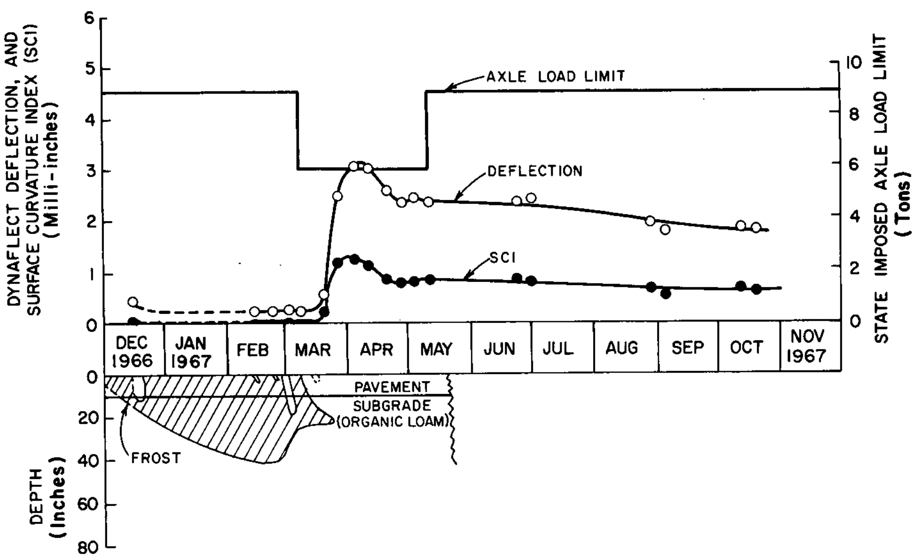

Figure B-16. Area 3, Section 4.

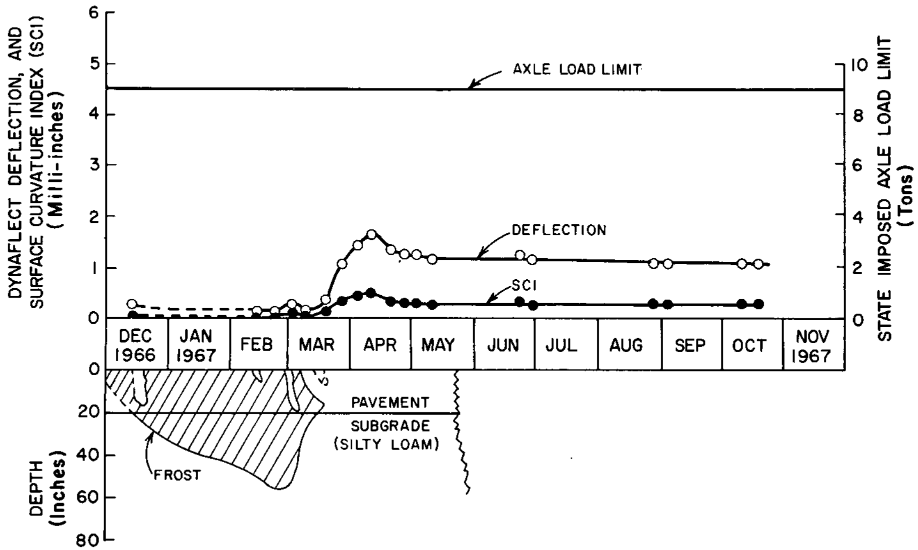

Figure B-17. Area 3, Section 5.

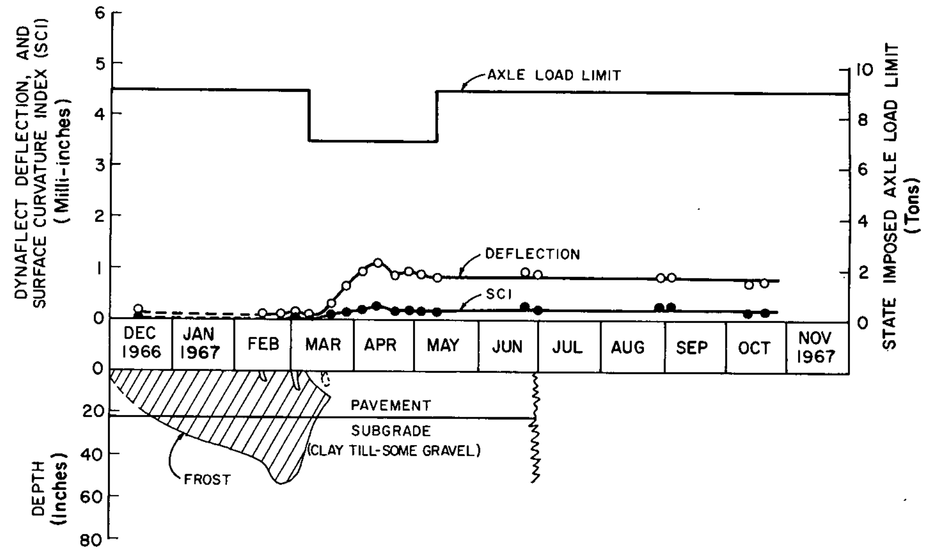

Figure B-18. Area 3, Section 6.

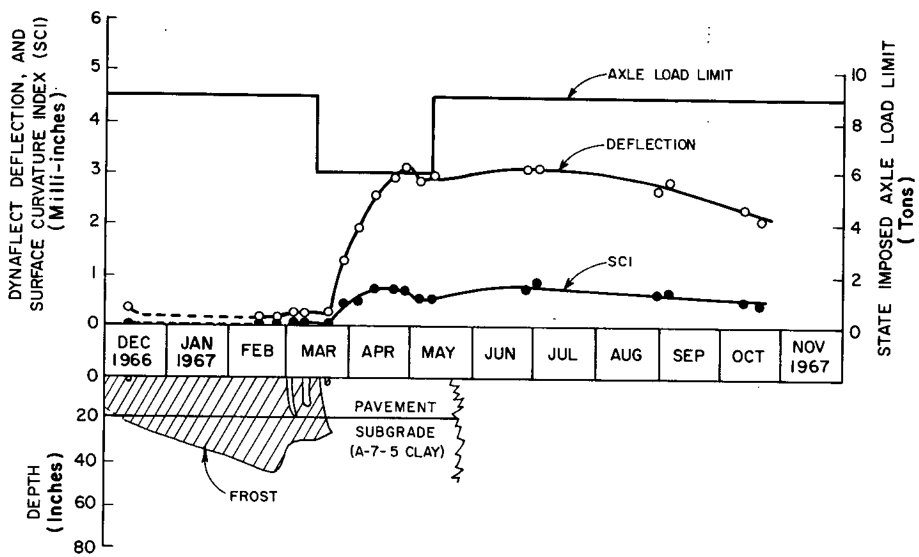

Figure B-19. Area 4, Section 7.

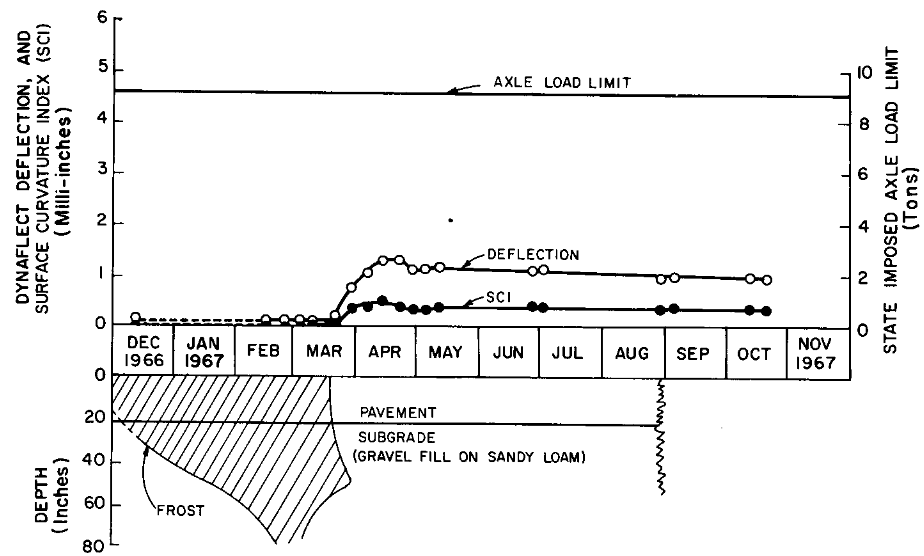

Figure B-20. Area 4, Section 8.

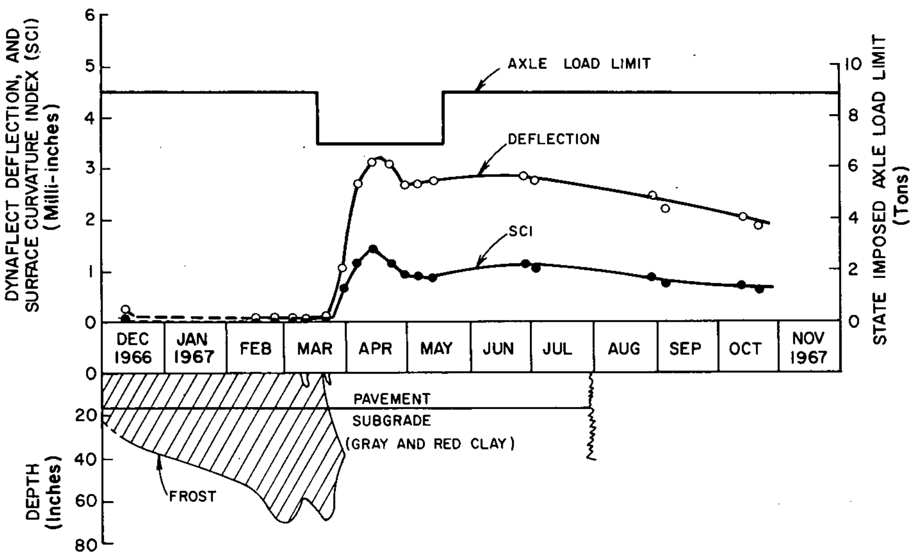

Figure B-21. Area 4, Section 9.

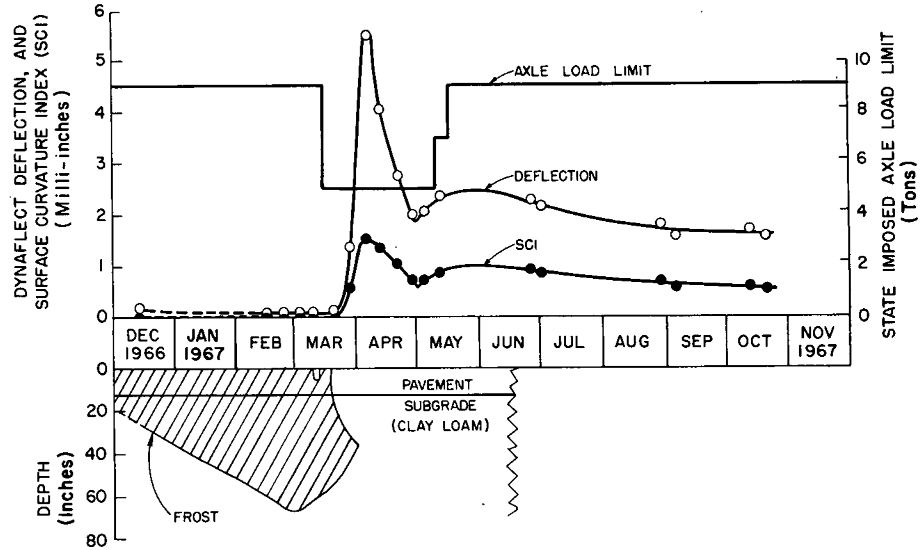

Figure B-22. Area 4, Section 10.

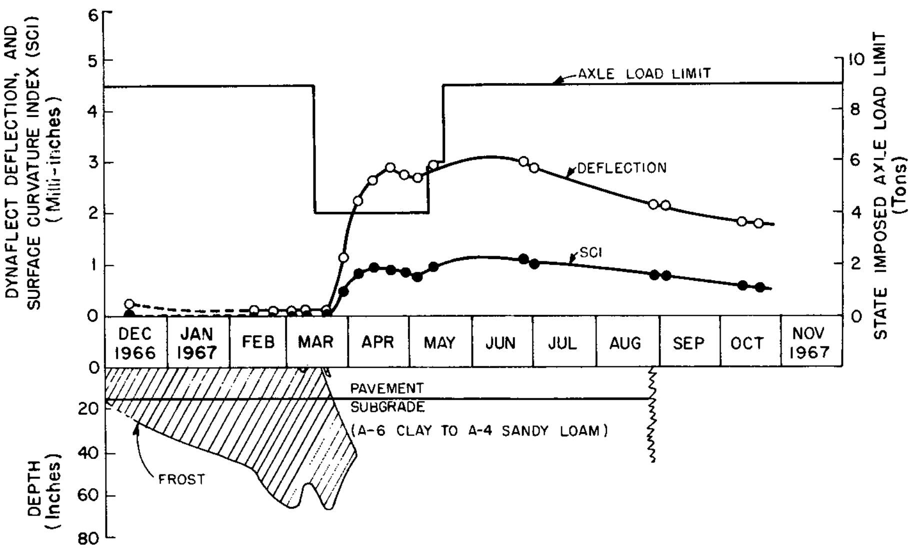

Figure B-23. Area 4, Section 11.

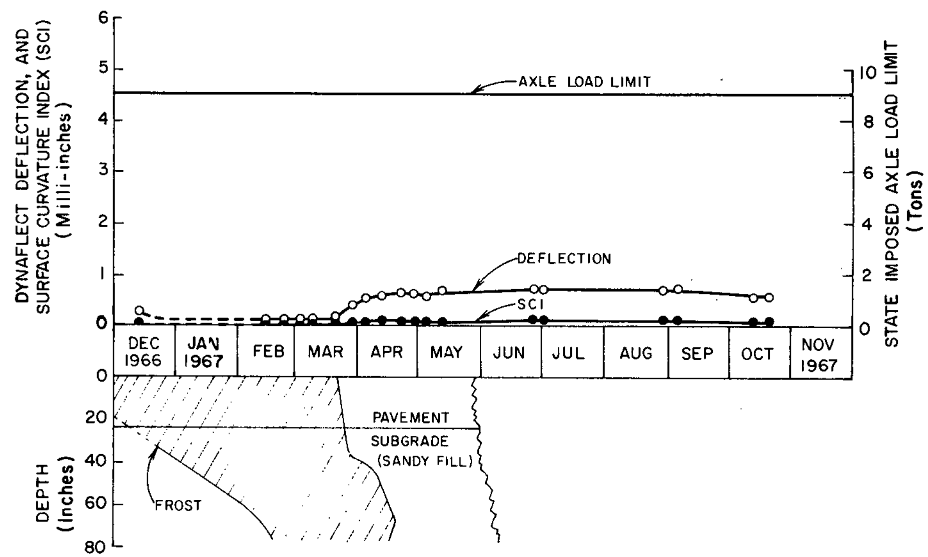

Figure B-24. Area 4, Section 12.

APPENDIX C

MAYS ROAD METER

The Mays Road Meter is a simple roughness recorder which gives an output of both cumulative roughness of a section and a chart on which a running record of the roughness is drawn graphically. A typical chart for a 0.2-mi section is shown in Figure C-1. The device may be mounted in the trunk of any automobile (preferably one which has coil springs on the rear axle) and may be operated by any individual who has had a minimum training period of one to two hours.

The device, mounted in the trunk of an automobile, is shown in Figure C-2. The two controls which are located in the front floorboard are shown in Figure C-3. In Figure C-4 an exploded view of the device is shown. In the following description of the operation of the instrument the letters referred to are those that are circled on Figure C-4.

The primary function of the instrument is to obtain a number which will approximate the roughness of a road surface in inches departure from the mean grade line. This is done by accumulating the changes of the vertical distance from car body to the differential housing which occurs as the car travels over any uneven surface. This changing distance, hereafter called the *X* motion, is transmitted to Pulley B by Cable A, which is fastened to the center of the differential housing. Pulley B has two functions: (1) to cause recording pen (C) to move left or right in direct proportion to the up or down *X* motion; and (2) to advance the paper tape, through use of a one-way clutch (D), in direct proportion to all upward components of the *X* motion.

The resulting record may be interpreted in two different ways. The length of the trace on the paper tape is easily converted to inches per mile roughness by multiplying the length of tape produced on a 1-mi section by 8, or on a 2/10-mi section by 40 (8 is the ratio of the paper chart drive to motion *X*). Also, since the pattern of roughness is shown by the recording pen, the severity of roughness in selected areas may be interpreted by marking these areas on the chart with the event marker (E). This event marker causes the recording pen to make a full excursion on the graph. The device is designed to be operated at a speed of 50 mph which enables measurements to be made without disrupting traffic flow.

Replicate runs were made on 18 sections near Austin, Texas, with a replication error of less than 3 percent. These sections were also rated by a panel of 19 members. An analysis was made of the Mays Road Meter data versus the panel rating using standard regression techniques. The results of this regression are shown in Figure C-5.

Specifications and procurement information may be obtained from Mr. Ivan K. Mays, File D-8, Texas Highway Department, Austin, Texas.

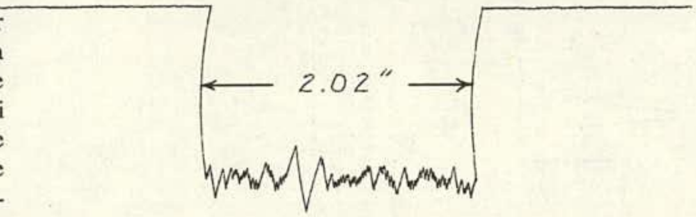

Figure C-1. Typical chart produced by 0.2-mi section of flexible pavement. The distance between beginning mark and end mark, 2.02 in., when multiplied by 40, gives a Roughness Index of 80.8 in. per mi.

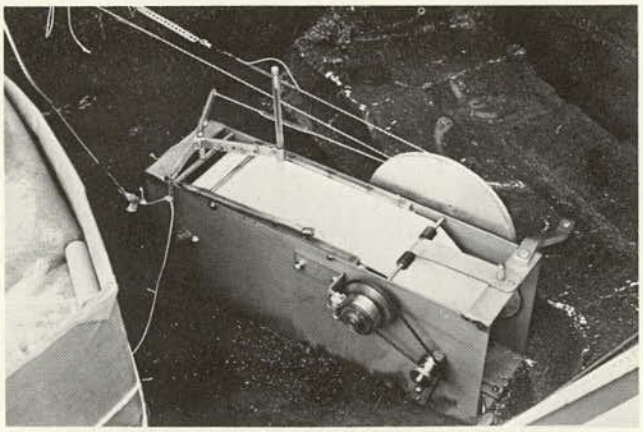

Figure C-2. Mays Road Meter mounted in trunk of automobile. Three cables extending to the left lead to the differential, the on-off lever, and the event marker.

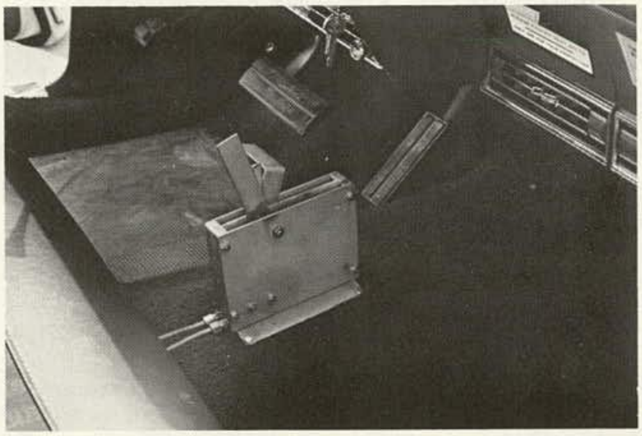

Figure C-3. The two controls of the Mays Road Meter. The straight lever is the on-off control; the L-shaped lever, the event marker.

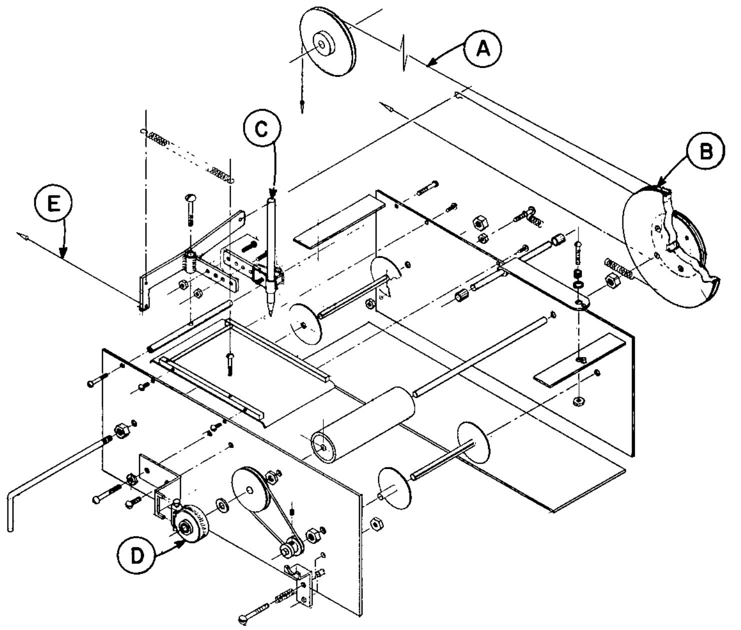

Figure C-4. The Mays Road Meter (patent applied for).

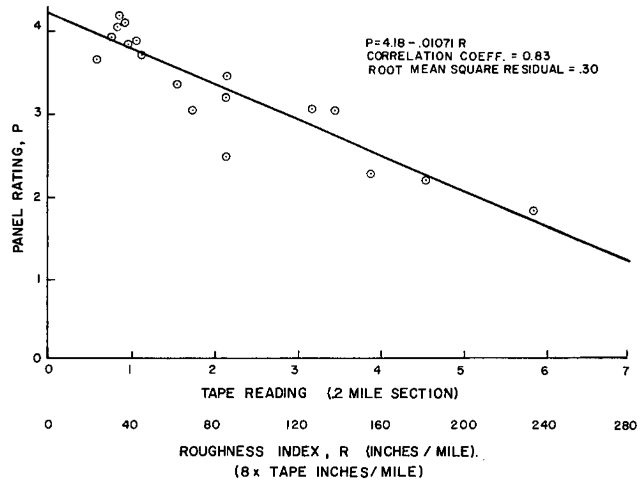

Figure C-5. Plot of panel rating, P, *vs Mays Road Meter chart readings, and regression results.*

APPENDIX D

ANALYSES OF VARIANCE FOR DETERMINING RELATIVE SENSITIVITY OF THE MEASURING SYSTEMS

INSTRUMENT OR TEST	VARIABLE ANALYZED	SOURCE OF VARIATION	SS	DF	MS	F	STD. DEV.
Dynaflect	w_1 (mils)	Total	164.282	239			
		Between sets	153.914	23	6.692	139.4	
		Within sets	10.368	216	0.04800		0.22
Dynaflect	SCI (mils)	Total	31.6496	239			
		Between sets	29.5682	23	1.286	133.4	
		Within sets	2.0814	216	0.009636		0.10
Curvature meter	Curvature (mils)	Total	26194.7	239			
		Between sets	22275.0	23	968.5	53.4	
		Within sets	3919.7	216	18.15		4.26
Benkelman beam	Deflection (mils)	Total	89142.8	239			
		Between sets	75743.8	23	3293.0	53.1	
		Within sets	13399.0	216	62.03		7.88
Plate bearing	Bearing value (kips)	Total	490.205	19			
		Between sets	433.716	9	48.19	8.53	
		Within sets	56.489	10	5.649		2.38

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* Highway Research Board Special Report 80.

Rep. No.	*Title*
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P. O. Box 7129
~~Boise,~~ Idaho 83707