The AASHO Road Test

Report 7

Summary Report

By the

HIGHWAY RESEARCH BOARD

of the

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Preface

The AASHO Road Test was conceived and sponsored by the American Association of State Highway Officials as a study of the performance of pavement and bridge structures of known characteristics under moving loads of known magnitude and frequency. It was administered by the Highway Research Board of the National Academy of Sciences—National Research Council, and was considerably larger and more comprehensive than any previous highway research study.

This is the last of a series of seven major reports on the AASHO Road Test. The first six are technical reports in which the project is described in considerable detail, the pertinent research data are discussed and summarized, and the findings are presented. A list of the reports in this series is given on page ii.

Efforts to summarize a project of the magnitude and scope of the AASHO Road Test are destined to result in a rather extensive report if attention is given to the important features of the project, to the findings, and to the qualifications that necessarily apply to the findings. This is such a report. The intent has been to include sufficient detail so that the technical or semi-technical reader may have a rather thorough understanding of the project and its findings. The rationale by which conclusions were reached and the data supporting the conclusions are not included. The reader who wishes to extend his knowledge of any phase of the project is referred to the appropriate technical reports of the series.

For the reader who wishes to have a very brief view of the project, a still further abridged summary of the principal objectives and findings is included as Chapter 1.

Acknowledgments

In addition to the men who served on the National Advisory Committee, hundreds of others on AASHO and Highway Research Board committees and advisory panels, on the project staff, in the Army Support Group, the Illinois Division of Highways, the Bureau of Public Roads, the automotive, petroleum, tire, cement and steel industries, and the technical observer group contributed to the AASHO Road Test. Undoubtedly, the country's foremost authorities in the various fields of interest were represented on these committees and panels and among the various consultants. Names of these persons are listed in the appropriate reports of this series.

Many organizations, industrial firms, and institutions of higher learning assisted in carrying out the AASHO Road Test by assigning personnel for various facets of the study. It is impractical to list the names of all individuals who participated. However, the efforts of the following organizations are particularly acknowledged:

The Bureau of Public Roads of the U. S. Department of Commerce, together with the Department of Defense, for technical advice and services in a great many areas.

The Illinois Division of Highways for technical advice and services of personnel from its headquarters in Springfield and District 3 office in Ottawa, and for providing its resident task force.

The Minnesota Department of Highways and the Indiana State Highway Department for extensive cooperation and assistance to the Performance Rating Panel.

Purdue University, the University of Illinois, and Lehigh University for technical advice and services.

The Portland Cement Association, The Asphalt Institute, and the several States for participation in materials testing programs.

The following organizations for the services of resident observer-consultants: The Asphalt Institute; the Portland Cement Association; the American Trucking Associations; the Canadian Good Roads Association; the Department of Highways, Province of Ontario, Canada; and the German Highway Research Board.

The American Petroleum Industries for technical advice and services.

General Motors Corporation for equipment, personnel, and technical advice in performing skid resistance experiments.

Shell Oil Company for equipment, personnel, and technical advice in dynamic testing of flexible pavements.

Contents

THE AASHO ROAD TEST

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Summary Report

Chapter 1

Condensed Summary of Principal Objectives and Major Findings

This chapter consists of a very brief summary of the principal objectives of the AASHO Road Test and the findings that relate to these objectives. More detailed summaries will be found in later chapters of this report.

The AASHO Road Test near Ottawa, Illinois, was conducted over a two-year period to provide research data useful in the design of efficient highways at economical cost for highway engineers. The Road Test was composed of separate major experiments: one relating to flexible pavement with asphalt concrete surfacing, one to rigid pavement with concrete surfacing, one to short-span bridges with steel beams and one to short-span bridges with concrete beams.

Construction of the specially-constructed test facilities began in August 1956, and test traffic was started on October 15, 1958. Ten lanes were tested under controlled loading ranging from 2,000-lb single-axle loads in one lane to 48,000-lb tandem-axle loads in another. A total of 1,114,000 axle loads had been applied to the surviving pavement and bridges when the traffic test was completed on November 30, 1960.

The structural design of highway pavements has been based on empirical techniques, augmented in large measure by long experience of highway engineers in the design and operation of highways. The excellent pavements in the nation's highway network are evidence of the success that highway designers have achieved in the design and construction of pavements to perform their function—to provide for the safe and efficient movement of traffic. Despite this successful experience, however, it has not been known, with the desired degree of certainty, whether the pavements that have served traffic well were constructed as economically as possible, or how greater traffic volumes or heavier axle loads would affect their life expectancy.

Highway administrators have long recognized the need for scientific investigation of the relationships among various factors that are involved in the design of highway pavements including those related to the pavement structure and those concerned with the magnitude and frequency of loads. More precise knowledge of these relations will provide assurance that future highways will serve with optimum efficiency and economy. The AASHO Road Test was one important step in a farseeing program conceived by the American Association of State Highway Officials to fill some of the gaps in current knowledge.

Since the performance of a pavement under traffic is affected by a large number of variables, a single comprehensive experiment, of such scope as to produce significant results with respect to *all* the variables, would become so complex and expensive as to be wholly infeasible. If kept within reasonable bounds of size and cost but still including all variables, it would very likely produce little or no information of value concerning the effect of *any* of the variables.

In consideration of these matters the sponsors of the AASHO Road Test chose to study only a few, most important relationships. Consequently, although the project was large by usual highway research standards, it was essentially a simple test program.

No attempt was made to study innovations in highway design or construction. Rather, the intent was to provide information on conventional types of flexible and rigid pavements. Research of a different type would be needed if the purpose were to develop new kinds of pavements and to test their performance characteristics.

One of the basic concepts of the experiment was to study and evaluate the performance of pavements and bridges through failure. Since failure was thus essential to the success of the research, all bridges and a substantial portion of the test pavements were designed to fail or otherwise to show severe distress under the test traffic. The direct comparison of types of pavements or bridges was not the intent of this experiment.

Construction of the test pavements was very carefully controlled. It would not be economically feasible in normal highway construction to provide the extraordinary materials control and field inspection facilities that were considered necessary for the construction of the test pavements. Consequently, the variability in the characteristics of the various pavement components was considerably lower than could be expected in routine highway construction. However, by present-day standards the specifications for such items as strength of materials and compaction of pavement components were not extraordinarily high. To illustrate this point, the compaction of the embankment soil was specified to average 97.5 percent of the standard AASHO test value. This value was considered to represent the density for embankment material that would have been obtained in routine highway construction in 1955.

The principal objective of the pavement research in the AASHO Road Test was to establish relationships showing how performance of pavements is influenced by structural design, represented by component thicknesses of the pavement structure, and loading, represented by the magnitude and frequency of axle loads, for both rigid and flexible pavements of conventional design. The most important findings of the Road Test relate to this objective.

These findings are presented in the form of equations and graphs showing the relationships sought. The equations are given in AASHO Road Test Report 5, "Pavement Research," along with several graphical representations that show the specific effects of particular variables on pavement performance. Some of the graphs are given in Chapters 6 and 7 of this report.

Although it has long been known that pavement life is affected by many things, among which are axle loads and number of load applications, the Road Test equations show, for the first time and for the Road Test conditions, the extent to which change in performance is associated with any specific change in axle load and number of repetitions thereof. For the Road Test conditions the equations can be used to estimate the design requirements for a specified level of pavement performance when a particular load and traffic volume is used or to estimate the life of an existing pavement considering the anticipated loads and traffic volume. These relationships, therefore, can be used as a basis for improved design procedures having far greater certainty than those employed in the past. Of course, the effects of extending the range of variables that *were* included in the project, such as load repetitions or pavement thicknesses, and the effects of variables that were *not* included must be accounted for in other ways.

The relationships between load and performance, as adjusted to incorporate cost and other variables, may also serve as a basis for determining the cost of providing highways for various load classes of vehicles and thereby furnish objective information for the establishment of an equitable highway-user tax structure.

A highly important by-product of the AASHO Road Test was the development of a new concept for the evaluation of pavement performance. The level of a particular pavement's ability to serve the traveling public has been termed its *serviceability*, and it is the *trend* of serviceability with time or load applications that has been defined as pavement *performance*. When a specified minimum degree of serviceability is reached, major maintenance or reconstruction is required.

Other important findings resulting from the pavement performance study include information on the equivalencies of single and tandem axle arrangements. For any given pavement design, the equations permit the determination of the single-axle load that would bring about the same performance as a given tandem-axle load. For example, the experiments showed that for a given loss in serviceability a flexible pavement would withstand about the same number of 33,000-lb tandem-axle loads as 18,000-lb single-axle loads, or about the same number of 41,000-lb tandem-axle loads as 22,400-lb single axle loads.

Similar figures for rigid pavement are 29,000-lb tandem versus 18,000-lb single and 36,000-lb tandem versus 22,400-lb single-axle loads.

Flexible pavements lost serviceability through the development of ruts and roughness in the wheelpaths and by cracking in the asphaltic concrete surfacing, eventually requiring patching of the surface.

Appreciable rutting developed in the flexible pavement test sections under the heavy channelized test traffic. The studies showed that, on the average, 32 percent of the surface rut was due to decrease in surface thickness, 14 percent to decrease in base thickness, 45 percent to decrease in subbase thickness, and only 9 percent to a rut in the embankment material. Additional compaction or consolidation of the pavement structure under traffic apparently was responsible for only a small amount of the decreases in thickness of the layers of various materials. Thus it is assumed that a large part of the rutting was associated with the lateral movement of the material outward from the center of the wheelpath.

For the Road Test conditions the tests showed that in the design of flexible pavement 1 in. of asphalt concrete was equivalent to 3 in. of crushed limestone base, or 4 in. of sand-gravel subbase in their load-carrying abilities.

Flexible pavement bases treated with bituminous material or cement were far superior to untreated crushed limestone or gravel bases in resisting loss of serviceability under load. An indication of this superiority can be seen in Table 5 of this report.

Rigid pavements lost serviceability by the development of roughness along the wheelpaths, by slab cracking or by the necessity of patching the pavement surface due to severe cracking and roughness. All of the failures in the rigid pavements were preceded by pumping of material from beneath the concrete slabs. Generally this material consisted of the subbase sand-gravel and included the coarser fractions of ¾- to 1-in. size. Severe pumping of the subbase material was experienced in the sections having the two thinnest slab thicknesses in each loop; however, some pumping appeared in all sections (except under the 2,000-lb axle load). Practically all pumping occurred along the pavement edge. No cracking was observed in Loop 1 where no traffic was operated.

In the rigid pavement experiments, the use of sand-gravel subbase increased the life of the pavements appreciably when pavements with subbase were compared to pavements with no subbase. However, increasing the subbase thickness from 3 to 9 in. produced no significant effect.

Half of the rigid pavement sections in the main experiment were reinforced with wire mesh and were constructed with transverse contraction joints spaced at 40 ft, whereas the other half were not reinforced and had 15-ft joint spacing. All of the transverse joints contained dowel bars for load transfer. During the two-year period of test traffic no significant difference in performance was found between the otherwise equivalent 40-ft reinforced and 15-ft nonreinforced sections.

Faulting occasionally occurred at cracks but never at the doweled transverse joints.

Another major objective was to find methods of predicting pavement performance. It was found that future performance of pavement could be predicted with reasonable accuracy from certain measurements of deflections and strains made at the time the pavement was constructed or during a critical period in the spring of the year.

The season of the year had a marked influence on the rate of failure of the test pavements, particularly in the case of the flexible pavements. Of all test sections in the main experiment that failed, 40 percent of the rigid and 5 percent of the flexible sections failed in the fall. Corresponding percentages for the winter periods were 11 and 9; in the spring periods, 22 percent of the rigid section failures occurred, while 80 percent of the flexible-section failures were found; and in the summer periods, 27 percent of the rigid and 6 percent of the flexible failures occurred. Test traffic associated with these failures was fairly uniformly distributed among the seasons. Twenty-six percent of the test traffic was applied in fall periods, 21 percent in winter periods, 25 percent in spring periods, and 28 percent in summer periods.

The combined effects of traffic and weathering on pavement surface skid resistance were studied. Coefficients of friction (for wet pavement) after 2 years and 1,100,000 axle-load applications averaged about two-thirds of the values for the pavements as built.

All of the findings discussed above relate specifically and only to the conditions at the Road Test site. Application of the results under other environments, and to other materials and procedures can be made only after careful consideration of all factors affecting pavement performance.

In further consideration of the findings related to pavement performance, it should be borne in mind that the test traffic was applied over a period of only two years. Consequently, it was necessary to relate performance to number of axle applications without consideration of deterioration that may have been associated with the effects of long-time, permanent changes in embankment and pavement structure condition due to weathering, or operations such as the use of chemicals for ice removal. However, in the two-year test period some such loss of serviceability undoubtedly did occur, even though it was not possible to separate these losses from losses associated with traffic.

An important part of the AASHO Road Test was a study of short-span highway bridges. Eighteen bridges were tested under traffic. Each was a simple span structure consisting of three beams and a reinforced concrete slab. Each bridge was constructed on a 50-ft span and was one traffic lane in width. Four of the bridges were reinforced concrete, four had prestressed concrete beams, and ten had steel beams.

The first objective—to determine the behavior of certain short-span highway bridges under repeated applications of overstress—was concerned with the fatigue life of structures subjected to repeated high stresses and with the manner in which distress is caused by repeated high stresses.

The second objective—to determine the dynamic effects of moving vehicles on these short-span highway bridges—was concerned with the behavior of individual test bridges under moving loads. It involved a correlation of observed dynamic effects with those predicted by theoretical computations.

The findings of the bridge research are discussed in detail in Report 4. In general, actual observations on the test bridges were in remarkably good agreement with those predicted by theories concerning deflection and strain in bridges. The observed distress caused by repeated applications of a stress indicated that the life of highway bridges can be predicted with reasonable accuracy on the basis of simple laboratory tests if the history of stresses in the bridge is known. The dynamic studies of the test bridges resulted in the formulation of theoretical concepts that will permit analytical evaluation of stresses and deflections of bridges caused by moving vehicles.

The behavior of composite steel bridges in which the slab was connected to the beams was clearly superior to that of noncomposite steel bridges. The behavior of prestressed concrete beams post-tensioned with parallel wire cables was inferior to that of beams pretensioned with seven-wire strands.

Chapter 2

History

The events leading to the three most recent large-scale highway research projects, Road Test One-MD, the WASHO Road Test and the AASHO Road Test, are described in detail in AASHO Road Test Report 1, "History and Description of the Project" (HRB Special Report 61A). The following is a summary of these events and the activities of the AASHO Road Test.

For many years the member States of the American Association of State Highway Officials had been confronted with the dual problem of constructing pavements to carry a growing traffic load and establishing an equitable policy for vehicle sizes and weights. The Association recognized the need for factual data for use in resolving the problem. Therefore, in September 1948, it set up a procedure for initiating and administering research projects to be jointly financed by two or more States.

In December of the following year a meeting was held at Columbus, at the request of the Governor of Ohio, to consider the problem of vehicle weight and its effect upon existing and future pavements. The conference was attended by representatives of the Council of State Governments and highway officials of 14 eastern and midwestern States. The need for more factual data concerning the effect of axle loads of various magnitudes on pavements was confirmed.

As a result, Road Test One-MD was conducted in 1950. An existing concrete pavement in Maryland was tested under repeated application of two single- and two tandem-axle loads. The Highway Research Board administered the test and published the results as HRB Special Report 4.

Concurrently, the Committee on Highway Transport of the American Association of State Highway Officials recommended that additional road tests be initiated by the regional members of the Association. As a result, the Western Association of State Highway Officials sponsored the WASHO Road Test, consisting of a number of specially-built flexible pavements in Idaho tested in 1953-54 under the same loads used in the Maryland test. The results of this test, also conducted by the Highway Research Board, were published as Special Reports 18 and 22.

In March 1951, the Mississippi Valley Conference of State Highway Engineers had started planning a third regional project. However, the idea of another regional project of limited extent was abandoned in favor of a more comprehensive road test to be sponsored by the entire Association. In October, complying with a request by the Association, a Highway Research Board task committee submitted a report, "Proposal for Road Tests," after which the Association appointed a working committee to prepare a prospectus on the project. By December it had been decided to include bridges in the research.

In June 1952, the Working Committee produced a report, "AASHO Road Test Project Statement." In July it selected a site for the project near Ottawa, Ill. In January 1953, it submitted a second report, "AASHO Road Test Project Program," and in August 1954, a third, entitled "Project Program Supplement." In May 1955, this committee produced its fourth and final report, "Statement of Fundamental Principles, Project Elements and Specific Directions."

Meanwhile, in March 1953, AASHO had formulated a plan for prorating the cost of the project among its member departments and, later, had received assurances of participation from the States, the Automobile Manufacturers Association, the Bureau of Public Roads and the American Petroleum Industry; the Department of Defense had agreed to furnish military personnel for driving the vehicles.

On February 22, 1955, the Highway Research Board with the approval of its parent organization, the National Academy of Sciences-National Research Council, accepted from the Association the responsibility to administer and direct the new project. The Board opened a field office at Ottawa in July 1955; and a task force of the Illinois Division of Highways moved to the site in August to undertake the preparation of plans and to prepare for the construction of the test facilities.

In March 1956, the Board appointed the National Advisory Committee as its senior advisory group and in April selected a project director.

In June 1956, the National Advisory Committee passed a resolution recommending that the Executive Committee of the Highway Research Board consider the inclusion in the facility of a fifth test loop to be subjected to light axle loads. This resolution, recommended by the Bureau of Public Roads, was based on the pending enactment of the Federal-Aid

Highway Act of 1956. In July, the Executive Committee of the Board approved this change and made additional changes involving special studies areas. The final layout of the test facilities is described in Section 1.2.2 of Road Test Report 5.

Construction of the test facilities began in August 1956, and test traffic was inaugurated on October 15, 1958. Test traffic was operated until November 30, 1960, at which time 1,114,000 axle loads had been applied to the pavement and the bridges.

A special studies program was conducted in the spring and early summer of 1961 over some of the remaining test sections. Strains, deflections and pressures were measured in these studies under a wide variety of vehicle types, load suspensions, tires and tire pressures. Special military vehicles, included at the request of the Army, as well as highway construction equipment, were included in these tests. The results of the studies are presented in Road Test Report 6.

During 1961, the research staff concentrated on analysis of the test data and the preparation of reports. Each of the major reports was approved by a review subcommittee of the National Advisory Committee and later submitted to the entire National Advisory Committee and the Regional Advisory Committees prior to its publication by the Highway Research Board. All reports were completed by the project staff, reviewed by the various committees, and submitted to the Executive Committee of the Board.

The field office for the project was closed in January 1962. However, the Highway Research Board agreed to continue certain studies associated with the Road Test pavement performance analyses in its Washington office. The results of these studies will be reported by the Highway Research Board.

INTENT OF THE AASHO ROAD TEST

The following formal statement of the intent of the Road Test was approved by the Executive Committee of the Highway Research Board January 13, 1961:

The AASHO Road Test plays a role in the total engineering and economic process of providing highways for the nation. It is important that this role be understood.

The Road Test is composed of separate major experiments, one relating to asphalt concrete pavement, one relating to portland cement concrete pavement, and one to short span bridges. There are numerous secondary experiments. In each of the major experiments, the objective is to relate design to performance under controlled loading conditions.

In the asphalt concrete and portland cement concrete experiments some of the pavement test sections are underdesigned and others overdesigned. Each experiment requires separate analysis. Eventually the collection and analysis of additional engineering and economic data for a local environment are necessary in order to develop final and meaningful relations between pavement types.

All of the short span bridges are underdesigned. Each is a separate case study.

Failures and distress of the pavement test sections and the beams of the short span bridges are important to the success of each of the experiments.

The Highway Research Board of the National Academy of Sciences-National Research Council has the responsibility of administering the project for the sponsor, the American Association of State Highway Officials, within the bounds of the objectives of the test. The Board is also responsible for collecting engineering data, developing methods of analysis and presentation of data, preparing comprehensive reports describing the tests, and drawing valid findings and conclusions. It is here that the role of the Highway Research Board ends.

As the total engineering and economic process of providing highways for the nation is developed, engineering data from the AASHO Road Test and engineering and economic data from many other sources will flow to the sponsor and its member departments. It is here that studies will be made and final conclusions drawn that will be helpful to the executive and legislative branches of our several levels of government and to the highway administrator and engineer.

Chapter 3

Objectives

The objectives of the AASHO Road Test as stated by the National Advisory Committee were as follows:

1. To determine the significant relationships between the number of repetitions of specified axle loads of different magnitude and arrangement and the performance of different thicknesses of uniformly designed and constructed asphaltic concrete, plain portland cement concrete, and reinforced portland cement concrete surfaces on different thicknesses of bases and subbases when on a basement soil of known characteristics.
2. To determine the significant effects of specified vehicle axle loads and gross vehicle loads when applied at known frequency on bridges of known design and characteristics.
3. To make special studies dealing with such subjects as paved shoulders, base types, pavement fatigue, tire size and pressures, and heavy military vehicles, and to correlate the findings of these special studies with the results of the basic research.
4. To provide a record of the type and extent of effort and materials required to keep each of the test sections or portions thereof in a satisfactory condition until discontinued for test purposes.
5. To develop instrumentation, test procedures, data, charts, graphs, and formulas, which will reflect the capabilities of the various test sections; and which will be helpful in future highway design, in the evaluation of the load-carrying capabilities of existing highways and in determining the most promising areas for further highway research.

The work done in connection with Objectives 1 and 5 and with some of the special studies mentioned in Objective 3, is discussed in detail in Report 5. Material relating to Objective 2 will be found in Road Test Report 4 and Objective 4 is discussed in Report 3. Other special studies suggested in Objective 3 are discussed in Report 6.

OBJECTIVITY OF FINDINGS

Discussion of the results given in the Road Test reports has generally been limited to specific relationships derived from the data. Restraint has been exercised in expressing opinions, conjectures, and speculations. Conclusions have been drawn only when supported by data acquired during the tests.

At the request of the National Academy of Sciences a panel of statisticians was appointed in 1955 so that professional advice was available for both the designs of the Road Test experiments and for the procedures by which the experimental data would be analyzed. It was not the function of this group to recommend variables nor levels for variables to be included in the Road Test. This was the responsibility of the National Advisory Committee, acting upon the proposals of the original AASHO Transport Committee's working committee. The statistical panel played an important role in the experimental layout through its recommendations for complete factorial designs, randomization, and replication.

Within the space, time and funds available, only a few variables could be studied thoroughly. The experiment was designed and the test facilities built specifically for the study of these variables. In general, mathematical models were developed to represent associations among experimental variables, then statistical methods were employed to determine the constants for the models and to describe the reliability of the evaluated models. Thus experimental designs and analytical procedures were developed in order to obtain unbiased estimates of the effects (and the statistical significance of many of the effects) of controlled experimental factors. The designs and procedures did not, however, make it possible to obtain effects of other factors that were either held constant or varied in an uncontrolled fashion, for example, embankment soil, strength of materials, and environmental conditions. Coefficients were obtained for the effects of axle load and axle configuration. In the cases of load effect on both pavement types and axle configuration effect on rigid pavement, the differences observed in performance were so great as to leave practically no doubt that the effects were significant.

Basic data will be made available to other groups equipped to perform independent analyses. Further analyses are encouraged by the Highway Research Board in the expectation that the over-all usefulness of the project will be enhanced.

APPLICABILITY OF FINDINGS

The findings of the AASHO Road Test, as stated in the relationships shown by formulas, graphs, and tables throughout the reports, relate specifically to the physical environment of the project, to the materials used in the pavements, to the range of thicknesses and loads and number of load applications included in the experiments, to the construction techniques employed, to the specific times and rates of application of test traffic, and to the climatic cycles experienced during construction and testing of the experimental pavements. More specific limitations on certain of the findings are given in the discussion of results in various sections of this report. *Generalizations and extrapolations of these findings to conditions other than those that existed at the Road Test should be based upon experimental or other evidence of the effects on pavement performance of differences in climate, soil type, materials, construction and maintenance practices and traffic.*

Chapter 4

Description of the Project

The AASHO Road Test was located near Ottawa, Illinois, in LaSalle County, about 80 miles southwest of Chicago (Fig. 1). The test facility was constructed along the alignment of Interstate 80. The site was chosen because the soil within the area is uniform and of a type representative of that found in large areas of the country, because the climate is typical of that found throughout much of the northern United States, and because much of the earthwork and pavement construction could ultimately be utilized in the construction of a section of the National System of Interstate and Defense Highways.

ENVIRONMENTAL CONDITIONS

The topography of the Road Test area is level to gently undulating with elevations varying from 605 to 635 ft. Drainage is provided by several small creeks which are tributaries of the Illinois River. Surface drainage, however, is generally slow. Geologic information indicates that the area was covered by ice during several glacial periods and that the subsurface soils were deposited or modified during these periods. Surface soils were subsequently derived from a thin mantle of loess deposited during the post-glacial period and were reasonably uniform in the area of the project. Soil drainage is generally poor. Bedrock is found 10 to 30 ft below the surface.

The upper layer of soil was from 1 to 2 ft thick and consisted generally of A-6 or A-7-6 soil with similar characteristics. The adjacent underlying stratum was usually from 1 to 2 ft thick and most of this material was fairly plastic A-7-6 soil. Samples of substrata generally exhibited A-6 characteristics.

In the interest of obtaining uniformity, the soil making up the top 3 ft of embankment directly under the test pavements was taken

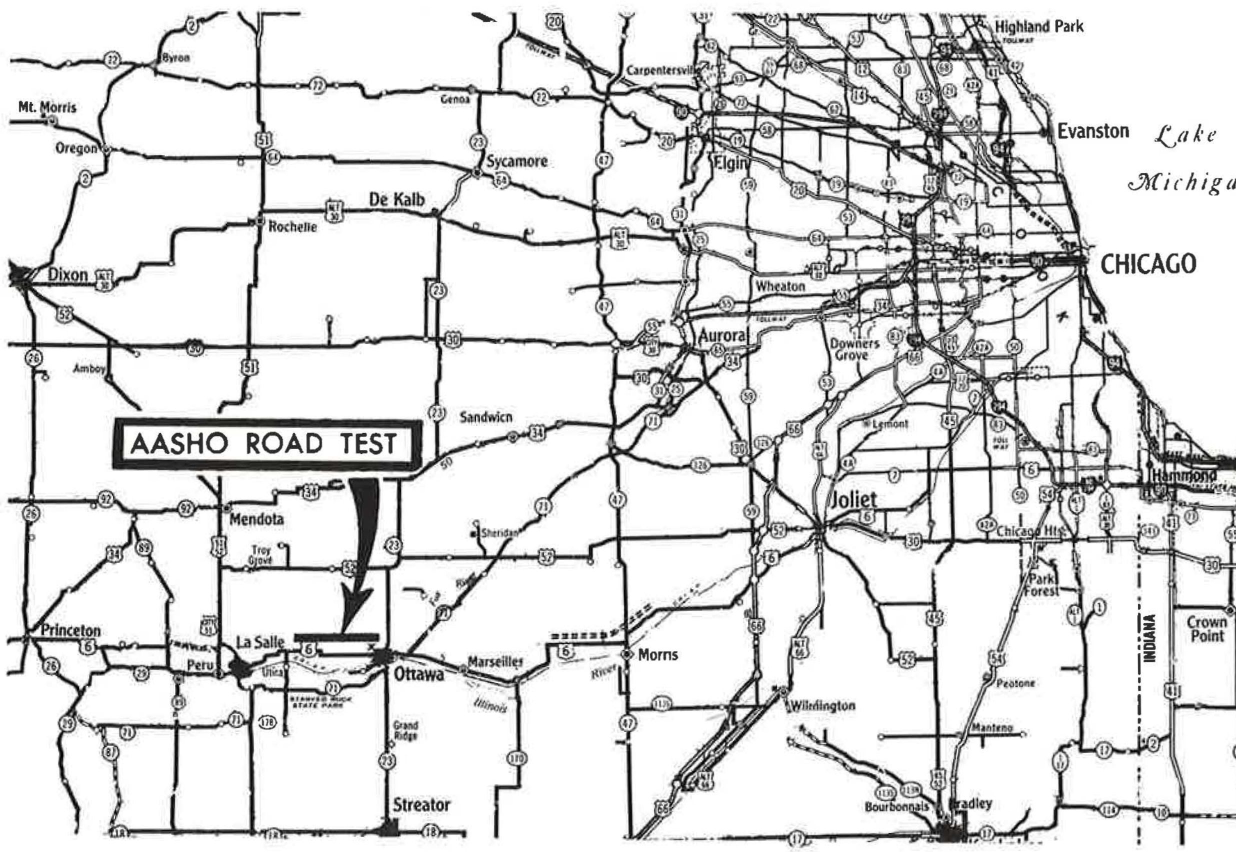


Figure 1. Site location.

from borrow areas near the project. This soil, underlying the surface stratum, was shown by tests to have a plasticity index from 11 to 15, a liquid limit from 27 to 32, and a grain size distribution of 80 to 85 percent finer than the 200 mesh sieve, 58 to 70 percent finer than 0.02 mm and 34 to 40 percent finer than 0.005 mm. Maximum dry densities were in the range of 114 to 118 pcf and optimum moisture contents in the range of 14 to 16 percent when compacted in accordance with standard procedure, AASHO T99-49.

The climate of the area is temperate and the average annual precipitation is about 34 in. of which about 2.5 in. occurs as 25 in. of snow. The average mean summer temperature is 76 F and the average mean winter temperature is 27 F. The soil usually remains frozen during the winter except for alternate thawing and freezing of the immediate surface. Normally the average depth of frost penetration in the area is about 28 in.

Summaries of climatological data observed at weather stations on the project are given in Figures 2 through 4 and frost depth information in Figure 5. Depth of frost under the test pavements was obtained by means of special instrumentation involving the measurement of electrical resistance of the soil as described in *Highway Research Abstracts*, Vol. 27, No. 4. More detailed climatological and frost information is available in the form of IBM listings in Data Systems 3300, 3301, 3140 and 3240. Figure 6 summarizes the observations made at the project on the elevation of the water table under the test pavements and adjacent natural ground.

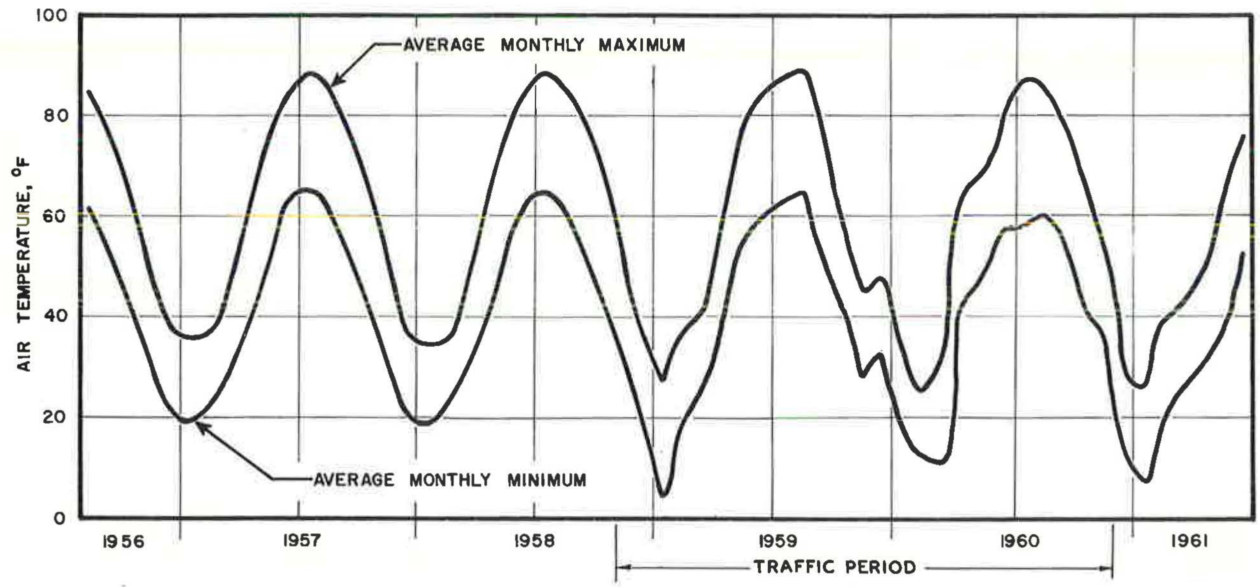


Figure 2. Average monthly air temperature at project.

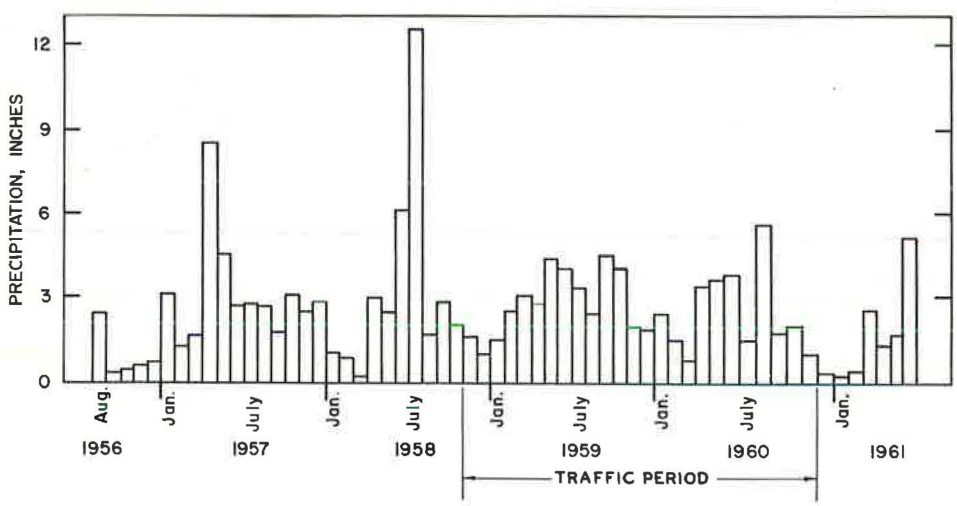


Figure 3. Precipitation at project.

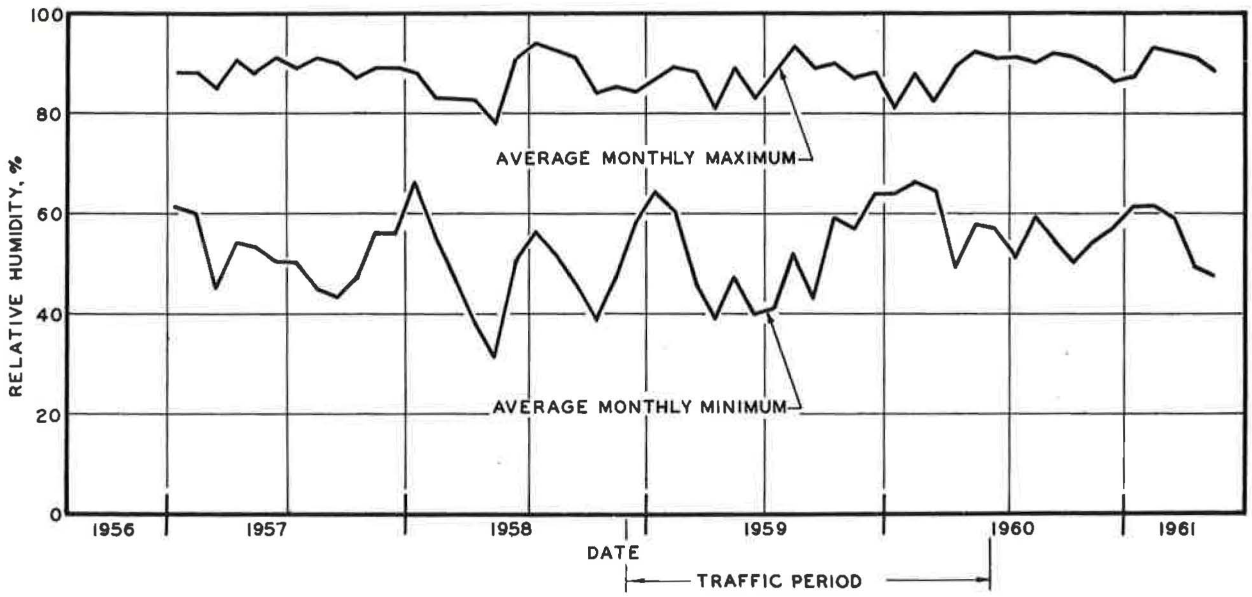


Figure 4. Relative humidity, weather station at Peoria, Ill.

TEST FACILITIES

The test facilities consisted of four large loops, numbered 3 through 6, and two smaller loops, 1 and 2. Test bridges were at four locations in two of the large loops. The layout of the six test loops, the administration area and the Army barracks is shown in Figure 7.

Each loop was a segment of a four-lane divided highway whose parallel roadways, or tangents, were connected by a turnaround at each end. Tangent lengths were 6,800 ft in Loops 3 through 6, 4,400 ft in Loop 2 and 2,000 ft in Loop 1. Turnarounds in the major loops had 200-ft radii and were superelevated so that the traffic could operate over them at 25 mph with little or no side thrust. Loop 2 had superelevated turnarounds with 42-ft radii. Centerlines divided the pavements into inner and outer lanes, called lane 1 and lane 2, respectively.

All vehicles assigned to any one traffic lane of Loops 2 through 6 had the same axle arrangement-axle load combinations. No traffic operated over Loop 1. In all loops, the north tangents were surfaced with asphaltic concrete and south tangents with portland cement concrete. All variables for pavement studies were concerned with pavement designs and loads within each of the 12 tangents. Each tangent was constructed as a succession of pavement sections called structural sections. Pavement designs, as a rule, varied from section to section. The minimum length of a section was 100 ft in Loops 2 through 6, and 15 ft in Loop 1. Sections were separated by short transition pavements. Each structural section was separated into two pavement test sections by the centerline of the pavement. Figure 8 shows the over-all layout of two typical test loops and locations of the test bridges and Figure 9 shows the actual layout of test sections for the two tangents of Loop 4. Test sections in the other loops were arranged in a similar fashion. (Fig. 9 is from Report 2 the bottom half of Fig. 13 and the bottom half of Fig. 21.) Details of the experiment designs are given in Report 1 and are summarized in Sections 2.1.1 and 3.1.1 of Report 5.

Chapter 8 is a summary of the bridge research. Details concerning all features of bridge research are given in Road Test Report 4.

An administrative area was located at the center of the project. Laboratories and offices were located in the building shown in Figure 10. Shop facilities for vehicle maintenance were provided in the building shown in Figure 11. A military installation called Wallace Barracks (Fig. 12) was provided by the National Academy of Sciences to house the Army Transportation Corps Road Test Support Activity.

CONSTRUCTION

A comprehensive description of the construction of the AASHO Road Test facilities is given in Road Test Report 2. Construction was supervised by the task force of the Illinois Division of Highways. On-site materials control and testing were provided by the Highway Research Board staff on the project. Conventional techniques for construction were employed, but extraordinary effort was put forth to insure uniformity of all pavement components. For example, no construction equipment other than that necessary for compaction was permitted to operate in the center 24-ft

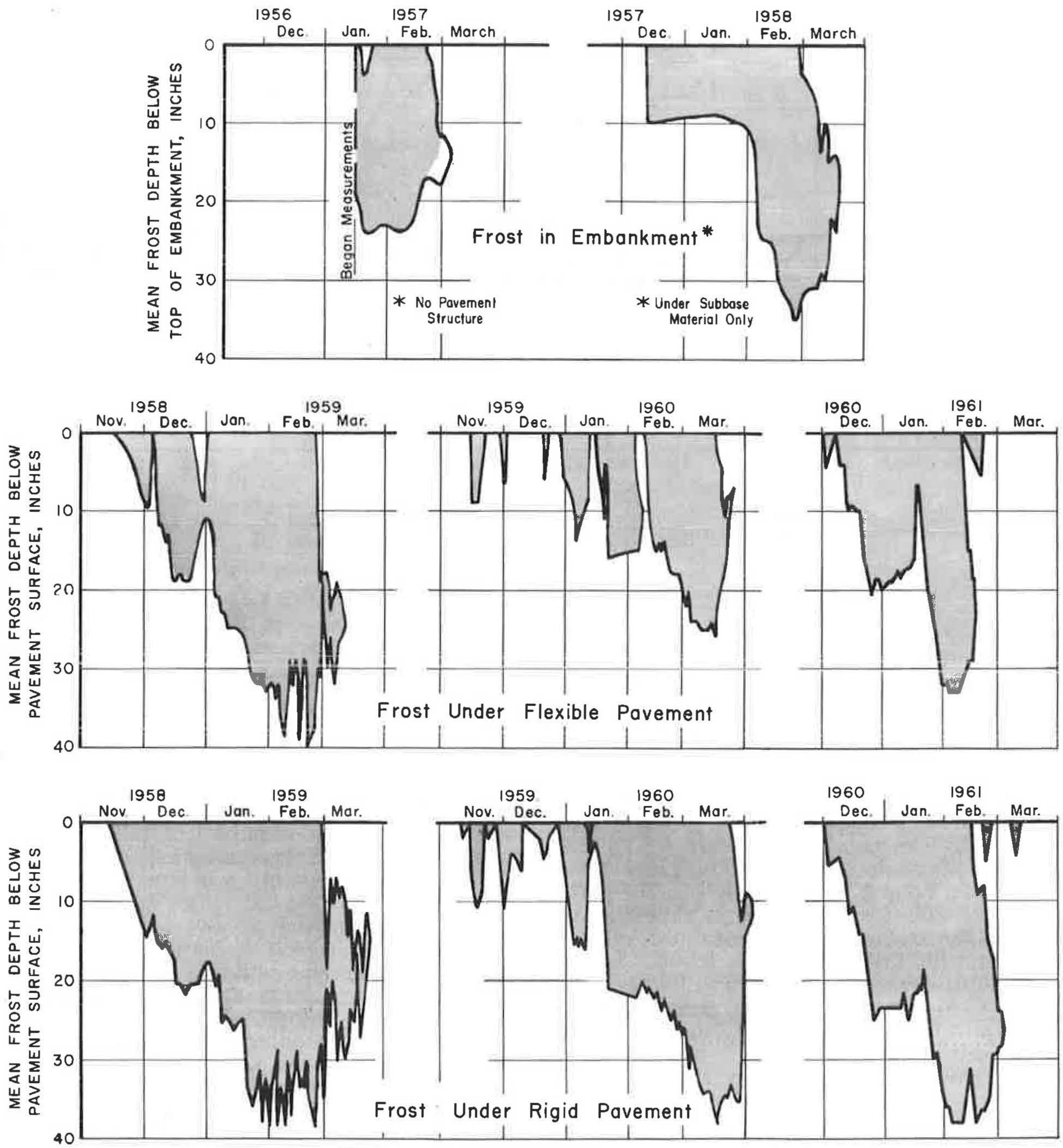


Figure 5. Frost depth.

width of the roadway, and all turning operations on the grade were limited to specially designated transition areas. Specifications for density of compacted embankment soil, subbase and base materials included stipulations of maximum densities as well as the conventional minimums.

These and other construction control measures were considerably more strict than those encountered in normal pavement construction. The purpose of these measures was to insure uniformity of the components of the various test sections in order to permit comparison of their performance on the basis of their design characteristics. No attempt at supercompaction or extraordinary construction was made. Rather, the specifications were such as to provide pavement components similar to those encountered in normal highway construction.

Construction was performed under contracts negotiated through normal Illinois contractual channels. It was started in late summer 1956

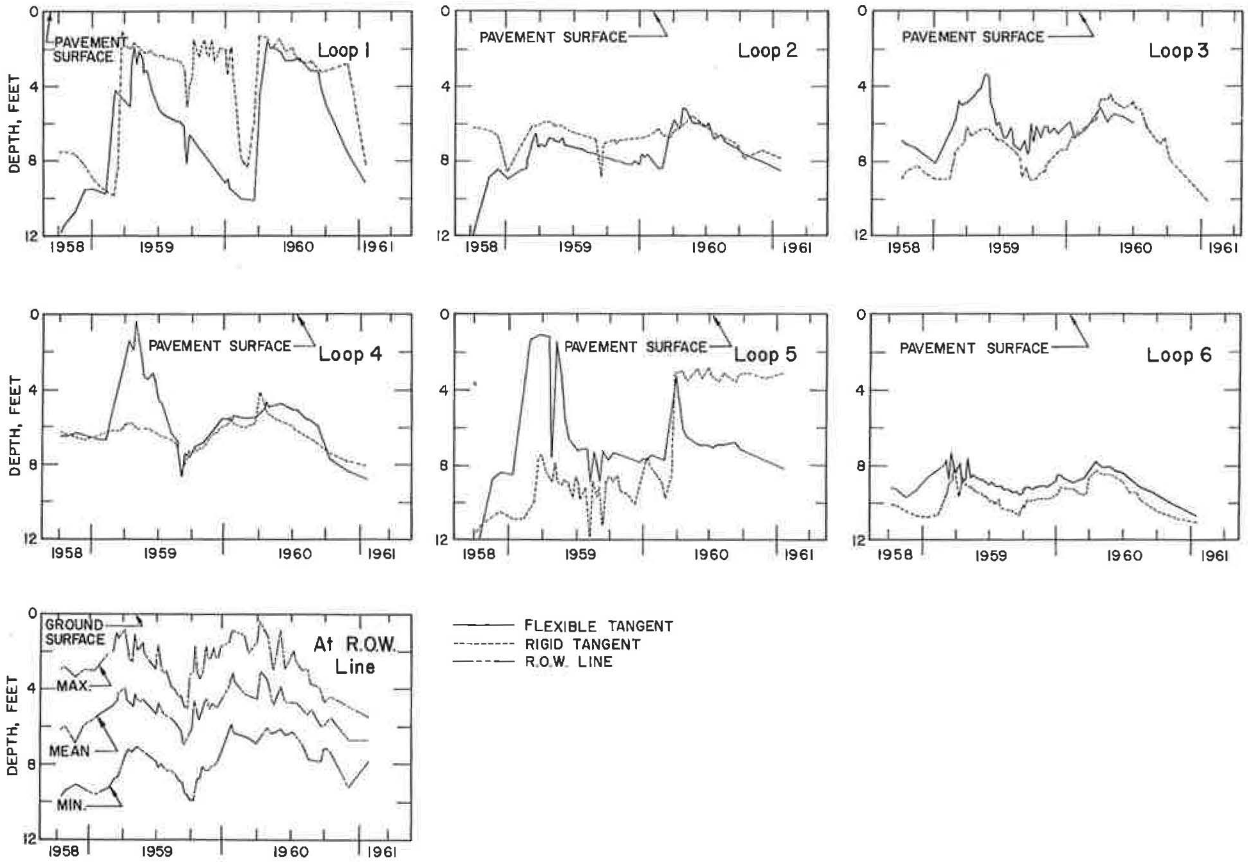


Figure 6. Water table data.

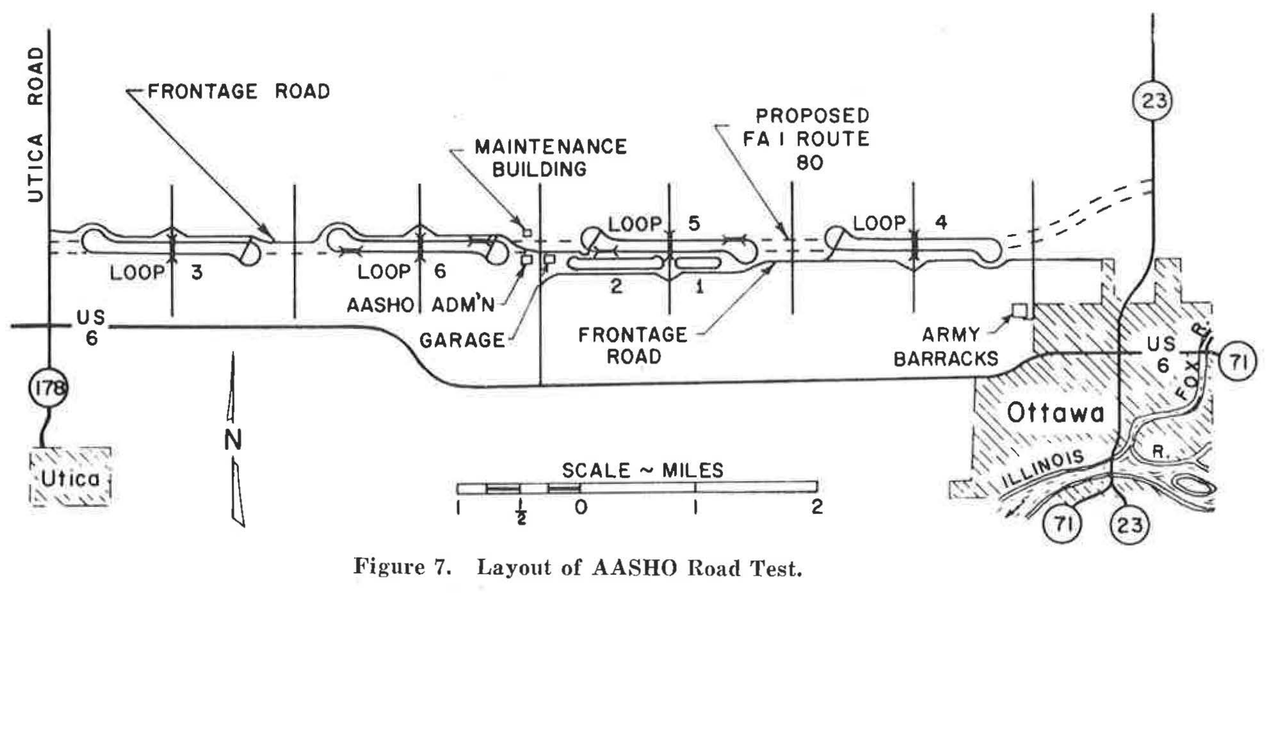


Figure 7. Layout of AASHO Road Test.

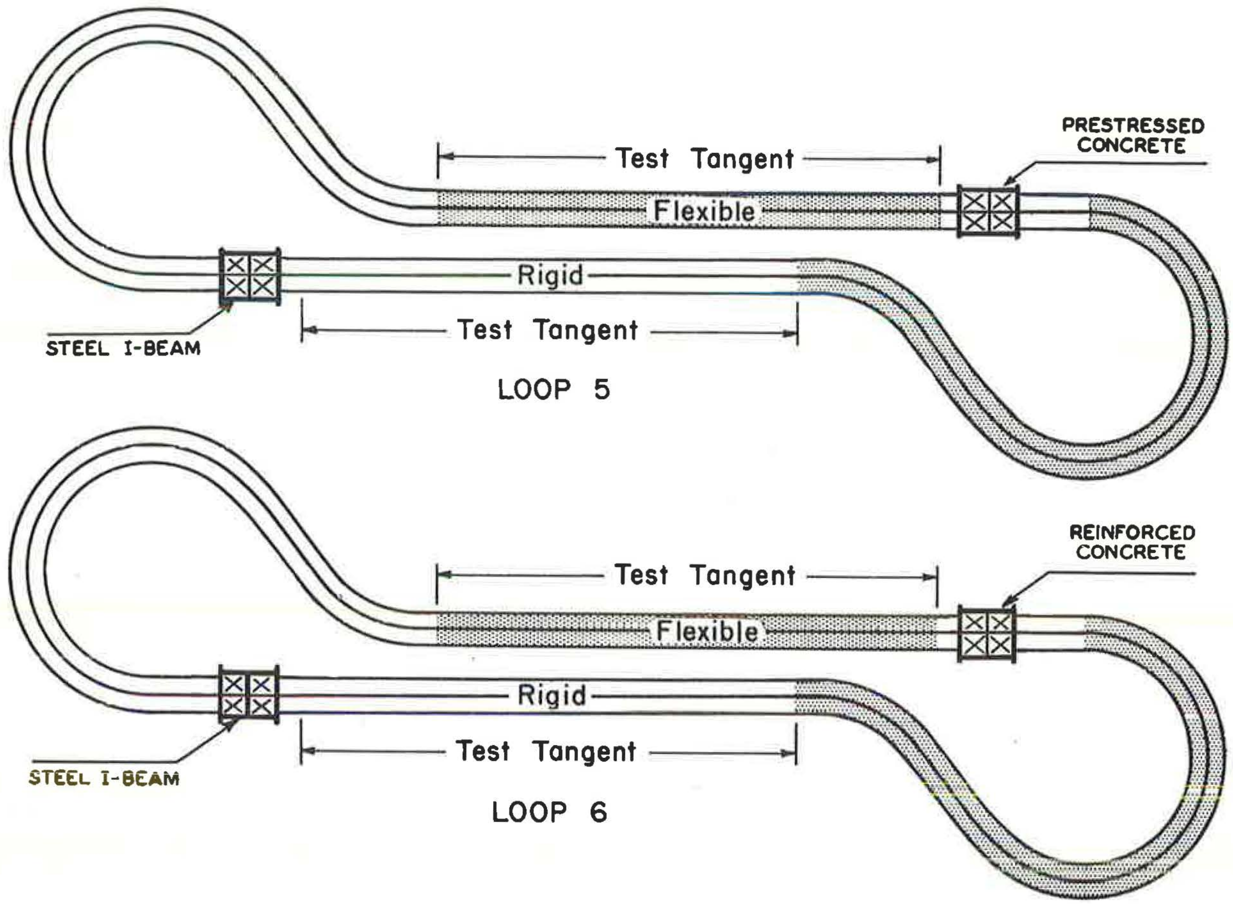


Figure 8. Location of test bridges.

and completed in time for test traffic to begin in the fall of 1958. S. J. Groves and Sons was the principal contractor in a joint venture with Arcole Midwest, Inc., in the embankment construction and with Rock Roads, Inc., as a subcontractor for asphaltic concrete surfacing. Valley Builders, Inc., built the bridges.

TEST TRAFFIC

A detailed description of the operation of the test traffic is presented in Road Test Report 3. As previously stated, Loop 1 was not subjected to test traffic. One lane of this loop was used for subsurface and special load studies, the other for observing the effect of environment on pavements not subjected to traffic. The remaining five loops, 2 through 6, were subjected to traffic for slightly more than two years. Every vehicle in any one of the ten traffic lanes had the same axle load and axle configuration. The assignment of axle loads and vehicle types to the various lanes is shown in Figure 13.

The vehicles were loaded with concrete blocks that were anchored down with steel bands and chains. Although the traffic phase was inaugurated on October 15, 1958, early operation indicated the need to readjust the height and arrangement of the test loads. This delayed full-scale traffic until November 5, 1958. From November 1958 to January 1960 controlled test traffic consisted of six vehicles in each lane of Loops 3 through 6, four vehicles in lane 1 of Loop 2 and eight vehicles in lane 2 of Loop 2. To achieve the intended number of load applications in the available time, the traffic was increased in January 1960 to ten vehicles in each lane of Loops 3 through 6, six in lane 1 and 12 in lane 2 of Loop 2. These vehicle distributions were selected in order that axle-load applications could be accumulated at the same rate in each of the ten traffic lanes.

All lanes had identical specifications for transverse placement, speed, and rate of axle-load accumulation. Tire pressure and steering axle loads were representative of normal practice. Some of the vehicles were gasoline and others diesel powered. Further information concerning the vehicles is contained in Road Test Reports 1 and 3.

Whenever possible (most of the time), traffic was operated at 35 mph on the test tangents. Traffic was scheduled to operate over an 18-hr, 40-min period each day, 6 days a week, except

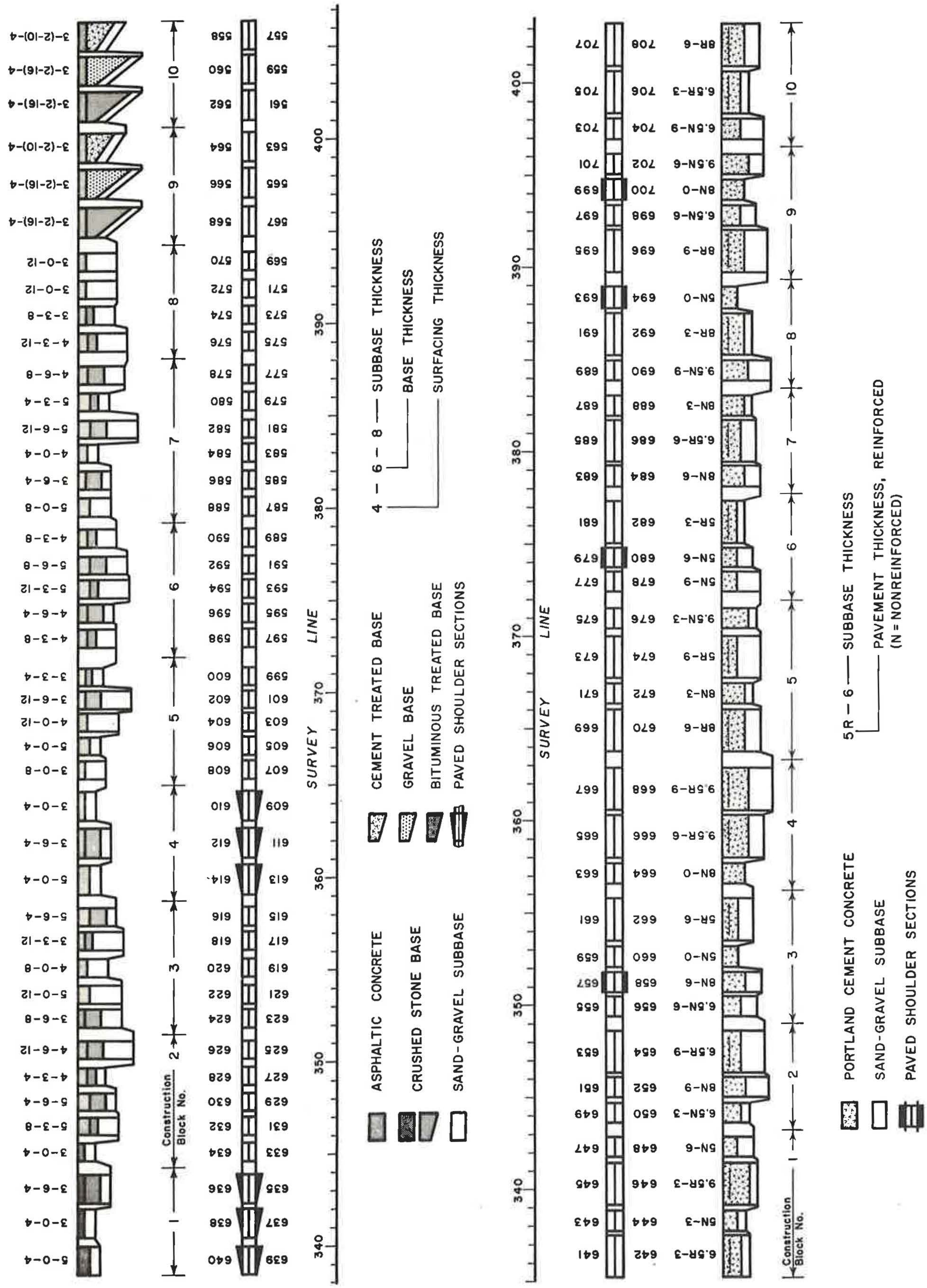


Figure 9. Layout of Loop 4; (top) flexible tangent, (bottom) rigid tangent.

Figure 10. Administration building.

Figure 11. Vehicle maintenance garage.

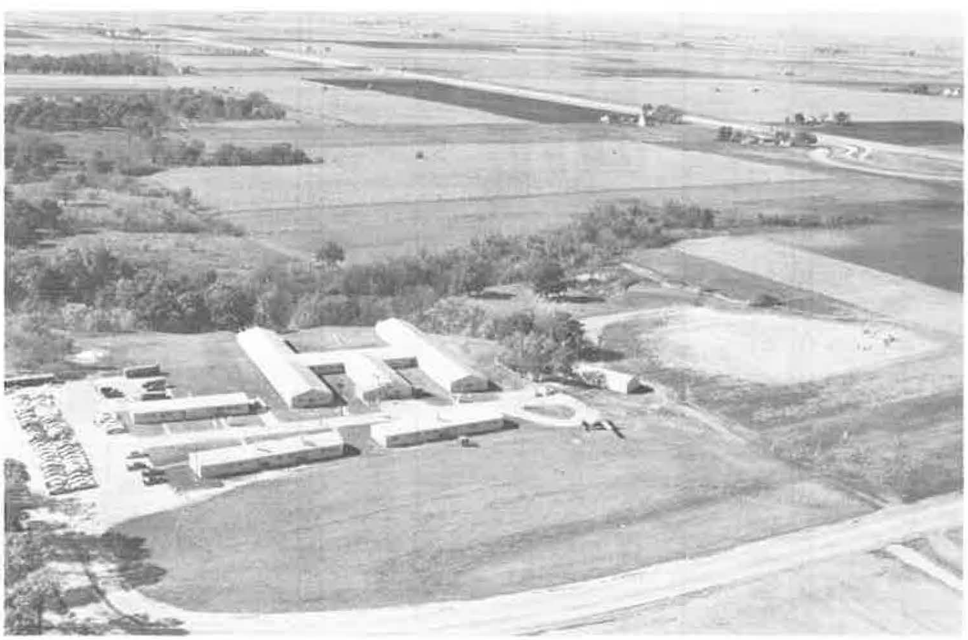


Figure 12. Army driver quarters (Wallace Barracks).

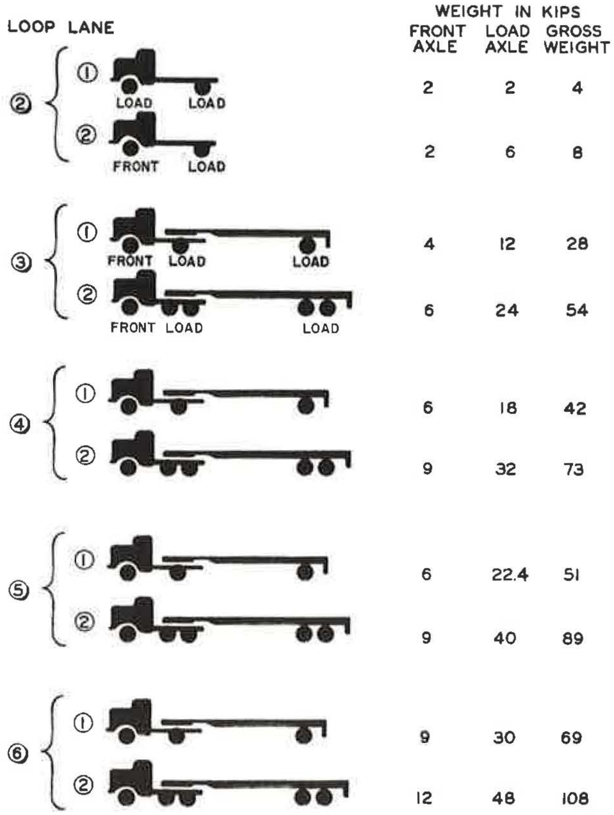


Figure 13. Typical test vehicle axle loadings.

that during the first 6 months of 1960 the schedule was extended to 7 days a week. The schedule was maintained except when pavement distress, truck breakdowns, bad weather and certain other causes made it impossible. A total accumulation of 1,114,000 axle-load applications was attained during the 25-month traffic testing period. To accomplish this, soldiers of the U. S. Army Transportation Corps Road Test Support Activity drove more than 17 million miles.

MEASUREMENT PROGRAMS

Each measurement program was designed to accomplish one or more of the following purposes: (1) to furnish information at regular and frequent intervals concerning the roughness and visible deterioration of the surfacing of each section; (2) to record early in the life of each section transient load effects that might be directly correlated with the ultimate performance of the section; and (3) to furnish, to the extent possible, additional information that might contribute to a better understanding of pavement mechanics.

Programs in the first category were concerned with measurements of permanent changes in the pavement profile along and across the wheelpaths, as well as the extent of cracking and patching of the surfacing. These measurements were given major emphasis since they were used to define the performance of each section as required by the first Road Test objective.

Programs in the second category included the measurement of strains and deflections, which became the basis for estimating pavement capability, as required by the fifth objective.

Finally, programs in the third category encompassed such measurements as the severity of pumping of rigid pavements, changes in layer thickness in flexible pavements, pavement temperatures, subsurface conditions, and numerous other measurements.

In general, measurements were restricted to those variables that had been demonstrated by previous research to be related significantly to pavement performance. A further restriction, applying especially to subsurface studies, was imposed by the overriding necessity to keep the test traffic moving.

In spite of these restrictions, a formidable amount of data was accumulated, and special electronic systems were evolved to facilitate the storage and initial processing of the data. For example, in the case of some programs, means were provided to record automatically in the field the desired information directly on perforated paper tape, thus eliminating the task of the manual reading of analog records. In another case, an electronic device was used to read field analog records and to punch the information on paper tape for immediate transference to an electronic computer. In general, automatic data handling was used wherever possible and the major portion of the data was stored on IBM cards.

Data from the various measurement systems were classified into data systems, and a particular system was identified by a four digit code. Appendix I of Report 5 lists major Road Test data systems concerned with pavement research and notes how the systems can be obtained from the Highway Research Board. Major data systems from the bridge research are listed in Appendix A, Road Test Report 4.

The text of this report contains many references to data systems whose contents are pertinent to the discussion. These references are explained in Appendix I of Report 5. For example, a reference to Data System 5121, or simply DS 5121, is explained in Appendix I as containing all routine Benkelman beam deflection data for flexible pavement sections on the traffic loops with an IBM printout of the data available on request.

Specific measurement programs are described in the appropriate sections of Chapters 2 and 3 of Report 5.

PAVEMENT MAINTENANCE

Detailed descriptions of maintenance criteria and procedures are given in Road Test Report

3. Complete maintenance histories of each test section are available in DS 6300.

The objectives of the Road Test were concerned with the performance of the test sections as constructed. Consequently, maintenance operations were held to a minimum in any section that was still considered under study. When the "present serviceability" (see Chapter 5 and, for more detail, Section 1.3, Report 5) of any section dropped to a specified level the section was considered to be out of test and maintenance or reconstruction was performed as needed.

Since the prime objective of the maintenance work was to keep test traffic operating as much as possible, minor repairs were made when required regardless of weather or time of day. The use of pierced steel aviation landing mats permitted traffic to operate through a complete driving period so that more conventional repairs could be made during the daily 5-hr, 20-min traffic break.

All repairs were made with flexible-type pavement material. Deep patches and reconstruction consisted of compacted crushed stone base material surfaced with hot-mixed asphaltic concrete. Overlays consisted of asphaltic concrete. Thin patches were made either with hot-mix or cold-mix materials. Crushed stone base material and cold-mix surfacing were stockpiled at several locations on the project, and hot-mix asphaltic concrete was generally purchased from a nearby contractor.

As a general rule, pavement maintenance was done by project forces with project-owned equipment. However, in the critical spring periods of 1959 and 1960, it was necessary to augment the project maintenance forces with additional men and equipment.

Chapter 5

Pavement Serviceability and Performance

The first objective of the Road Test was designed to obtain relationships between the performance of the pavement and the pavement design variables for various loads. In order to define performance, a new concept was evolved founded on the principle that the prime function of a pavement is to serve the traveling public satisfactorily. Briefly, it was considered that a pavement that maintained a high level of ability to serve traffic over a period of time is superior in performance to one whose riding qualities and general condition deteriorated at a more rapid rate under the same traffic. The term "present serviceability" was adopted to indicate the momentary ability of a pavement to serve traffic, and the performance of the pavement was represented by its serviceability history in conjunction with its load application history.

Though the serviceability of a pavement is patently a matter to be determined subjectively, a method for converting it to a quantity based on objective measurements was devised. Since the Road Test was concerned only with the structural features of the pavement, such items as grade, alignment, access, condition of shoulders, slipperiness and glare were excluded from consideration in arriving at a value for pavement serviceability.

The serviceability of each test section was determined every two weeks during the traffic testing phase, and performance analyses were based on the trend of serviceability with increasing number of load applications. The serviceability-performance concept is described in detail in Appendix F of Road Test Report 5.

RATING OF PAVEMENTS IN SERVICE

Serviceability was found to be influenced by longitudinal and transverse roughness as well as the extent of cracking and patching. The proportionate contribution of these factors to an over-all serviceability rating is a matter of subjective opinion. Furthermore, the degree of serviceability loss to be associated with a given change in any one of these elements depends on subjective judgment. To obtain a good estimate of the opinion of the traveling public in these subjective matters a Pavement Serviceability Rating Panel was appointed. This panel included highway designers, highway maintenance engineers, highway administrators, men with materials interests, trucking interests, automobile manufacturing interests and others. These men made independent ratings of the ability of 138 sections of pavement, located in three States, to serve high-speed, mixed truck and passenger traffic. Both rigid and flexible pavements were included, and certain sections were selected for rating in each of five categories ranging from very poor to very good. At approximately the same time that the panel rated these pavement sections, Road Test field crews measured variations in longitudinal and transverse profiles, as well as the amount of cracking and patching of each section.

By multiple regression analysis it was possible to correlate the present serviceability rating with the objective measurements of longitudinal profile variations, the amount of cracking and patching and, in the case of flexible pavements, transverse profile variations (rutting). For both types of pavement this analysis resulted in a formula whereby pavement measurements would be used to compute a "present serviceability index" which closely approximated the mean rating of the panel. The necessary measurements and serviceability index computations were made for each Road Test section at two-week intervals throughout the traffic phase.

Formulas for the present serviceability index of both the flexible and rigid pavements, together with the definitions of the measurements entering into them, are given at the end of this Chapter. The method of measuring longitudinal profile variations was the same for both pavement types and is described below.

The instrument used for recording longitudinal profile variations was the longitudinal profilometer pictured in Figure 14 and shown schematically in Figure 15.

The instrument output was a continuous analog of the slope of the pavement in each wheelpath, together with 1-ft distance marks along the margin of the tape (Fig. 16). The tapes were fed into an automatic electronic chart reader (Fig. 17) that measured the ordinate of the chart at intervals equivalent to 1 ft on the pavement, digitized this information and punched it on perforated paper tape suitable for use as an input to the project's digital computer.

To correlate profile variation with serviceability ratings made by the panel, the hundreds of slope measurements taken in each section were reduced to a single statistical parameter representing the roughness of the section. The

Figure 14. AASHO Road Test Profilometer.

parameter selected was the variance of the slope measurements, abbreviated *SV*.

The slope variance for each section was calculated by the digital computer directly from the tape output of the chart reader. For use by other agencies, the Road Test staff has developed a simplified profilometer (Fig. 18), designated the CHLOE Profilometer, whose output is slope variance. Thus, neither a chart reader nor a digital computer is required when the CHLOE Profilometer is used.

It was found that of the several types of measurements used in the serviceability index formulas, longitudinal profile variation of a section of pavement, when represented by the logarithm of the slope variance, correlated most highly with the rating of that section by the panel.

PAVEMENT PERFORMANCE DATA

Pavement performance analyses were based on the trend of the serviceability index (determined at intervals of two weeks, or more often when required) with increasing axle applications.

Each 2-week period was termed an "index period," and the last day of each period was called an "index day." Index days were numbered sequentially from 1 to 55, the first occurring on November 5, 1958, and the fifty-fifth on November 30, 1960. Because all sections had been subjected to almost the same number of applications of axle loads on any given date, the pairing of an index value with an index day is equivalent to specifying the serviceability index corresponding to a given number of axle applications.

The serviceability history of each section was converted to a "smoothed serviceability history" by a moving average technique. Typical serviceability data and smoothed serviceability histories are shown in Figure 19.

It was observed early in the traffic phase of the Road Test, confirming experience elsewhere, that for sections of pavement which were not adequately designed for the particular load, the rate of deterioration was related to seasonal changes. This was especially so in the case of flexible pavements. The design of the Road Test experiment did not permit a clearcut comparison of the damage rate in the

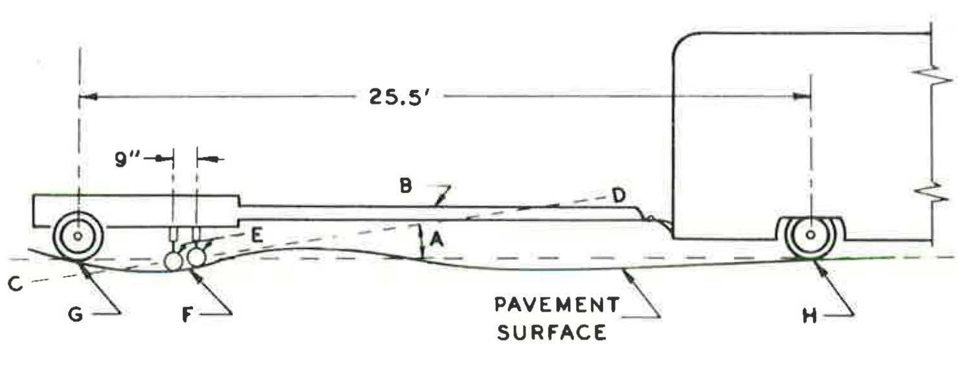


Figure 15. Schematic of AASHO Profilometer.

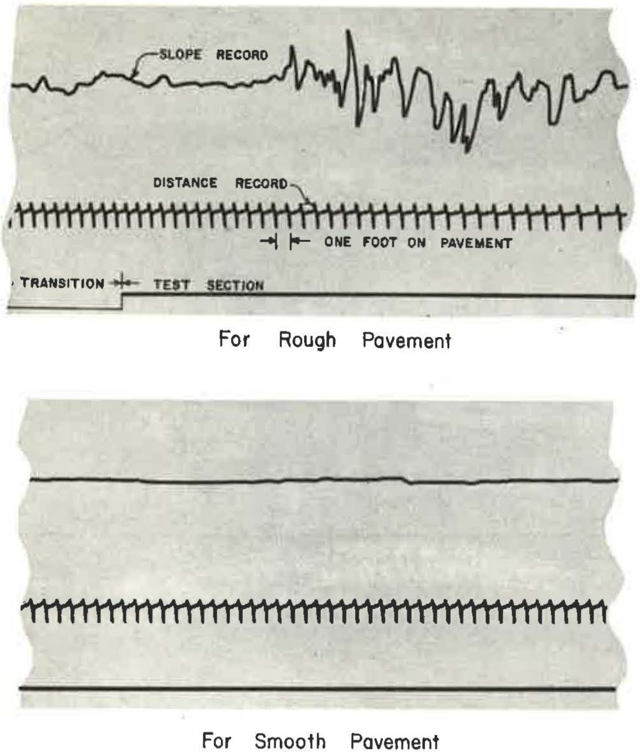


Figure 16. Typical longitudinal profilometer record.

various seasons since sections that failed in one season were not available for observation during subsequent seasons. Nevertheless, Table 1, giving the percentage of failures occurring in each season for each type of pavement, suggests that damage rate was relatively low in winter for both types of pavement and relatively high in spring for flexible pavements.

Changes in the effect of load with seasons suggested the use of a "seasonal weighting function," designed to reflect the general variation above and below a "normal" value in the strength of the test sections. The actual axle-load applications in one index period could thus be modified by the seasonal weighting function to produce a "weighted" number of applications.

Weighted application could then be substituted for actual applications in the performance analyses.

PROCEDURES FOR ANALYSIS

The analyses of performance resulted in empirical formulas wherein performance was associated with load and pavement design variables. To use mathematical procedures for the analyses it was necessary to assume some analytical form or model for these associations. In addition to the experimental variables the models include constants whose values were either to be specified or to be estimated from the data. Thus the analytical procedures were for the estimation of constants whose values were unspecified in the model—constants that indicate the effects of design and load variables

Figure 17. Electronic analog chart reader.

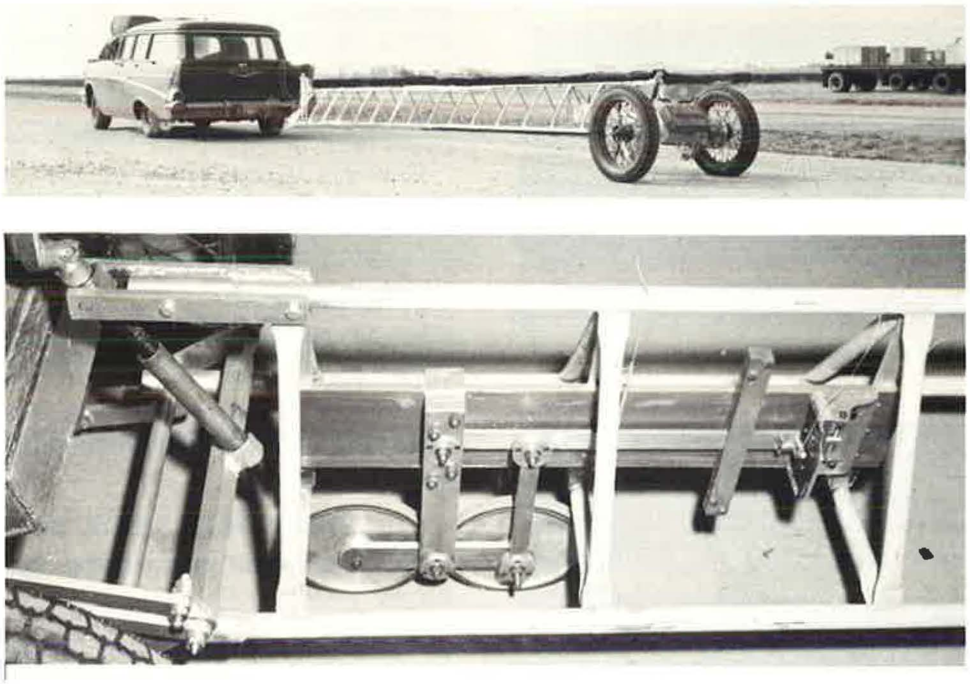


Figure 18. CHLOE Profilometer.

upon performance. The procedures also included methods for estimating the precision with which the data fit the assumed model. The procedures used in the Road Test analyses are set forth in detail in Appendix G of Road Test Report 5.

There are many different mathematical forms that can be used as models for serviceability trends, and several of these may fit the data with more or less the same precision. Different models were tested for goodness of fit to the Road Test performance data. Preference for one model over another was governed mainly by relative goodness of fit, but con-

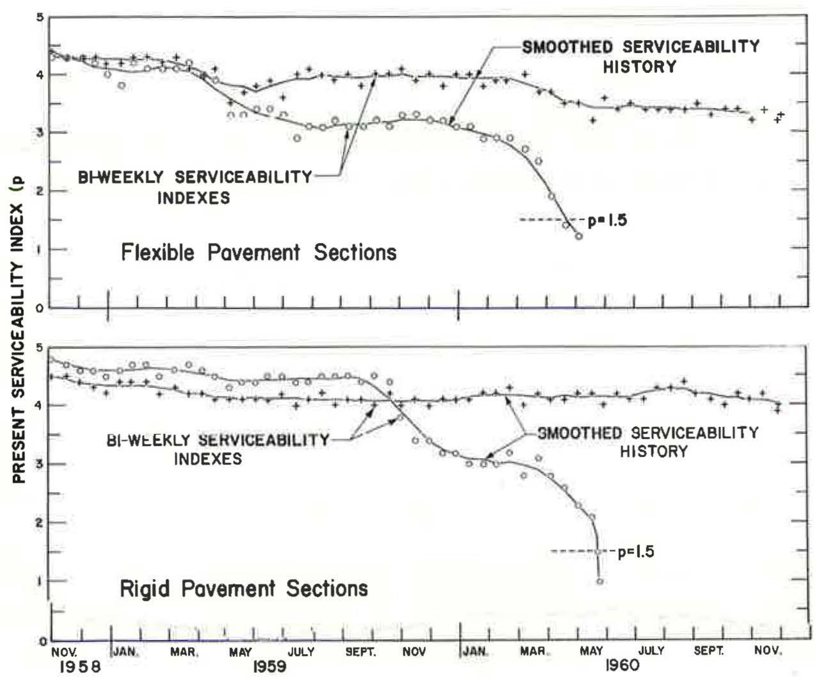


Figure 19. Typical serviceability histories.

TABLE 1

PAVEMENT FAILURE, BY SEASONS

Season	Axle-Load Applications ($\times 10^3$)	Seasonal Distribution Section Failure[1] (%)	
		Rigid	Flexible
Fall			
1958 Oct., Nov.	9	0	3
1959 Sept., Oct., Nov.	109	28	1
1960 Sept., Oct., Nov.	173	12	1
All	291	40	5
Winter			
1958-59 Dec., Jan., Feb.	64	0	4
1959-60 Dec., Jan., Feb.	167	11	5
All	231	11	9
Spring			
1959 March, April, May	59	0	57
1960 March, April, May	215	22	23
All	274	22	80
Summer			
1959 June, July, Aug.	109	3	3
1960 June, July, Aug.	209	24	3
All	318	27	6
Total	1,114	100	100

[1] A section was considered to have failed when its serviceability index dropped to 1.5. Table includes only factorial sections (first replicates) in Design 1.

sideration was also given to relative agreement with highway design practice and experience for traffic conditions beyond the Road Test.

The mathematical model ultimately chosen for both the flexible and rigid pavement analyses is of the form

$$p = c_o - (c_o - c_1)\left(\frac{W}{\rho}\right)^{\beta} \qquad (1)$$

in which

$c_1 \leqq p \leqq c_o$;

p = the serviceability trend value;

c_o = the initial serviceability trend value (for the Road Test $c_o = 4.5$ for rigid pavements, and 4.2 for flexible pavements—these values were the means of the initial serviceability of test sections);

c_1 = the serviceability level at which a test section was considered out of test and no longer observed (for the Road Test $c_1 = 1.5$);

W = the accumulated axle load applications at the time when p is to be observed and may represent either weighted or unweighted applications.

ρ and β are functions of design and load to be discussed later.

The assumed relationship between β and the design and load variables was

$$\beta = \beta_o + \frac{B_o\,(L_1 + L_2)^{B_2}}{(a_1 D_1 + a_2 D_2 + a_3 D_3 + a_4)^{B_1}\, L_2^{B_3}} \qquad (2)$$

in which

β_o = a minimum value assigned to β;

L_1 = the nominal load axle weight in kips (*e.g.*, for 18,000-lb single-axle load, $L_1 = 18$; for 32,000-lb tandem-axle load, $L_1 = 32$);

L_2 = 1 for single-axle vehicles, 2 for tandem-axle vehicles;

D_1, D_2 and D_3 = the three pavement design factors: surfacing, base and subbase thickness for flexible pavement; and reinforcement, slab thickness and subbase thickness for rigid pavement.

The remaining symbols of Eq. 2 are positive constants whose values were either to be assigned as was done for β_o or to be estimated by means of the analysis.

Equations in this same form were determined from analysis of the rigid pavement data and the flexibile pavement data, respectively.

The algebraic form assumed for the association of ρ with the design and load variables is

$$\rho = \frac{A_o\,(D + a_4)^{A_1}\, L_2^{A_3}}{(L_1 + L_2)^{A_2}} \qquad (3)$$

where D ($= a_1 D_1 + a_2 D_2 + a_3 D_3$) represents a "thickness index" of the pavement, L_1 and L_2 are as defined for Eq. 2, and the remaining symbols are constants whose values are either to be assumed or to be estimated from the analysis.

Evaluation of the constants in Eqs. 2 and 3 is reported in Chapter 6 for flexible and Chapter 7 for rigid pavements.

Eqs. 2 and 3 when evaluated and used in conjunction with Eq. 1 thus represent the first goal of the Road Test—to associate performance with design and load variables.

At various stages in the development of the equations, tests were made for the significance of pavement design factors, and statistics were computed to express the degree of correlation between observations and corresponding predictions from the equations. Finally, average residuals were used to indicate the extent to which observations were scattered from the corresponding calculated values of p and log W.

Average residuals, correlation indexes, and inferences from the significance tests are summarized in Report 5.

Many different models and fitting procedures were studied and one selected from which the performance equations fit the Road Test data with satisfactory precision. In time, other models may be found that also fit the data satisfactorily and which may prove equally or more useful.

PRESENT SERVICEABILITY INDEX FORMULAS

Flexible Pavement

$$p = 5.03 - 1.91 \log (1 + \overline{SV}) - 0.01\sqrt{C + P} - 1.38\overline{RD}^2 \qquad (4)$$

in which

p = present serviceability index;

$\overline{SV}$ = mean of the slope variance in the two wheelpaths;

$C + P$ = measures of cracking and patching in the pavement surface; and

$\overline{RD}$ = measure of rutting in the wheelpaths.

Rigid Pavement

$$p = 5.41 - 1.80 \log (1 + \overline{SV}) - 0.09\sqrt{C + P} \qquad (5)$$

in which

p = present serviceability index;

$\overline{SV}$ = mean of the slope variance in the two wheelpaths; and

$C + P$ = measures of cracking and patching in the pavement surface.

Chapter 6

Flexible Pavement Research

FLEXIBLE PAVEMENT EXPERIMENTS

Detailed descriptions of the flexible pavement experiments can be found in Road Test Report 1 (Special Report 61A). Comprehensive but less detailed descriptions appear in Chapter 2 of Road Test Report 5 (Special Report 61E).

About one-half of the pavement that comprised the test facilities at the AASHO Road Test was of the flexible type consisting of asphaltic concrete surfacing constructed on various combinations of base and subbase. In all, 468 test sections were provided. Each test section was 12 ft (one traffic lane) wide and most of them were 100 or 160 ft long.

More than half of the flexible test sections were included in the experiment to study the effect on pavement performance of varying the thicknesses of the structural layers of the pavement system and varying the test loading. Each loop that was tested under traffic (Loops 2 through 6) included test pavements with three different thicknesses of asphaltic concrete surfacing, three different thicknesses of crushed limestone base, and three different thicknesses of sand-gravel subbase (except Loop 2 where only two subbase thicknesses were tested). The axle loads that were applied over the test pavements increased by loops so that in Loop 2, 2,000-lb single-axle loads were operated in one lane and 6,000-lb single-axle loads in the other; and, at the other extreme, in Loop 6, 30,000-lb single-axle loads were operated in one lane and 48,000-lb tandem-axle loads in the other. The thicknesses of the components of the pavement structure were similarly increased loop by loop so that in Loop 2 the thinnest pavement consisted of 1 in. of asphaltic concrete surfacing on zero base and zero subbase and in Loop 6 the thickest pavement consisted of 6 in. of asphaltic concrete surfacing, 9 in. of crushed stone base, and 16 in. of sand-gravel subbase. Table 2 shows the pavement component thicknesses provided in all loops. Considerable overlap in pavement design across loops was provided so that many designs were common to two loops, several were common to three loops and a few appeared in four loops. This arrangement made it possible to study the effect of different loads on identical designs of pavements. In each loop a certain number of designs were replicated. Variation in the performance of sections constructed to identical designs in a given lane provided a measure of the effects of uncontrolled variables. It developed that such effects were small enough to leave practically no doubt as to the significance to the main variables in the flexible pavement test (design and load).

In addition to the main experiment described above, a similar set of test sections was constructed in Loop 1, but not subjected to any test traffic. Additional test sections were provided in Loop 1 to permit study of subsurface conditions. In Loop 2 an experiment containing 24 test sections utilizing surface treatment rather

TABLE 2

PAVEMENT COMPONENT THICKNESS
FLEXIBLE PAVEMENT

Item	Loop					
	3	6	5	2	1	4
Test axle loadings (lb)	12,000 S[1] 24,000 T	30,000 S 48,000 T	22,400 S 40,000 T	2,000 S 6,000 S	No Traffic	18,000 S 32,000 T
Factorial test sections	60	60	60	44	48	60
Special study sections	24	24	24	24	16	24
Asphalt concrete Surfacing thicknesses (in.)	2,3,4	4,5,6	3,4,5	0[2],1,2,3	1,3,5	3,4,5
Base thicknesses (in.)	0,3,6	3,6,9	3,6,9	0,3,6	0,6	0,3,6
Subbase thicknesses (in.)	0,4,8	8,12,16	4,8,12	0,4	0,8,16	4,8,12

Note: Designs of special study sections are not shown here.
[1] S = single, T = tandem axle configuration.
[2] Surface treatment.

than asphaltic concrete surfacing was included. In each of Loops 3, 4, 5 and 6, twelve test sections were set aside for a special study of the effectiveness of shoulder paving and twelve sections were provided for a special study of base type. In the base type studies, four bases were considered: crushed stone similar to that used in the main experiment, uncrushed rounded gravel as used in certain base construction in Illinois, bituminous-treated uncrushed sand-gravel, and cement-treated uncrushed sand-gravel.

The materials used in the flexible test pavements and the methods of construction are described in detail in AASHO Road Test Report 2 (Special Report 61B) along with comprehensive summarizations of materials control test data. In order to insure uniformity of the foundation for all test pavements, pavement structures were constructed over especially prepared embankment soil 3 ft thick. This embankment soil was taken from selected borrow areas in the vicinity of the project, hauled to the road site, and carefully compacted in nine 4-in. layers. The characteristics of this material are shown in Table 3. The characteristics of other materials used in the construction of the flexible pavement test sections are shown in Table 4.

TABLE 3

CHARACTERISTICS OF EMBANKMENT SOIL

Classification (AASHO M–145)	A–6
Average values, borrow pit samples:	
Max. dry density, AASHO T–99–49 (pcf)	116
Optimum moisture content (%)	15
Liquid limit (%)	29
Plasticity index	13
Grain size, finer than (%):	
No. 200	81
0.02 mm	63
0.005 mm	42
Specific gravity	2.71
Average of construction tests:	
Density (% max. dry dens.)	97.7
Moisture content (%)	16
Constructed embankment tests:	
Laboratory CBR, soaked	2–4
Field in-place CBR, spring	2–4
Modulus of subgrade reaction, spring, k	45

TABLE 4

CHARACTERISTICS OF MATERIALS, FLEXIBLE PAVEMENTS [1]

Item	Subbase	Crushed Stone Base	Gravel Base	Cement-Treated Base	Asphalt-Treated Base	Asphaltic Concrete	
						Surface Mix	Binder Mix
Aggregate gradation, % passing:							
1½-in. sieve		100	100				
1-in. sieve	100	90	98	100	100		100
¾-in. sieve	96	80		96	96	100	
½-in. sieve	90	68	74	90	90	92	75
No. 4 sieve	71	50	49	71	71	65	36
No. 40 sieve	25	21	23	25	25	22	13
No. 200 sieve	7	11	9	7	7	5	4
Plasticity index, minus No. 40 material	N.P.	N.P.	3.5				
Max. dry density[2] (pcf)	138	139	140	138	149[3]	151[3]	154[3]
Field density (% max. dry dens.)	102[4]	102	104	101	97	97	97
Asphalt[5] content (% total mix)					5.2	5.4	4.5
Cement[6] content (% by wt.)				4.0			
7-Day compressive strength (psi)				840			
Laboratory tests:							
Marshall stability					1,600	2,000	1,800
Marshall flow					10	11	11
Total voids (%)					6.2	3.6	4.8

[1] Identification: Subbase, uncrushed natural sand-gravel; Crushed stone base, crushed dolomitic limestone; Gravel base, uncrushed natural gravel; Treated base, asphalt cement or portland cement and subbase material; Asphaltic concrete, crushed dolomitic limestone and uncrushed natural sand with dolomitic limestone dust filler.
[2] AASHO T99-57.
[3] Laboratory density using Marshall procedure.
[4] Before subgrading.
[5] 85–100 penetration grade asphalt.
[6] Type I portland cement.

PAVEMENT PERFORMANCE

As discussed in Chapter 5 the performance of the test pavements under traffic was defined as the trend of the history of serviceability of the pavements with increasing load applications. The serviceability of the test pavements was determined every two weeks throughout the course of the traffic test by means of an index computed from measurements taken on the pavement surface. Serviceability of flexible pavements was lost as roughness in the wheelpaths increased, as cracking of the surfacing developed, as it was necessary to add patches to the pavement surface, and as ruts developed in the wheelpaths. These elements were measured at two-week intervals and, by means of an equation developed as a result of the work of the Pavement Rating Panel, a serviceability index value was computed for each section. The plot of the biweekly serviceability indexes against increasing numbers of load applications formed the serviceability history for each test section. Figure 20 shows typical serviceability histories for three flexible pavement sections and three rigid pavement sections. Data taken from the histories at the points shown on the curves were analyzed to find the relationships between performance, design and loading.

These performance analyses resulted in equations that show mathematically the relationships sought in the first Road Test objective. These equations are most conveniently displayed in graphical form. Figure 21 is a plot from the equations showing the flexible pavement structures needed for any given number of weighted axle-load applications in order to prevent deterioration of the pavement's serviceability to the point below 2.5 (mid-fair serviceability). Weighted axle-load applications are applications adjusted to account for the fact that load applications generally cause more distress in the spring than the same number of applications would cause in the summer or in the fall. Pavement structure is represented by a thickness index which is simply a combination of surfacing, base and subbase given by the formula shown. This combination is such that about 1 in. of surfacing is equivalent to 3 in. of base or 4 in. of subbase.

The equations and curves represent serviceability trend data observed in a large number of test pavements. Some Road Test sections failed sooner and some later than indicated by the smoothed curves; thus, some allowance should be made for the scatter of the data. Through a statistical analysis it was found that the scatter corresponds to approximately ±14 percent of the thickness index values given by the curves. If comparisons are made with observed performance of actual highways in service, additional allowance should be made to account for differences between the Road Test and the actual highway in materials, method of construction, environment and loading history.

These relationships are not intended to be design equations; however, they can serve as a basis for design procedures in which variables that were not included in the Road Test, such as soil type, are considered.

The relationships shown in Figure 21 can also be shown in a different form as in Figure 22. The thickness index has the same meaning as in Figure 21 and represents the thicknesses of the structural components of the pavement. Figure 22 plots the thickness index against load. The different sets of curves are for different numbers of applications of load sustained by the test pavements before the serviceability fell to 2.5.

The relationship between single and tandem axle configuration can be readily determined

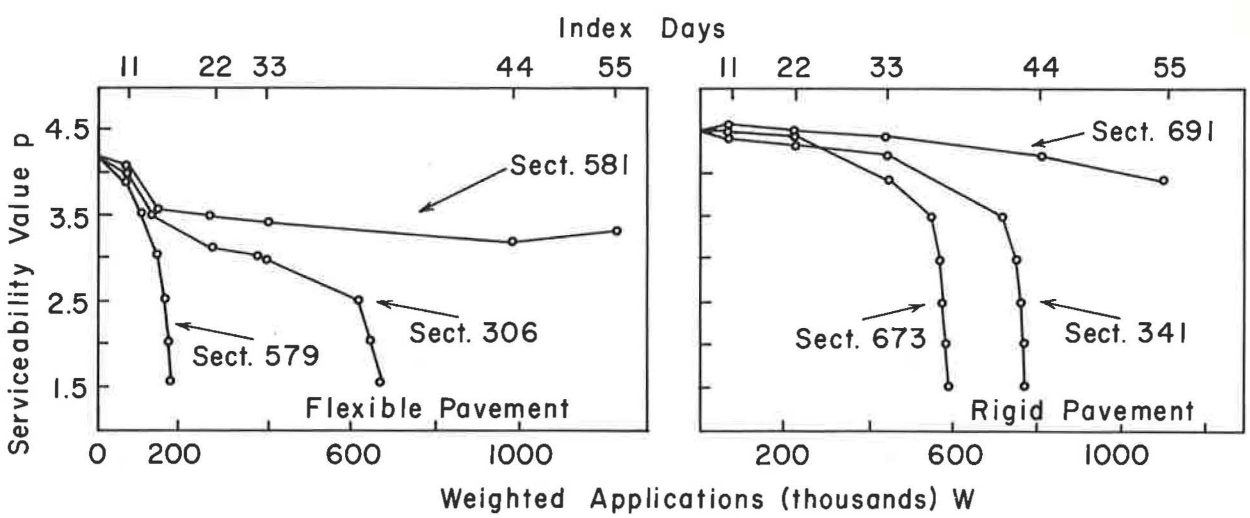


Figure 20. Pavement serviceability trends.

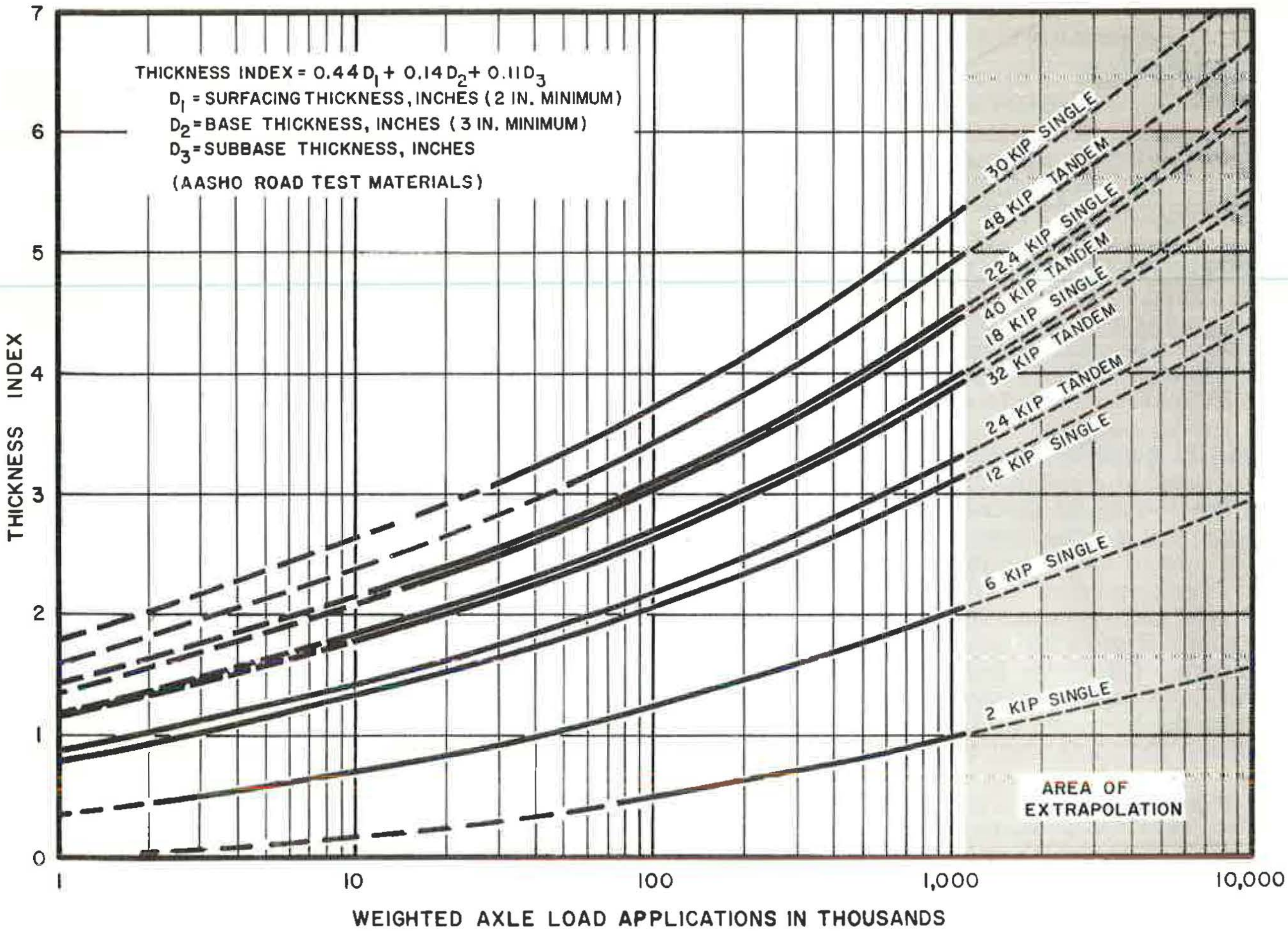


Figure 21. Main factorial experiment, relationship between design and axle application at $p = 2.5$ (from Road Test equations).

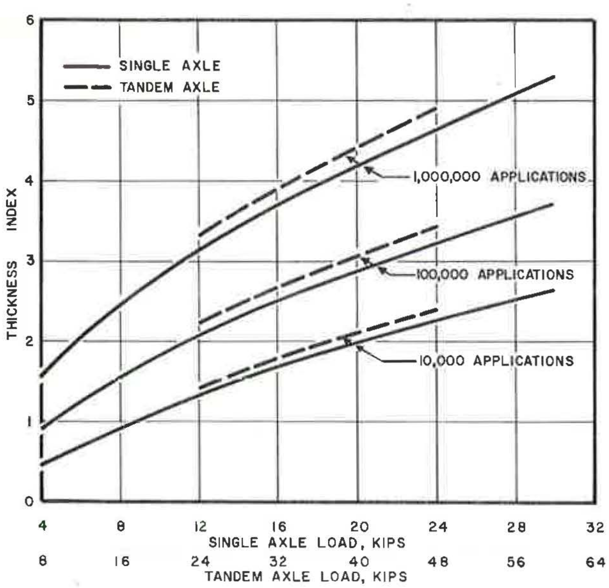


Figure 22. Main factorial experiment, relationship between design and load at $p = 2.5$.

for flexible pavements from Figure 22. It can be seen that a pavement, under Road Test conditions, with thickness index slightly less than 4.0 would withstand 1,000,000 applications of an 18-kip single-axle load before its serviceability fell to 2.5. A pavement with the same thickness index would withstand a million applications of a tandem-axle load of about 33,000 lb for the same loss in serviceability. Similar equivalencies may be found for other loads; *e.g.*, 22,400-lb single versus 41,000-lb tandem.

The equations from which these curves (Figs. 21 and 22) were plotted are among the most important findings of the AASHO Road Test. Here for the first time a test program of sufficient magnitude has been conducted to establish the effect of load repetitions on pavement performance. Engineers can now estimate how much difference there will be in the requirements for pavement structure if axle loads or frequency of loading are changed or if additional service life is desired. Also, for a given pavement structure, engineers can estimate how much difference in life can be expected if axle loads or frequency are changed. Furthermore, for a given axle load and for an estimated number of axle-load applications, the pavement structure needed to prevent deterioration to any specified level of serviceability can be determined. Of course, these findings apply specifically only to Road Test conditions. Generalizations to other areas, materials, and climates will require experimental or other evidence of the effects of other conditions on performance.

PAVED SHOULDER EXPERIMENT

All results from the AASHO Road Test were not positive or useful. The flexible pavement experiment in which the effectiveness of paved shoulders was studied is an example of one that was not. Here the designers of the experiments chose over-all pavement structures for the paved shoulder experiments that were too thin to survive more than about 100,000 load applications. Consequently, with few exceptions, all of the sections failed early in the test regardless of the width of paved shoulder. It was concluded that the experiment produced no clear evidence of any effect of paved shoulders on performance of the test pavements. If thicker designs had been used the effect of paved shoulders on performance might well have been more evident.

ANALYSIS BY WHEELPATHS

Observation of the Road Test flexible pavements disclosed that distress generally started in the outer wheelpath near the pavement edge and progressed more rapidly in this wheelpath than it did in the inner wheelpath near the pavement centerline. Since the data from which serviceability histories were constructed were taken by wheelpaths, it was possible to perform analyses of the performance of the flexible pavement by wheelpaths. An independent analysis of the inner wheelpath performance was made as was an analysis of the outer wheelpath performance. These analyses disclosed that the performance relationships previously described for both wheelpaths had very nearly the same characteristics as those for the outer wheelpath alone. This indicates that since most distress in flexible pavement generally occurs first in the outer wheelpath, pavement structure designs based on the requirements for the outer wheelpath alone may be nearly the same as the structure design needed for an entire pavement. On the other hand, the analysis of inner wheelpath performance when compared with over-all section performance disclosed that appreciably less pavement structure was required for the inner wheelpath than was required for the outer wheelpath or the section as a whole. For example, in all lanes except under the 2-kip load about 2 in. more asphaltic concrete, or 6 in. more base, would have been required for the outer wheelpath for the entire test section to prevent loss of serviceability to 2.5 for a million load applications than was required for the inner wheelpath.

SPECIAL BASE TYPE EXPERIMENTS

An important investigation within the flexible pavement experiment involved a study of the relative effectiveness of certain treated and untreated bases. Four base types were studied: crushed stone, uncrushed gravel, and cement-treated and bituminous-treated sand-gravel. There were 12 test sections in each of Loops 3, 4, 5 and 6 in this study. The bases in this experiment were constructed in wedge shapes varying from thick to thin in the direction of traffic. Each section was 160 ft long and for purposes of study was divided into four 40-ft subsections. The average base thickness varied from subsection to subsection in about 3-in. increments.

The experiment design was such that no mathematical analysis of the performance was attempted. A graphical analysis was made that permits comparison of the performance of the stone, cement-treated and bituminous-treated bases. Most of the sections containing the untreated gravel base failed early in the test and are omitted from the major analyses of performance.

Table 5 gives the results of the graphical analysis. The thickness of each base type needed to prevent loss of serviceability below 2.5 at 1,114,000 applications (the end of the traffic test) are given for the various Road Test loads. The base thickness figures apply to pavement structures that also include 3-in. asphaltic concrete surfacing and 4-in. subbases.

TABLE 5

THICKNESS OF BASE[1] REQUIRED TO MAINTAIN SERVICEABILITY AT $p = 2.5$ AT 1,114,000 LOAD APPLICATIONS, FROM GRAPHICAL ANALYSIS

Load (lb)	Cement-Treated Uncrushed Sand-Gravel	Crushed Dolomitic Limestone	Bituminous-Treated Uncrushed Sand-Gravel
12,000 S[2]	7[3]	10	3
24,000 T[2]	7[3]	12	4
18,000 S	8	13	5[3]
32,000 T	8	13	6[3]
22,400 S	10	15[3]	7
40,000 T	10	15[3]	7
30,000 S	12	20	11
48,000 T	11	18	10

[1] With 3-in. asphaltic concrete surfacing and 4-in. subbase.
[2] S = single axle; T = tandem axle configuration.
[3] Interpolated or extrapolated values.

Examination of Table 5 discloses that the treated bases were far superior to the untreated bases, and that the bituminous-treated base was somewhat better than the cement-treated base in resisting loss of serviceability under load. It should be noted that these treated bases were of a relatively high type. The cement-treated base had 4 percent cement by weight and an 840-psi 7-day compressive strength, and the asphalt-treated base had 5.2 percent asphalt cement and a Marshall stability of 1,600 (Table 4).

STRUCTURAL DETERIORATION

As previously stated, flexible pavements lost serviceability when they developed roughness along the wheelpaths, cracking, ruts in the wheelpaths, and when it was necessary to patch the pavements. Considerable study was devoted to the behavior of the various pavement components and their influence on these modes of serviceability loss. Transverse profiles were determined from precise level surveys and from an automatic electronic profile device, thickness measuring instruments were installed in the pavement, trenches were cut transversely in failed sections, and the development of rutting in the wheelpaths was frequently measured as was longitudinal profile with the AASHO profilometer. Some of the instruments used in these measurements are shown in Figures 23, 24, and 25.

The trench studies disclosed that rutting was due primarily to decreases in thickness of the surfacing, base and subbase. The data showed that, on the average, 32 percent of the surface rut was due to decrease in surface thickness, 14 percent to decrease in base thickness, 45 percent to decrease in subbase thickness, and only 9 percent to a rut in the embankment material.

Decreases in thickness of the layers of material were apparently caused only to a small extent by additional compaction or consolidation under the traffic. Thus, it was assumed that a large part of the rutting was associated with movement of the material laterally from the center of the wheelpaths.

In sections that survived the test, rutting developed at a faster rate during the first year of traffic than during the second year. In test sections in the special base experiment there appeared to be an optimum thickness for each load and base type insofar as rutting was concerned. As base thickness increased from this optimum, rut depth remained essentially constant. As base thickness decreased from this optimum, rut depth increased rapidly.

Careful records were kept of the formation of cracks in the pavement surfacing. An equation was developed for computing the number of axle loads sustained by a pavement before alligator cracking appeared. This equation disclosed that for the same thickness the surfacing material was 3.3 times as effective as the base material and about 4 times as effective as the subbase material in preventing surface cracking. Figure 26 shows the types of distress noted in the flexible pavements.

DEFLECTION STUDIES

The fifth Road Test objective called for means to estimate future pavement performance based on measurements that could be taken early in the life of a pavement. A great deal of effort at the Road Test and the greatest part of the million-dollar instrumentation program was directed towards the fulfillment of

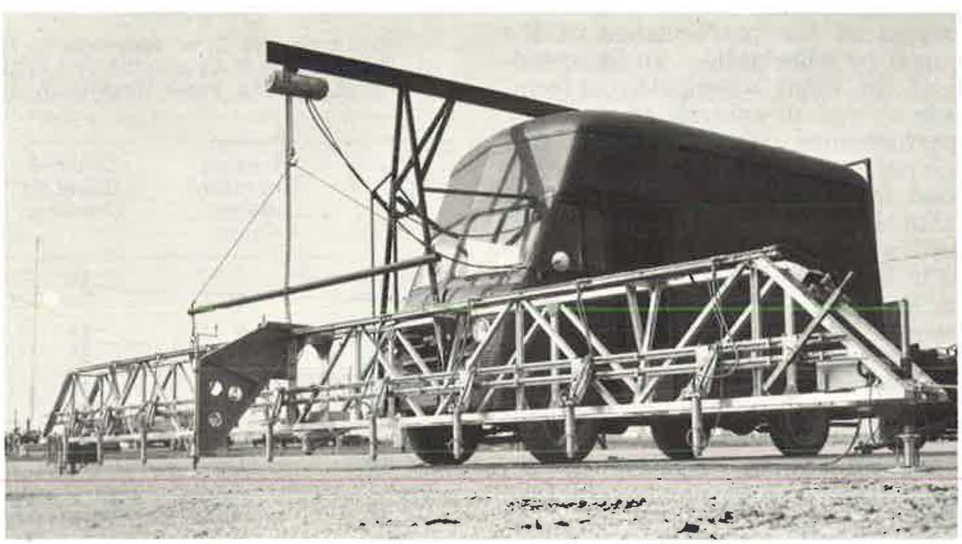


Figure 23. Transverse profilometer truss and van.

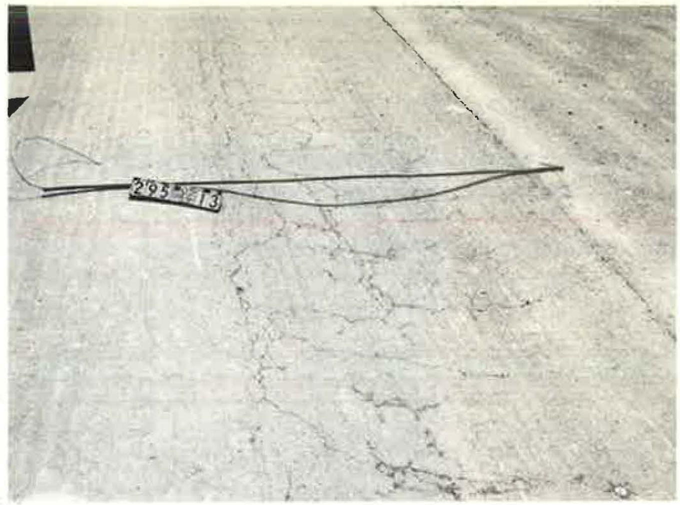
Figure 24. Electrical device used to measure vertical movement of pavement.

this objective. In flexible pavements deflections of the pavement surface measured under moving wheel loads proved to be good predictors of future pavement performance.

A high degree of correlation was found between pavement design and deflections measured in the fall immediately after the construction of the pavement. There was also high correlation between deflections measured in the critical spring period and pavement design. These relationships for the various Road Test single-axle loads are shown in Figure 27. D_1, D_2 and D_3 are the thicknesses in inches of surfacing, base and subbase, respectively; d is

Figure 25. Manual rut depth gage.

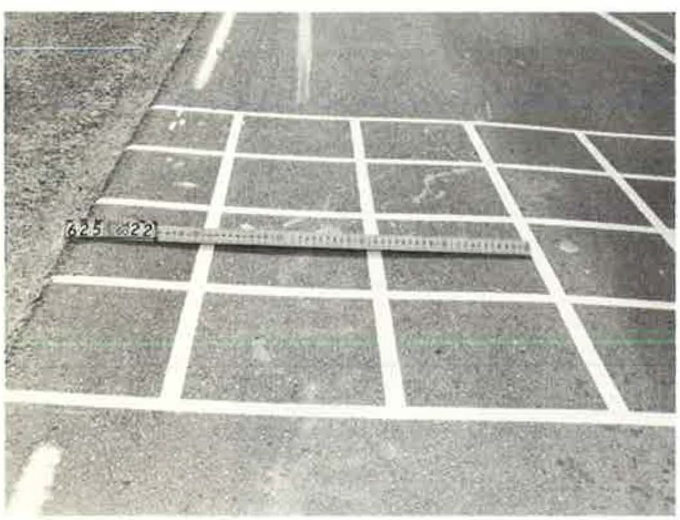
Evidence of longitudinal rutting, water in wheelpaths after a rain in a no-traffic period.



Pronounced rutting, Class 2 cracking.

Minor rutting, slight displacement of transverse grid lines in wheelpaths.

Class 2 cracking.



Moderate rutting, no displacement of longitudinal grid line.

Class 3 cracking.

Figure 26. Typical distress in flexible pavement.

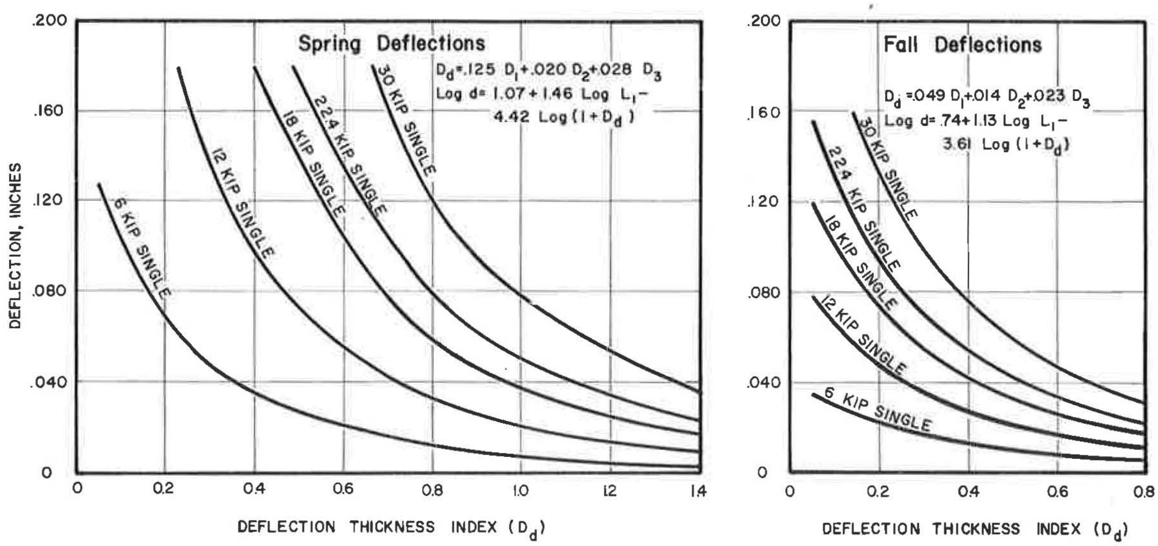


Figure 27. Relationship between pavement design and creep speed deflection (from Road Test equations).

deflection in inches; and L_1 is axle load in thousands of pounds.

Equations were also derived to relate deflection to load, to vehicle speed, and in the nontraffic loop, to seasons of the year. Deflections of flexible pavement surfacing increased almost linearly with load and decreased with increasing vehicle speed. Increasing vehicle speed from 0 to 50 mph resulted in about a 50 percent reduction in deflection.

Studies were also made of the effect of surfacing temperature on deflection. It was shown that deflections increased with surface temperature up to about 70 or 80 degrees and remained essentially constant above this level.

The main purpose of the deflection studies as previously stated was to show relationships between deflection and future pavement performance. Figure 28 shows graphically the results of these studies. The curves were plotted from equations developed from the deflection-performance data. Axle applications are plotted on the vertical scale in logarithmic form. The applications shown are the number of loads that can be applied before the pavement reaches a serviceability of 2.5. On the horizontal scale the deflection is shown. The curves on the left were derived from deflection data taken in the fall of 1958 immediately after construction was completed and prior to test traffic. The curves on the right were developed from deflections taken in the critical spring period. From the right-hand curves it can be seen that if the spring deflection under an 18,000-lb single-axle load was about 0.035 in. the pavement withstood on the average one million ap-

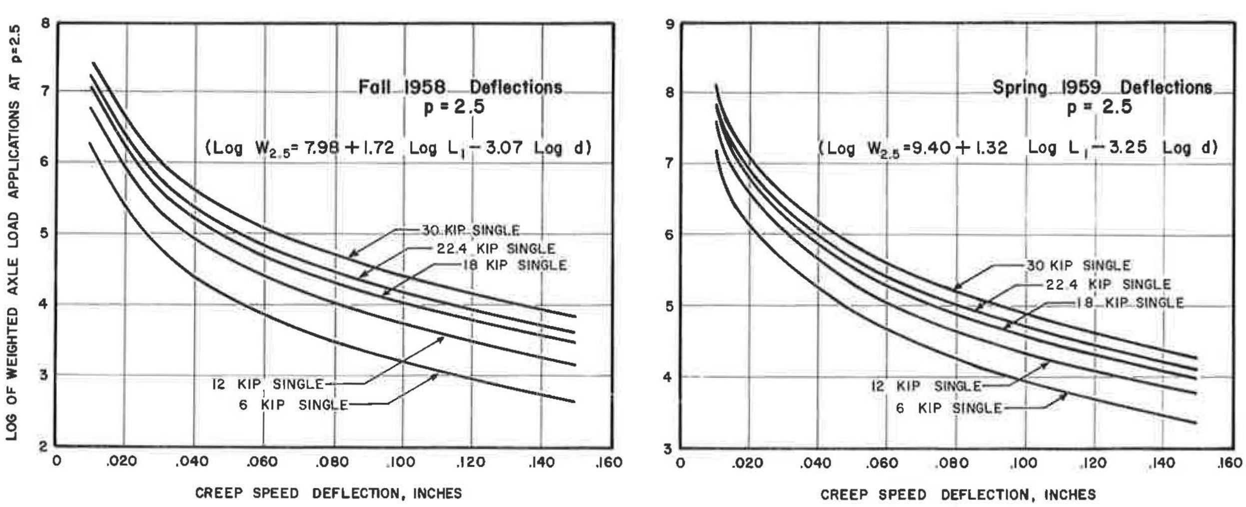


Figure 28. Main factorial experiment, relationship between performance and creep speed deflection (from Road Test equations).

plications (log of 1,000,000 = 6.0) of 18,000-lb single-axle loads before its serviceability fell to 2.5. However, if the spring deflection under the same load was of the order of 0.073 in. the pavement withstood only 100,000 18,000-lb axle applications (log of 100,000 = 5.0).

STUDY OF OVERLAYS

A study of the effectiveness of asphaltic concrete overlays included 99 flexible pavement test sections. It was clear that overlays were highly effective as a means for extending the service life of these pavements.

Attempts at mathematical analysis designed to establish specific relationships between performance and overlay design were unsuccessful, because the outcome of each analysis proved to be highly dependent on the assumptions made concerning the mathematical model for the analysis. Further work will be attempted by the Highway Research Board.

Chapter 7

Rigid Pavement Research

RIGID PAVEMENT EXPERIMENTS

Detailed descriptions of the rigid pavement experiments can be found in Road Test Report 1 (Special Report 61A). Comprehensive but less detailed descriptions appear in Chapter 3 of Road Test Report 5 (Special Report 61E).

About half of the pavement that comprised the test facilities at the AASHO Road Test was of the rigid type consisting of portland cement concrete surfacing constructed on various thicknesses of sand-gravel subbase or directly on the embankment soil. A total of 368 rigid pavement test sections were provided. Each was 12 ft wide and about half of them were 120 ft long and the other half were 240 ft long.

Most of the rigid test sections were included in the experiment to study the effect on pavement performance of varying thicknesses of the concrete slab and subbase, the effect of varying the reinforcement of the concrete and the effect of varying the test loading. Each test loop that was tested under traffic included test pavements with four different thicknesses of portland cement concrete surfacing (except Loop 2 where three slab thicknesses were provided) and three different sand-gravel subbase thicknesses. Half of the pavements contained mesh reinforcement and tranverse joints with dowels for load transfer. Joints were spaced at 40-ft intervals in the reinforced slabs. The other half of the rigid pavements had no mesh reinforcing, but the transverse joints were also doweled. The joint spacing in the nonreinforced pavements was 15 ft. Loads operated over the rigid pavements were identical to those applied over the flexible test pavements.

The thicknesses of the components of the pavement structure were increased loop by loop. The thinnest pavement (Loop 2) consisted of 2.5 in. of portland cement concrete on no subbase, and the thickest pavement (Loop 6) consisted of 12.5 in. of portland cement concrete on 9 in. of subbase. Table 6 shows the rigid pavement variables provided for all loops. As in the flexible pavement experiment, many designs were common to two loops, several were common to three loops, and twelve designs were common to Loops 3, 4, 5 and 6. This arrangement made it possible to study the effects of different loads on identical pavement designs. In each loop a certain number of designs were replicated in order to provide a means for determining the magnitude of experimental error.

In addition to the main experiment described above, a similar set of test sections was constructed in Loop 1, but not subjected to test traffic. Additional test sections were provided in Loop 1 to permit study of subsurface conditions. In each of Loops 3, 4, 5 and 6, twelve additional test sections were provided for a study of the effectiveness of shoulder paving and a study to compare performance of slabs on subbase with performance of slabs resting immediately on embankment soil.

The materials used in the rigid test pave-

TABLE 6

PAVEMENT COMPONENTS
RIGID PAVEMENT

Item	Loop					
	3	6	5	2	1	4
Test axle loadings (lb)	12,000 S[1] 24,000 T	30,000 S 48,000 T	22,400 S 40,000 T	2,000 S 6,000 S	No Traffic	18,000 S 32,000 T
Factorial test sections	56	56	56	40	48	56
Special study sections	12	12	12		8	12
Concrete slab thicknesses (in.)	3.5, 6.5, 5.0, 8.0	8.0, 11.0, 9.5, 12.5	6.5, 9.5, 8.0, 11.0	2.5, 3.5, 5.0	2.5, 9.5, 5.0, 12.5	5.0, 8.0, 6.5, 9.5
Subbase thicknesses (in.)	0[2],3,6,9	0[2],3,6,9	0[2],3,6,9	0,3,6	0,6	0[2],3,6,9

Note: All slab thicknesses occur as both reinforced and plain pavement.
[1] S = single, T = tandem axle configuration.
[2] Not in factorial experiments.

ments and the methods of construction are described in detail in AASHO Road Test Report 2 (Special Report 61B) along with comprehensive summarizations of materials control test data. As on the flexible pavement test tangents, pavement structures were constructed over a specially prepared embankment soil 3 ft thick. The characteristics of this material are given in Table 3. The characteristics of the other materials used in the construction of the rigid pavement test sections are given in Tables 4 and 7. Mesh reinforcement, dowel and tie bars were selected in accordance with ACI recommendations for the slab thicknesses involved.

As for the flexible sections, construction of rigid test pavements was performed by paving contractors working under rigid specifications and strict controls in the interest of obtaining uniformity of the pavement components. No extraordinary measures for increasing pavement life were taken. The specifications were such as to provide pavement components similar to those obtained in normal highway construction.

PAVEMENT PERFORMANCE

Rigid pavement performance was also defined as the trend of the history of serviceability with increasing load applications. Serviceability of the test pavements was determined every two weeks throughout the course of the traffic test by means of an index computed from measurements taken on the pavement surface. Serviceability of rigid pavements was lost as roughness in the wheelpaths increased, as large cracks developed in the surface, and as it was necessary to add patches to the pavement surface. The plot of the biweekly serviceability indexes against increasing number of load applications formed the serviceability history for each test section. Data taken from these histories were analyzed to find the relationships among performance, design and loading.

TABLE 7

CHARACTERISTICS OF MATERIALS, RIGID PAVEMENT[1]

Item	For Pavement Thicknesses	
	5 In. and Greater	2.5 and 3.5 In.
Design characteristics:		
Cement content, bags/cu yd	6.0	6.0
Water-cement ratio, gal/bag	4.8	4.9
Volume of sand,[2] percent total agg. vol.	32.1	34.1
Air content, %	3–6	3–6
Slump, in.	1.5–2.5	1.5–2.5
Maximum aggregate size,[3] in.	2.5	1.5
Compressive strength, psi:		
14 days	4,000	4,000
1 year	5,600	6,000
Flexural strength, psi:		
14 days	640	670
1 year	790	880

[1] For characteristics of subbase, see Table 4; Type I cement was used.
[2] Uncrushed natural sand.
[3] Uncrushed natural gravel.

These analyses yielded equations that show mathematically the relationships sought in the first Road Test objective. The equations are most conveniently displayed in graphical form. Figure 29 is a plot prepared from the equations showing the pavement structure needed for any given number of weighted applications in order to prevent deterioration of the pavement's serviceability below 2.5. The axle-load applications are not weighted as they were in the case of the flexible pavement experiment since no rational weighting function for rigid pavements was found.

The vertical scale (Fig. 29) contains slab thickness only. It was not found necessary to include a term for subbase thickness in the equation nor a term for pavement reinforcement. Although pavements with subbase performed considerably better than those on the embankment soil, no significant effect of varying subbase thickness over the range from 3 to 9 in. was found. Furthermore, there was no significant difference in performance of those sections having 40-ft joints and mesh reinforcement and those sections having 15-ft joint spacing and no reinforcement. As previously stated, the transverse joints in all concrete sections had load transfer dowels.

As in the case of the flexible pavements, the equations and curves represent serviceability trend data from a large number of test pavements. Some Road Test sections failed sooner and some later than indicated by the smooth curves; thus, some allowance should be made for the scatter of the data. The scatter of Road Test rigid pavement performance data was such that the slab thickness may be estimated from the equations to within about ±12 percent. As for flexible pavements, the performance of actual rigid pavements in service may well vary from that predicted by the Road Test performance equations due to the fact that conditions and materials, environment and loading are unlikely to be identical to those at the Road Test.

Figure 30 was also developed from the rigid pavement performance equations. Here the required slab thickness is plotted against axle load for three different numbers of load applications sustained before the serviceability fell to 2.5. These curves provide a convenient means to determine the tandem-axle load that will be associated with performance equivalent to that under any given single-axle load. For example,

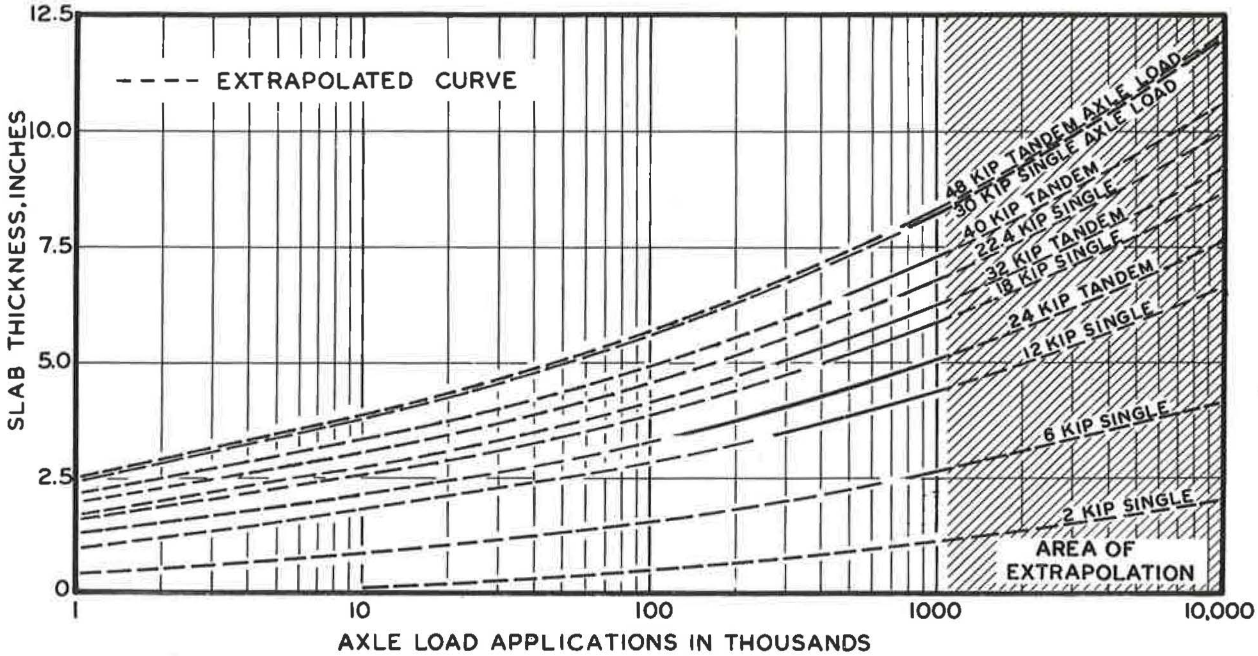


Figure 29. Rigid pavement performance curves from Road Test equation, experiment design 1, for p = 2.5.

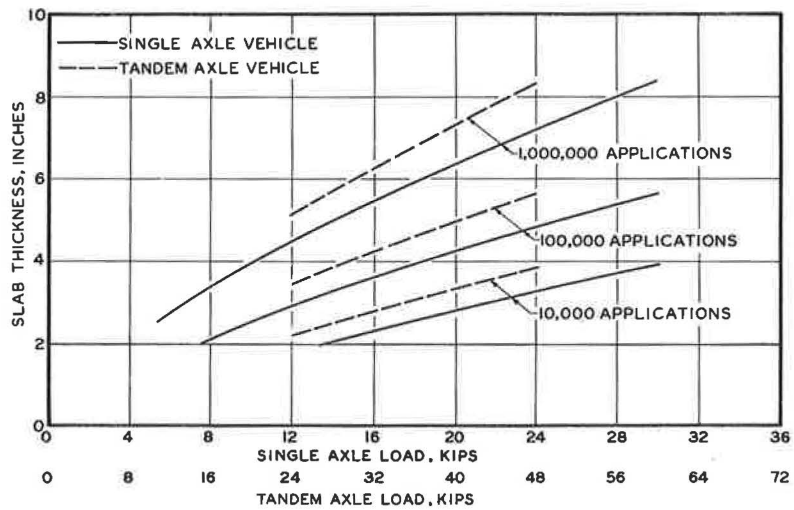


Figure 30. Single-tandem axle load relationship from Road Test equation, experiment design 1, for p = 2.5. All curves extrapolated except 1,000,000 applications.

according to Figure 30, a 6-in. slab carried 1 million applications of 18,000-lb single-axle load or 1 million applications of 29,000-lb tandem-axle load before its serviceability fell to 2.5. Other similar equivalencies may also be found; *e.g.*, 22,400-lb single versus 36,000-lb tandem.

The equations from which these curves were developed are the most important findings of the rigid pavement experiment. From these equations, for conditions similar to Road Test conditions, engineers can determine how much difference there will be in the requirements for pavement structure if axle loads are changed, or for a given pavement structure, how much the life may be affected if axle loads are changed. Also for a given axle load and an estimated number of axle-load applications the pavement structure needed to prevent deterioration to a specified level of serviceability can be determined.

SUBBASE—PAVED SHOULDER EXPERIMENT

No increase in life resulted from use of paved shoulders. However, the results may have been affected in some cases by damage to the shoulders by test traffic. Sections with subbase had an average life about one-third longer than that of sections without subbase.

STRUCTURAL DETERIORATION

Rigid pavements lost serviceability when they developed roughness along the wheelpaths, when cracking developed, and when it was necessary to patch the pavement surface. Careful records were maintained of the development of cracks in paving slabs and of pumping of material from beneath the slabs. Transverse trenches were cut through many failed sections to permit the study of subsurface components.

These studies disclosed that all failures in rigid pavements were preceded by pumping of material from beneath the concrete slabs. Generally, this material consisted of the subbase gravel including the coarser fractions. Pumping of embankment soil was generally confined to those sections constructed without subbase. Severe pumping of the subbase material was experienced only in the sections with the two thinner slab thicknesses in each loop. However, some pumping appeared in all sections (except Loop 2, lane 1). Very little material pumped through joints or cracks—rather, the major pumping noted was along the pavement edge. Figure 31 shows typical examples of edge pumping.

Pumping apparently was not related to subbase thickness nor was any consistent difference found between pumping in reinforced and nonreinforced pavements.

At the end of test traffic, data indicated that pumping increased as load increased (the greater the load the more the pumping, given equal slab thickness) and decreased as slab thickness increased (the thicker the slab the lesser the pumping, given equal load).

Faulting occasionally occurred at cracks but never at transverse joints (all joints were doweled). There was a tendency for the cracking per unit of surface area in reinforced sections with 40-ft panel lengths to exceed that in nonreinforced sections with 15-ft panel lengths. No part of the cracking of pavements in the traffic loops was attributed solely to environmental changes since no cracks were observed in the non-traffic loop.

From cracking data, equations were derived from which the number of axle applications associated with any level of cracking can be computed for a given pavement design and load. Figure 32 shows the four classes of cracks reported in the Road Test cracking surveys. Figure 33 shows the development of cracking in a test section with increasing load applications.

STUDIES OF STRAIN AND DEFLECTION

Within the rigid pavement experiment considerable study was devoted to developing means for predicting future pavement performance from dynamic measurements of strains or deflections under moving loads. Furthermore, studies of strain distribution on the surface of pavement slabs were made.

The first phase of this study involved determination of relationships between strains and deflections on the one hand, and pavement design, load, temperature and speed on the other. Road Test Report 5 includes graphs and equations showing these relationships.

The second phase of the study involved determination of equations by which future performance could be predicted from strain and deflection measurements. The average life (to a serviceability of 2.5) of sections all having the same slab thickness could be predicted with satisfactory accuracy from the average of 24 edge strains measured at the same point at different times under a moving single-axle load. Similar predictions could be made from slab edge and corner deflections measured under standing or creep speed loads. However, these predictions were somewhat less accurate.

Observations of deflections measured under loads disclosed that the general level of deflections measured at approximately the same time of day over a period of several months did not change appreciably with increasing number of load applications. Other factors being equal, strains and deflections were directly proportional to magnitude of load; that is, the heavier the load, the greater the strain or deflection.

Air temperature and radiation and the resultant temperature differences between top and bottom of the slabs had a considerable effect on the deflections at slab corners which sometimes increased severalfold from afternoon to early morning of the following day. Strains and deflections measured at a point 7.5 ft from the transverse joint along the pavement edge were also affected but not to such a great extent. The corner deflection of the 40-ft reinforced slabs usually exceeded the deflection of the 15-ft nonreinforced slabs provided load, slab thickness, and temperature conditions were the same. On the other hand, strain and deflections measured 7.5 ft from the joint along the pavement edge were not affected significantly by panel length.

Edge strain and corner deflection decreased as vehicle speed increased. For example, an increase in speed from 2 to 60 mph decreased the strain or deflection by about 30 percent.

Figures 34, 35, 36, 37, 38 and 39 illustrate some of the instrumentation used in measuring strain and deflection in the rigid pavements at the Road Test.

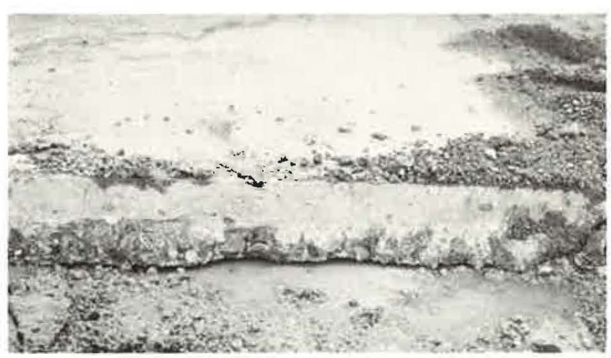
Void in shoulder through which subbase material was ejected from beneath pumping slab.

Subbase material ejected from beneath pavement overnight and deposited along edge.

Typical pile of subbase material pumped from beneath pavement, showing change in gradation of material from fine to coarse in direction of traffic, toward reader.

Embankment material pumped from beneath a pavement constructed without a subbase.

This void beneath pavement extended more than 5 ft from edge.



Transverse cross-section of a pumping slab showing void beneath pavement.

Figure 31. Examples of pumping.

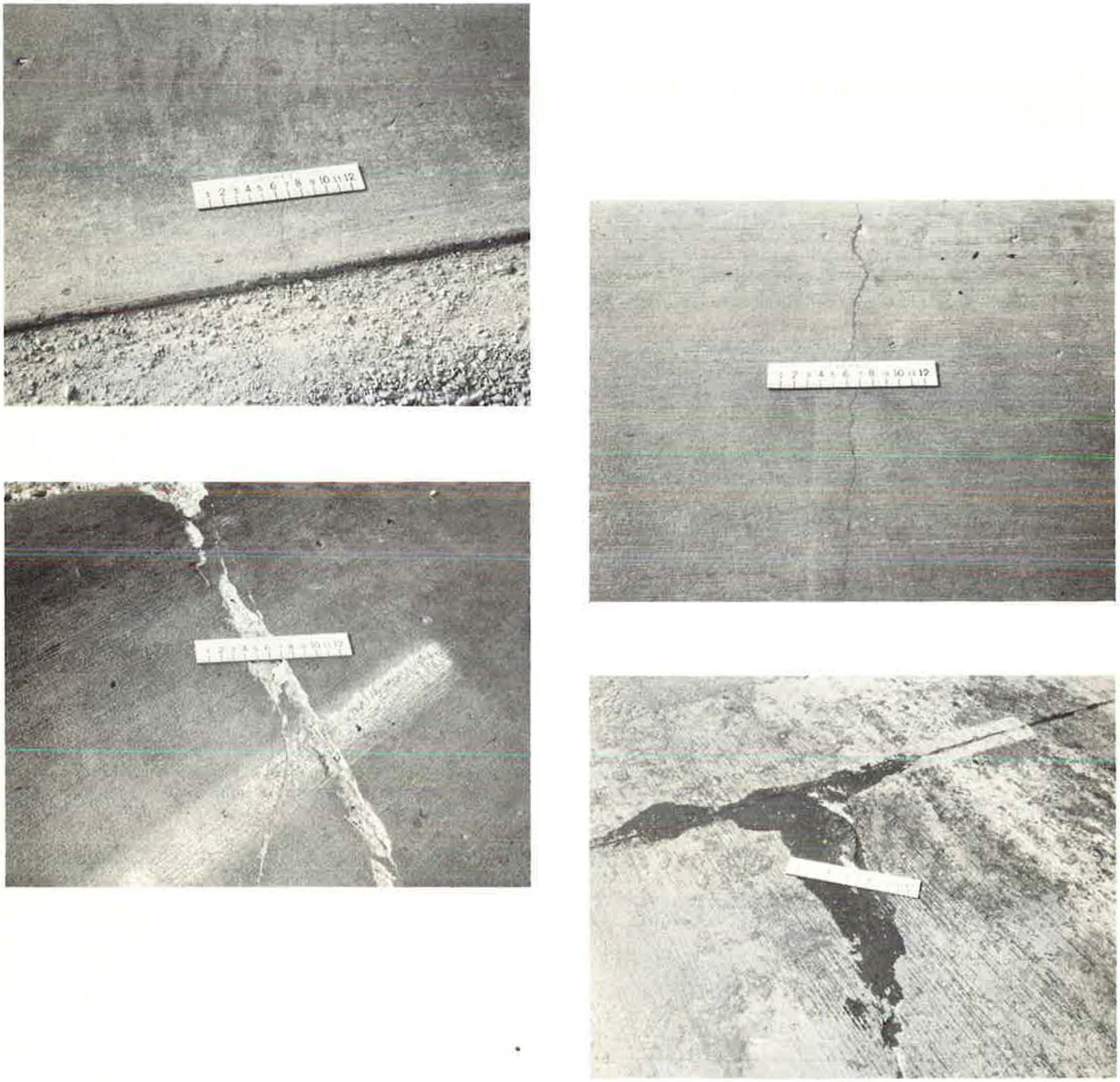


Figure 32. Examples of the four classes of cracks in rigid pavement at the Road Test: upper left, Class 1; upper right, Class 2; lower left, Class 3; lower right, Class 4. Only Class 3 and 4 cracks entered into the determination of the serviceability index.

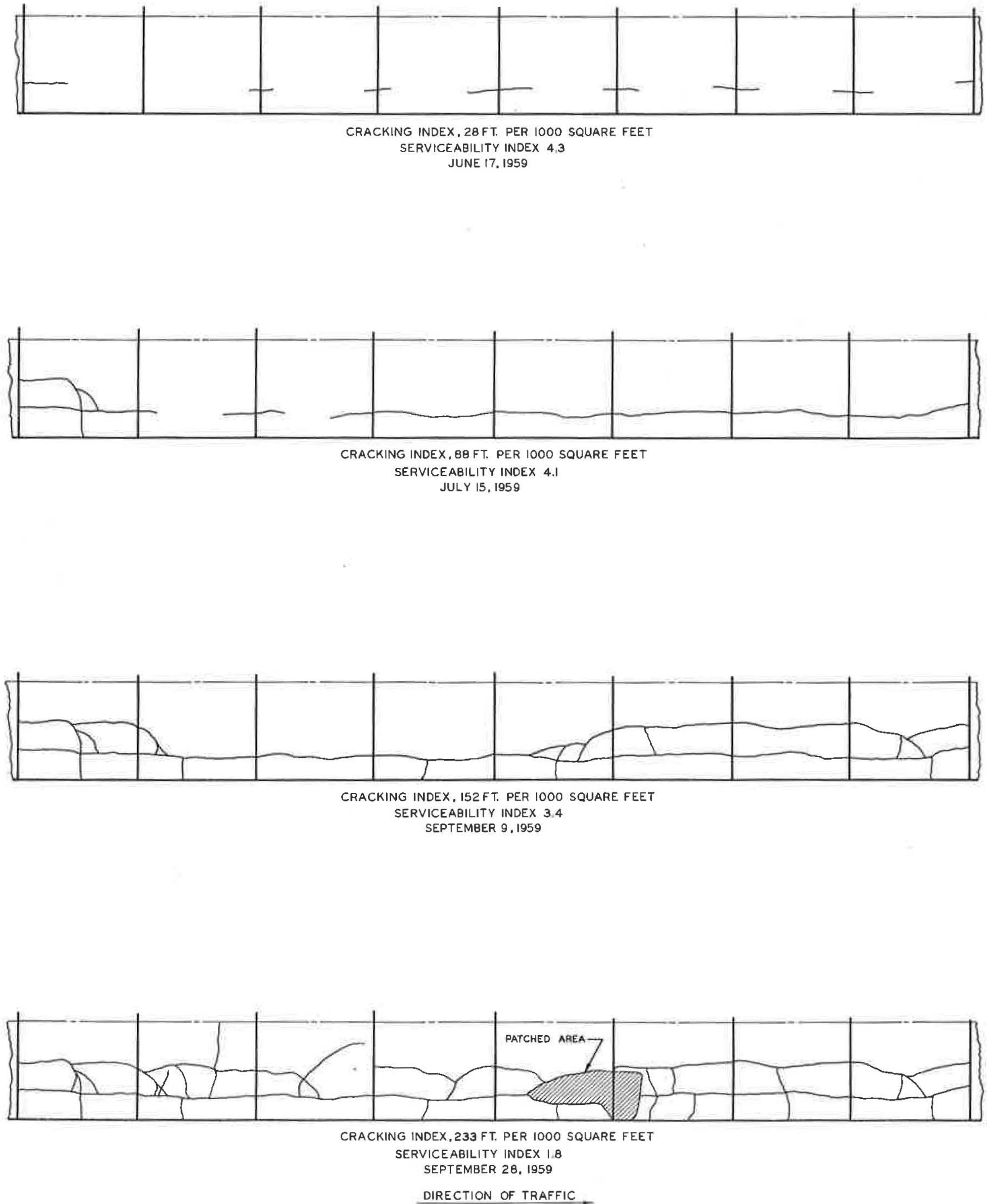


Figure 33. Progression of cracking in a 3.5-in. nonreinforced section with paved shoulders on 6.0 in. of subbase, 24-kip tandem-axle load.

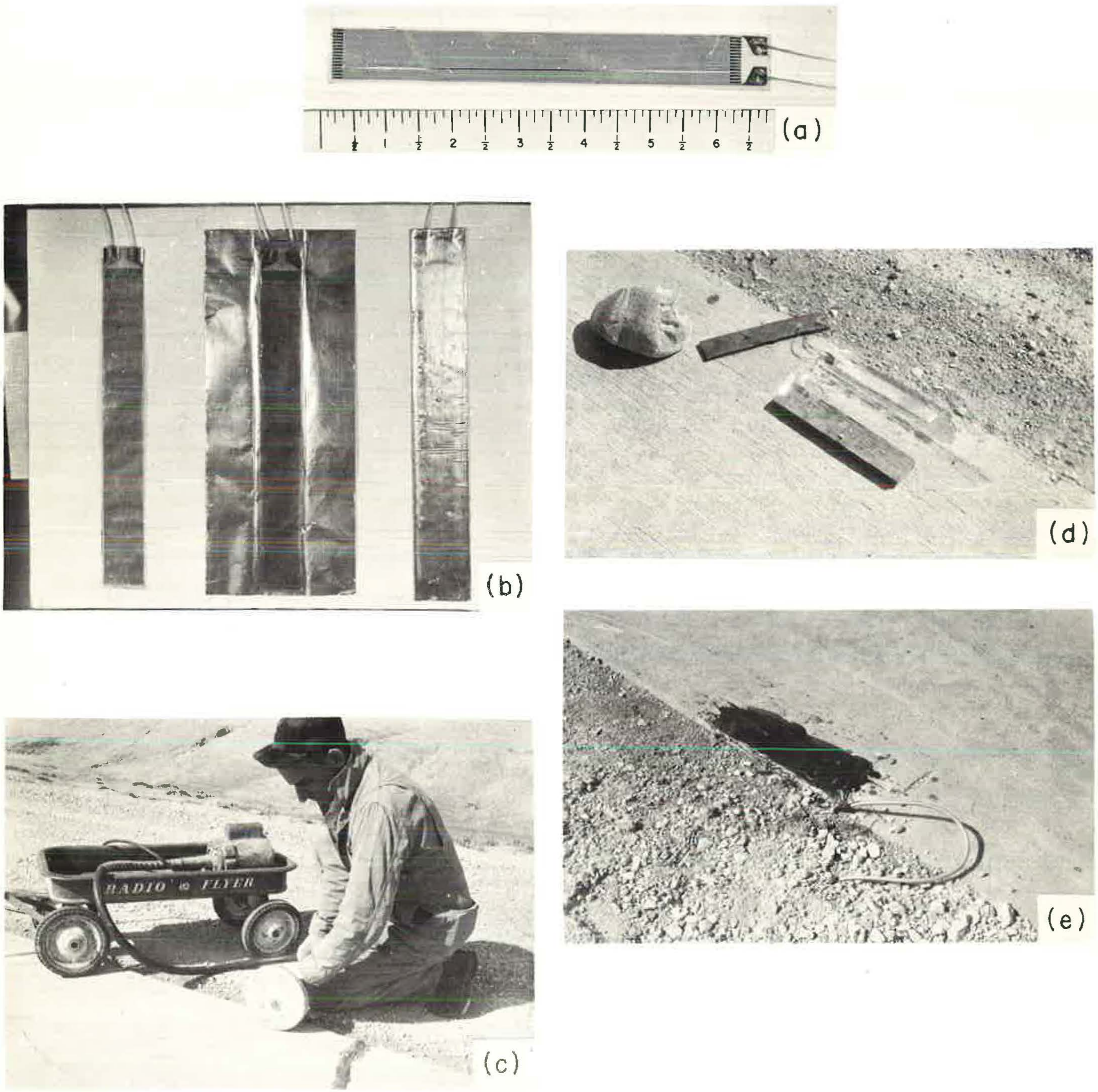


Figure 34. Successive stages in installation of strain gages on edge of pavement in traffic loops.

Figure 35. Instrument van taking dynamic measurements. Device on pavement just ahead of truck measures transverse placement.

Figure 36. Instrumentation used in measurement of dynamic deflection at panel corners.

Figure 37. Measuring static rebound deflection with the Benkelman beam.

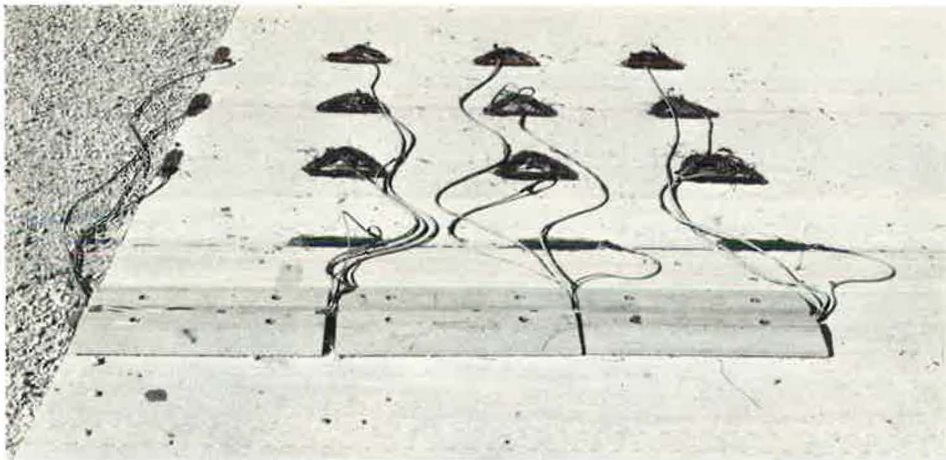


Figure 38. A finished installation of strain gages in Loop 1. There were 18 installations of this type. Ramp protected cables from truck-mounted vibrating loader.

Figure 39. Truck-mounted vibrating loader. Load was transmitted to pavement through inverted A-frames and wooden pads. Front tires were lifted from pavement to minimize vibration at front axle.

Chapter 8

Bridge Research

BRIDGE EXPERIMENT

Detailed descriptions of the structures and materials used in the Road Test bridge experiments can be found in Road Test Report 2 (Special Report 61B); general description of the experiments can be found in Road Test Report 1, and a comprehensive description of the experiments, test results, analyses and findings can be found in Road Test Report 4 (Special Report 61D).

The original bridge research program included 16 slab and beam bridges. It was planned as a series of case studies expected to yield information on how similar structures would behave under repeated application of load resulting in overstress. Four of the overstressed bridges failed early in the test program. Two of them were replaced with additional test bridges.

Each bridge was a simple span structure consisting of 3 beams and a reinforced concrete slab. The beams, spanning 50 ft, were wide-flanged, rolled steel I-beam sections with or without cover plates; precast, prestressed concrete I-sections; or reinforced concrete T-beams cast monolithically with the slab. The slabs were 15 ft wide. They provided one 14-ft lane for the test traffic. Figure 40 shows one set of 4 bridges.

The steel bridges included noncomposite and composite designs. In prestressed concrete bridges both pretensioned and post-tensioned beams were used. The beams for the reinforced concrete bridges were of a conventional T-beam construction.

Of the original 16 bridges, 8 were built with steel beams, 4 with reinforced concrete beams, and 4 with prestressed concrete beams. The two replacement bridges had steel beams.

Two principal studies were conducted. A study of behavior of the bridges under repeated overstress and a detailed study of the effects of moving vehicles on the response of the bridges. Figures 41, 42, 43 and 44 show some of the instruments used in the bridge studies.

The beams of any one bridge were subjected to a selected stress level during each passage of the standard test vehicle. Two levels of the maximum tensile stress were chosen for each type of beam as follows:

1. 27,000 psi and 35,000 psi for the steel beams.

Figure 40. Set of four completed bridges.

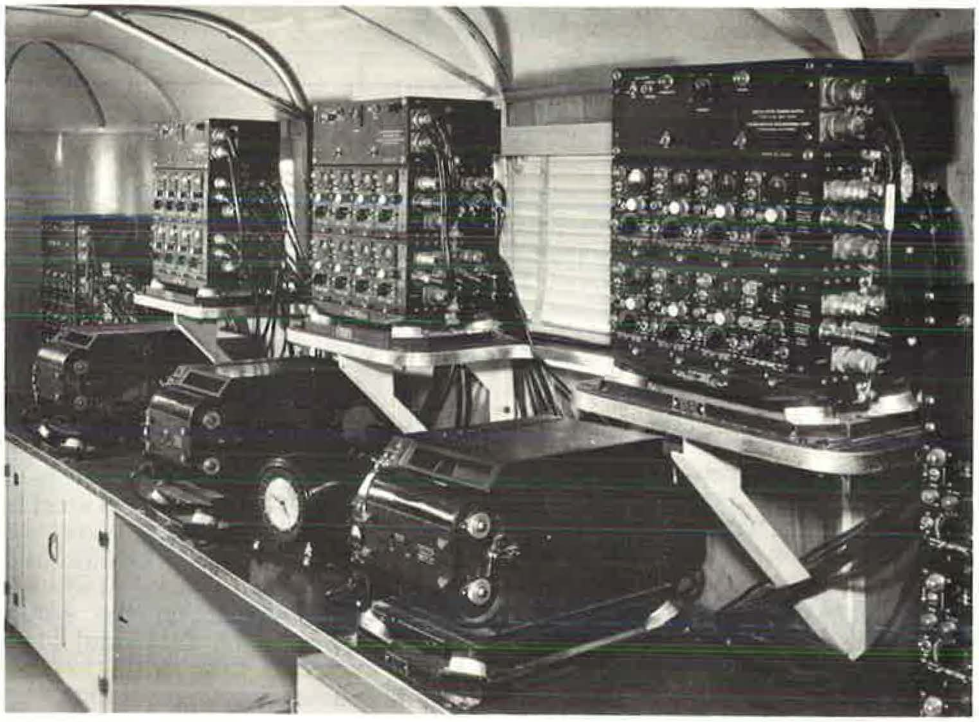


Figure 41. Amplifiers and recording oscillographs in bridge trailer.

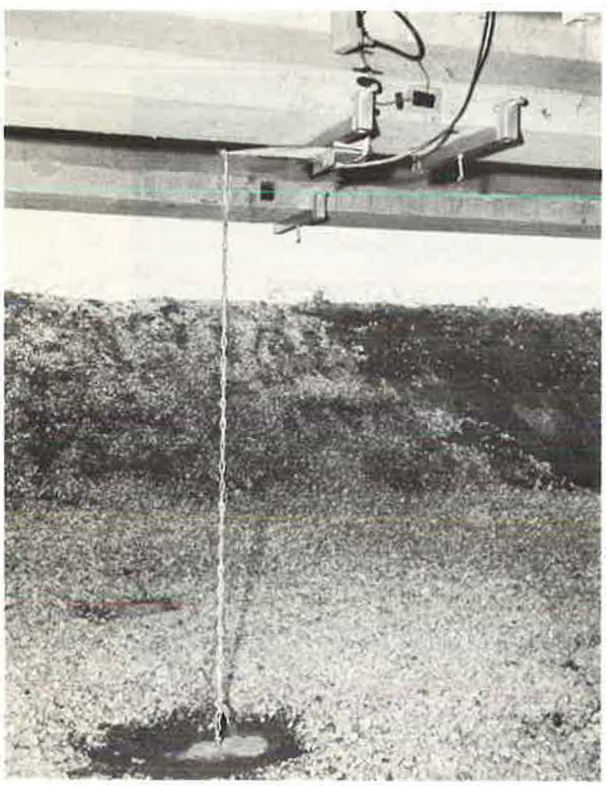


Figure 42. Cantilever deflectometer in place.

2. 300 psi and 800 psi for the concrete of the prestressed concrete beams.

3. 30,000 psi and 40,000 psi for the reinforcing bars of the reinforced concrete beams.

The selected stress levels were substantially in excess of standard design stresses. The choice of levels was dictated by the objective of the bridge research concerned with the effects of repeated overstress under test traffic. In steel beams the fatigue strength of rolled beams with partial-length cover plates and the progression of yielding were of primary interest. In prestressed bridges the attention was focused on the fatigue cracking of concrete subjected to tensile stresses and on the fatigue behavior of the prestressing steel in cracked beams. In reinforced concrete beams the effect of repeated stressing on the width and spacing of tensile cracks, and the fatigue behavior of deformed bars were studied.

The regular test vehicles in Loops 5 and 6 operated over the test bridges. Transverse placement on the bridges was so arranged that the vehicles traveled directly over the center beams.

FATIGUE STRENGTH

Fatigue data were obtained during the regular test traffic period from November 1958 through November 1960. The bridges that sur-

Figure 43. Brackets and scales for measurement of beam elevations.

vived the test were subjected to 556,100 vehicle load applications. After the regular Road Test was completed, additional data on fatigue behavior were obtained by vibrating some of the bridges near their natural frequency. The major findings were as follows:

1. Fatigue cracking in varying amounts occurred in five steel beam bridges that had partial-length cover plates welded to the bottom flanges of the beams. In these beams, the minimum stresses at critical points were 8,300 to 22,100 psi; the minimum stresses were

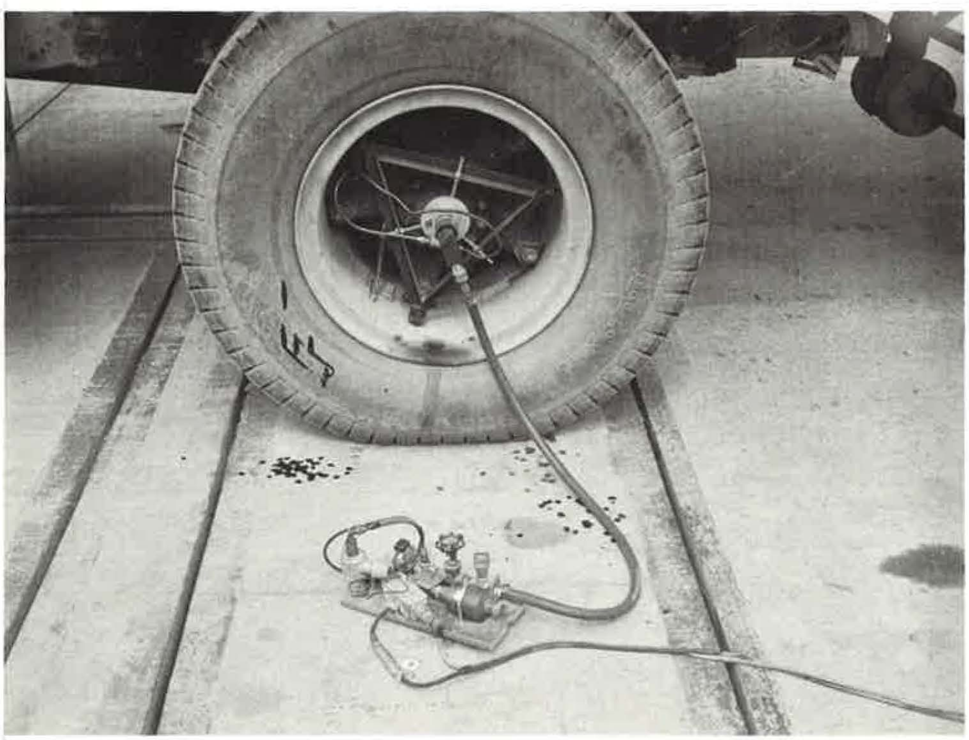


Figure 44. Equipment for determination of differential tire pressure.

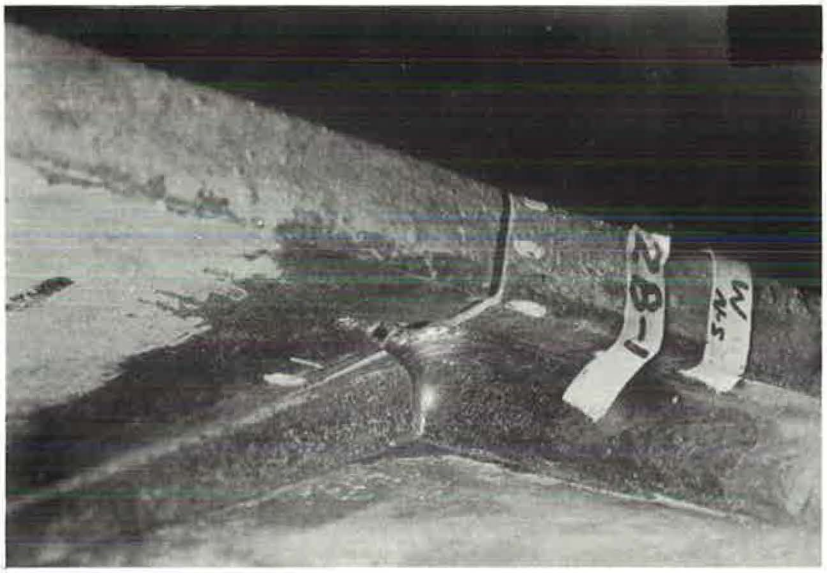


Figure 45. Fatigue crack in bottom flange of a steel beam at the end of a cover plate.

caused primarily by dead load (the bridge without vehicle). The test vehicles caused live-load stresses with means, at the ends of the cover plates, ranging from 12,500 to 26,000 psi. Cracking occurred between 477,900 and 536,000 trips of the test vehicles. Figure 45 shows a fatigue crack in the bottom flange of a steel beam at the end of a cover plate.

2. Fatigue failures occurred in the steel bars of two reinforced concrete bridges. Here, the minimum stress in the steel bars was 16,400 psi, and the test vehicles caused additional stresses with a mean range of 22,600 psi. Failures occurred after approximately 730,000 cycles of stress of which 556,100 were applied by the test vehicles and 173,900 by mechanically vibrating the bridges. Figure 46 shows fatigue failure of reinforcing bars in one of the test bridges.

3. In both of the previous cases the fatigue distress occurred in the same manner as that observed in laboratory tests of beams and the number of stress cycles agreed reasonably well with computed estimates. Thus laboratory fatigue data can be used to forecast the life to failure, within reasonable limits, whenever a good estimate can be made of the magnitude and number of repetitions of stress.

4. A steel beam bridge without cover plates showed no fatigue cracking after 392,400 trips

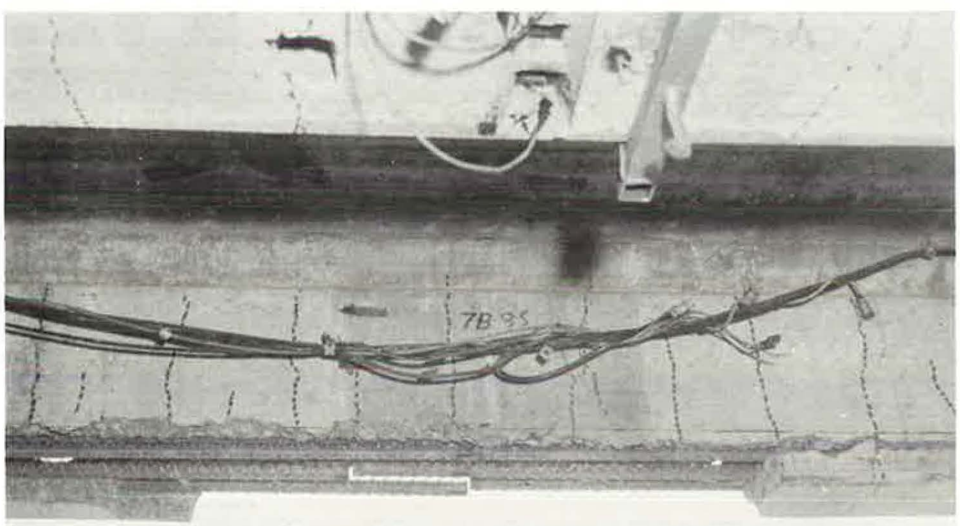


Figure 46. Fatigue failure of bars in Bridge 7B.

of the test vehicles. The minimum stress was 12,700 psi. This, too, was in accord with laboratory data that showed that these beams could have withstood approximately 2,000,000 repetitions of a 28,000-psi stress range in addition to the minimum stress.

5. In the most highly-stressed prestressed concrete bridge there was a minimum stress of 146,000 psi in the prestressing steel. The mean stress ranges caused by the test vehicles were 20,200 to 26,200 psi. Laboratory tests had established an endurance limit of 49,000 psi in the stress range. Thus, the laboratory data indicated that failure was not likely, and none occurred up to 556,700 cycles of stress.

6. Fatigue cracking of concrete was detected in prestressed concrete beams subjected to tensile stresses lower than the modulus of rupture of the concrete. However, the cracking was detected only with the aid of a microscope, and had no observable effects on the behavior of the bridge.

COMPARISON OF BRIDGE TYPES

The Road Test bridges reproduced only certain aspects of a typical highway bridge. The following major differences should be kept in mind: the test bridges had only three beams and were only one lane wide; the stress levels during the regular test traffic were above those normally experienced in the actual service life of a highway bridge; and the duration of the tests was only 2.5 years.

The three major kinds of test bridges were designed under different criteria and therefore direct comparisons of the relative performance of the steel, prestressed concrete, and reinforced concrete structures could not be made. However, there were at least four bridges of each major type and comparisons of relative performance were made within all three such groups. Such comparisons support the following conclusions:

1. The behavior of composite steel bridges (where the beams and the deck slab were connected) was clearly superior to the behavior of noncomposite bridges (where the bond between beams and slab was deliberately broken and there was practically no interaction).

2. Some prestressed concrete beams were post-tensioned with parallel-wire cables and some were pretensioned with 7-wire strands. In the beams stressed with parallel-wire cables, severe cracking caused a radical change in the response of the beams to loading. The stiffness of the beams decreased substantially, and there was an indication of progressive loss of bond between the concrete and the cables. The ultimate flexural capacity of the bridge was decreased by bond failure. On the other hand, cracking of the beams with 7-wire strand caused practically no change in the response of the beams to loading. Bond was preserved and deflections of the bridge were essentially the same as those of an uncracked bridge.

3. The steel bars in some reinforced concrete beams were stressed to about 33,000 psi while others were stressed to about 42,000 psi. In both, the maximum crack width in the concrete exceeded 0.01 in. in the unloaded condition. The test vehicles caused a maximum additional opening of 0.002 in. However, there was a greater number of the larger cracks in the higher stressed beams. Cracking of reinforced concrete beams increased with traffic; Figure 47 shows the progression of crack development in one of the beams of a concrete bridge.

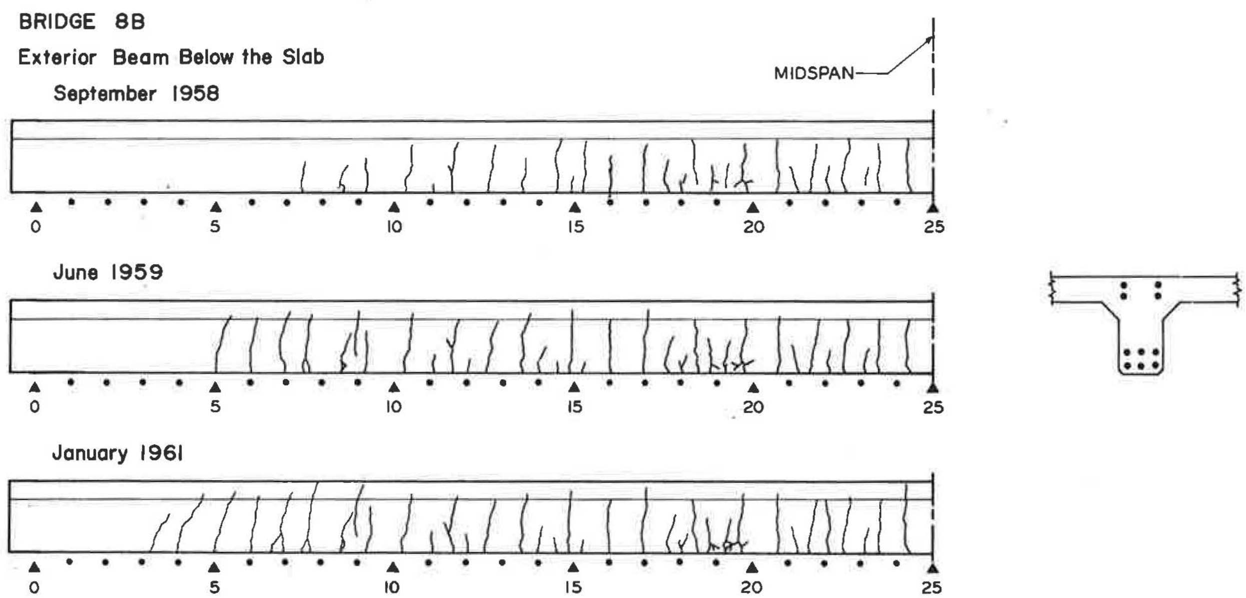


Figure 47. Crack patterns on reinforced concrete beams.

DYNAMIC RESPONSE

In addition to the studies of the effects of repeated overstress, extensive investigation was conducted of the so-called impact effects caused by moving vehicles. Special vehicles were operated under carefully controlled conditions over certain of the bridges, and strain and deflection histories at appropriate parts of the structure were determined during each vehicle passage. Experimental data and analytical studies demonstrated that the dynamic response of a bridge is very sensitive to a number of parameters, some of which cannot be controlled or even measured accurately. For example, it was found that the interleaf friction in the suspension spring system of a truck had an extremely important effect on the dynamic response of a bridge.

A theory of dynamic response, evolved by a research team at the University of Illinois, was tested with data taken in these studies. The major findings of this investigation were as follows:

1. The results of dynamic tests on the bridges agreed satisfactorily with those obtained from the theory. However, the agreement was obtained only by including in the analysis all pertinent characteristics of the bridges and the vehicles.

2. Because of the special conditions of the bridge tests, the magnitudes of the observed impacts are not indicative of those which would be obtained under more typical conditions. However, the theory can be used to evaluate impact factors for various types of bridges and vehicles used on the highway system.

3. The observed effects of irregularities (roughness) of the bridge decks and approach slabs re-emphasized the importance of the smoothness of pavement and deck surfaces. Furthermore, limiting vehicle speed to about 15 mph or less resulted in a drastic reduction of impact, a finding particularly significant in relation to the operation of overloads over highway bridges.

ULTIMATE STRENGTH

The bridges that survived tests with repeated high overstress were tested to failure with increasing loads. Ten bridges were included in the study; four had steel beams, four had prestressed concrete beams, and two had reinforced concrete beams.

The ten bridges were subjected to passages of vehicles having successively heavier loads. Each load was applied 30 times. The testing was discontinued when the slab was crushed, when the tension steel was fractured, or when an already extreme permanent set continued to increase at an increasing rate with each passage of the test vehicle. All ten bridges had previously been subjected to approximately 550,000 stress repetitions caused by the regular test traffic. In addition, four bridges had been subjected to accelerated fatigue tests which increased the total number of stress cycles to approximately 1.5 million.

The tests were designed to study the response of the bridges to loads approaching their ultimate capacity, to determine the manner of failure under moving loads and to provide data for checking ultimate strength theories. Figure 48 shows the configuration and dimensions of the test vehicles. The principal findings were as follows:

1. All steel beam bridges included in this study failed by yielding of the beams and accumulation of a large permanent set (more than 12 in.). Noncomposite steel bridges were tested until the permanent deformations increased at an increasing rate with each successive pass of the same load. For the one composite bridge limitations on test vehicle capacity led to discontinuation of the testing before the slab was crushed. However, at the conclusion of the test the total permanent set

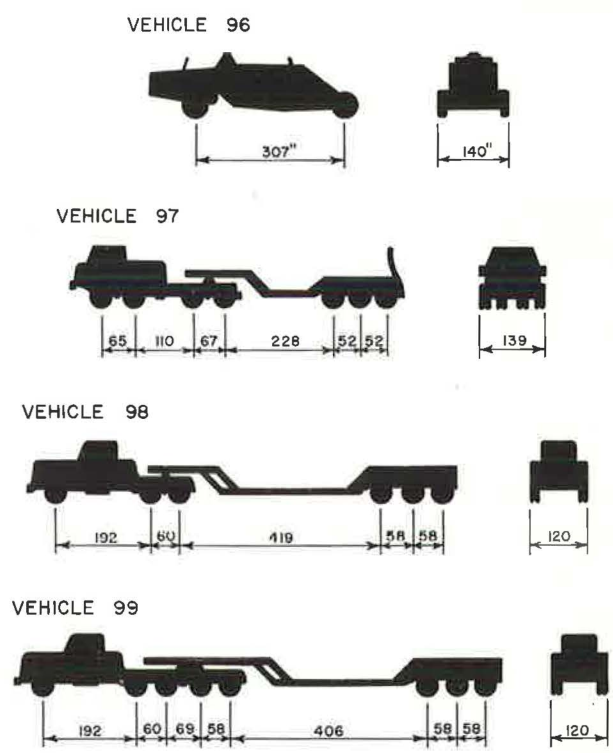


Figure 48. Special test vehicles.

at midspan exceeded 13 in. Figure 49 shows a noncomposite bridge at the end of the test.

2. Of the four prestressed concrete bridges in this study, three failed by fracture of the prestressing steel and one by crushing of the concrete slab following an apparent bond failure between the wires and the grout. The beams of the latter bridge had been extensively cracked by the regular test traffic. Figure 50 shows prestressed concrete bridges after failure.

3. Both reinforced concrete bridges in this study failed by yielding of the tension reinforcement followed by crushing of the slab. The permanent set at failure exceeded 14 in. in both structures. Figure 51 shows these bridges at the end of the study.

4. The live-load moments at failure were 2.2 to 6.6 times the design moments caused by the assigned test vehicles. The total moments at failure, including both dead and live loads, where 2.1 to 3.7 times the design moments that would be permitted on the basis of the current allowable design stresses.

5. The total moments at failure were in satisfactory agreement with the moments computed by the plastic and ultimate strength analyses thus indicating that such analyses can be used to evaluate the heaviest load that can cross a bridge.

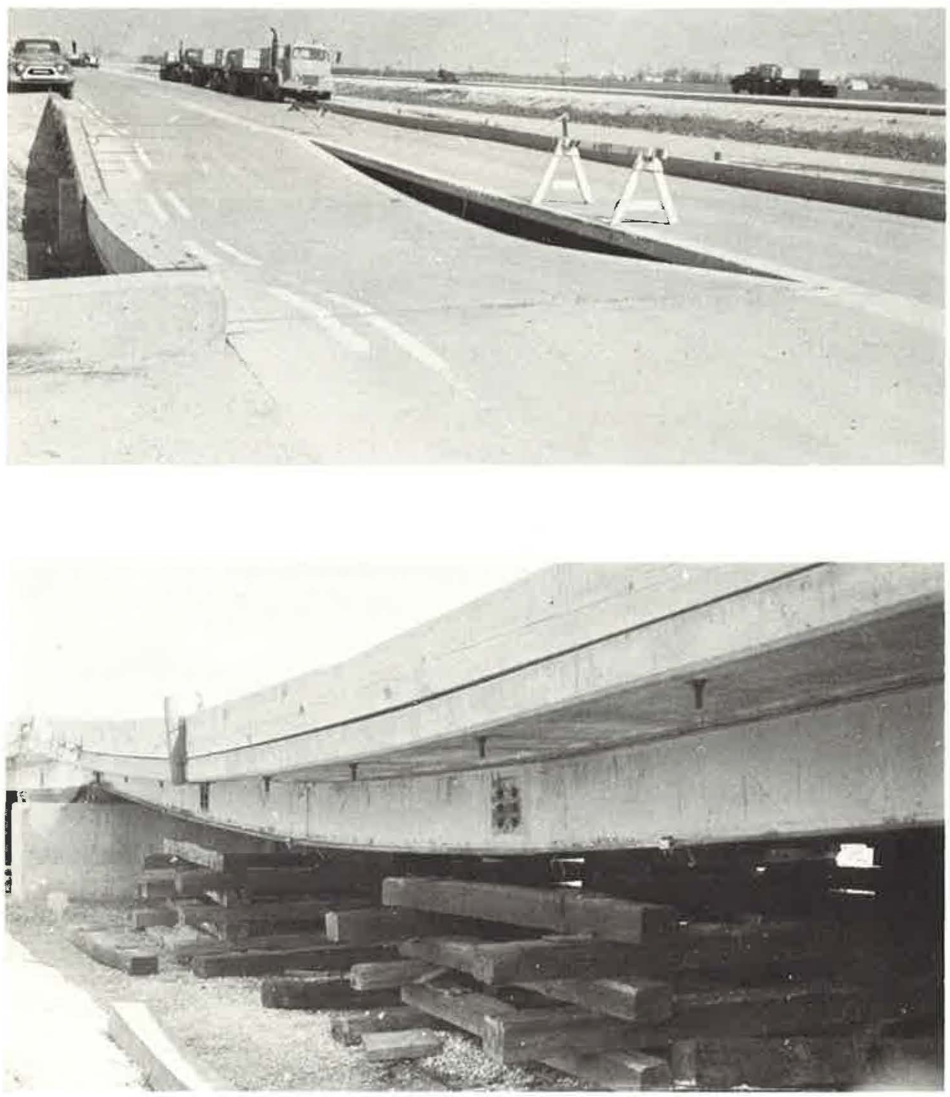


Figure 49. Bridge 1A at end of test.

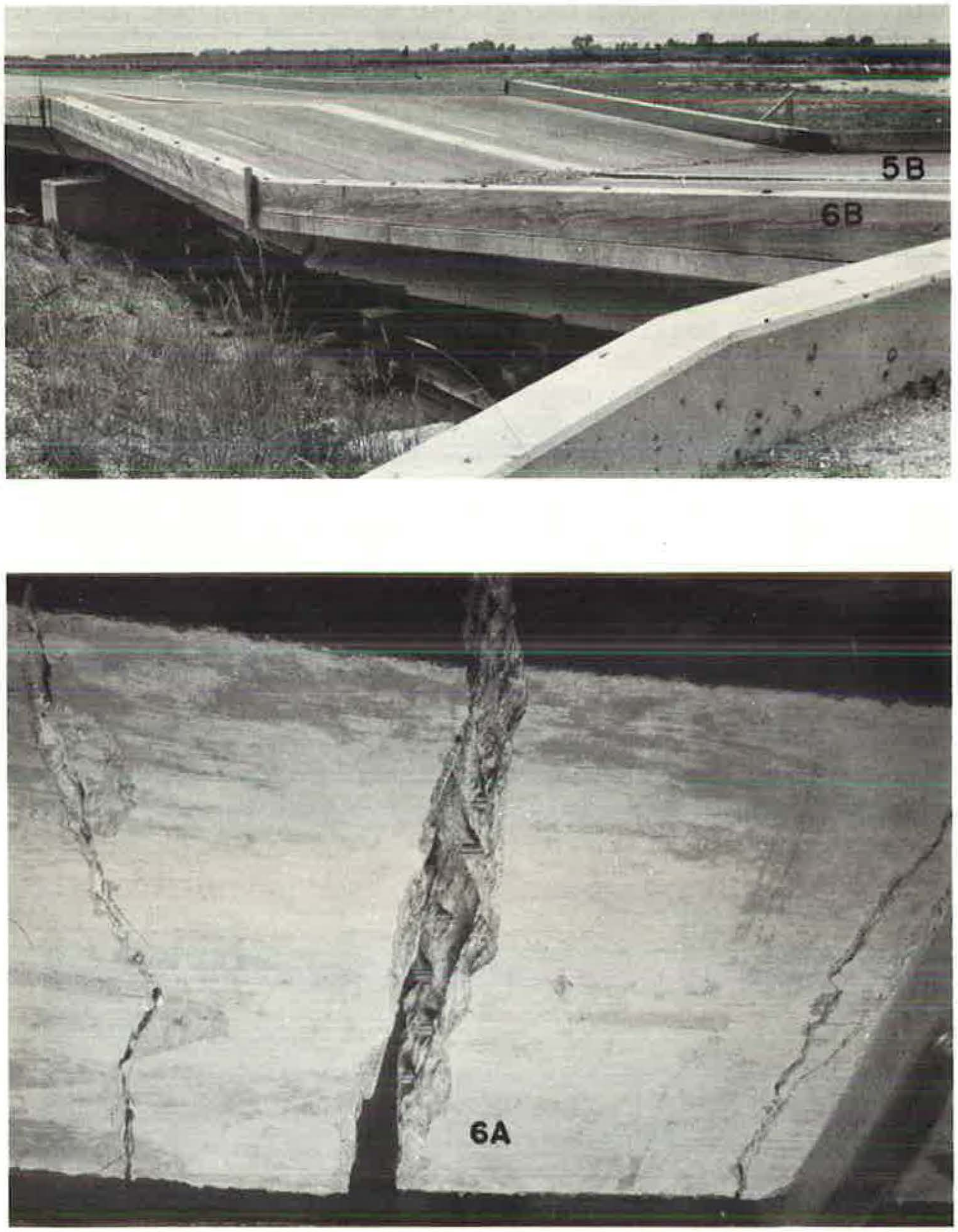


Figure 50. Prestressed concrete bridges after failure.

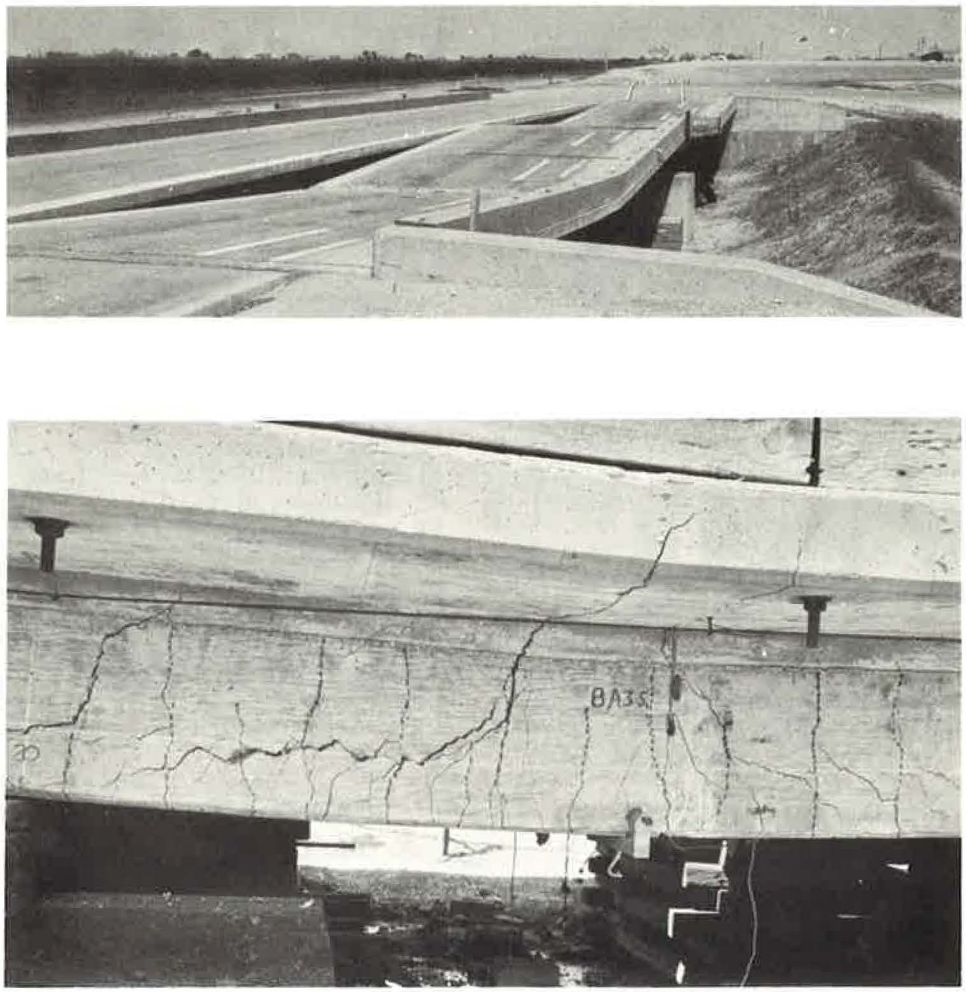


Figure 51. Bridges 8A and 8B after failure.

Chapter 9

Special Studies

In this chapter, studies are discussed that were conducted during the main test but which were not directly associated with major pavement or bridge research. Other studies are discussed that were conducted primarily for the Department of the Army during the special study program that followed the main test.

The experiment design and the instrumentation available did not have the refinement to detect adequately the effects of the variables of tire pressure, tire design, vehicle suspension and the several vehicle and axle configurations used in the post-test studies. These tests were conducted primarily to detect gross trends in the dynamic measurements of strains and deflections and dynamic axle loads, to raise questions for future research and to provide a basis for developing better testing techniques and instrumentation to identify and measure the critical responses of vehicle and pavement. Many of the findings of these special studies were not definitive but the summaries reported should suggest further areas of research. The special studies are described in detail in Road Test Report 6 (Special Report 61F).

PAVEMENT PERFORMANCE—LOOP 2

Certain test sections in Loop 2 were subjected to 32,000-lb tandem-axle loads applied by military vehicles with conventional tires or with low pressure, low silhouette (LPLS) tires. This program was designed to provide comparisons between the performance of similar pavement sections subjected to vehicles with the same loading and axle configurations but with different tire designs and pressures. Prior to these studies, lane 1 of Loop 2 had been subjected to over a million 2,000-lb axle loads and lane 2 to the same number of 6,000-lb axle loads. The previous traffic on the test pavements used in this study possibly influenced the test results in favor of the LPLS tires. Figure 52 shows the vehicles used in this study —note particularly the tires.

In this experiment, about 16,400 axle loads were applied. In the flexible pavements the loss of serviceability for the sections subjected to the LPLS tires was generally less than that for the comparable sections subjected to the conventional (standard military tread) tires. The sections subjected to the conventional tires showed a greater increase in cracking and patching than did the sections subjected to the LPLS tires, however, the increase in depth of rut was greater for the LPLS sections than for the conventional tire sections. Only the sections tested under conventional tires in this study had shown cracking during the main Road Test. Furthermore, rutting that had developed during the main Road Test was some-

Figure 52. M-52 tractor-semitrailers equipped with LPLS tires (left) and conventional tires (right).

what greater in the sections subjected in this study to conventional tires.

The relative performance of replicate sections subjected to both LPLS and conventional tires based on serviceability loss, increase in cracking and patching, and increase in rut depth indicated a beneficial but not highly significant effect of the LPLS tires.

In the rigid pavements, loss of serviceability for sections subjected to LPLS tires was generally less than that for the sections under the conventional tires. However, only a few tenths of a point loss in serviceability was noted. Somewhat more cracking developed during this test in the slabs tested under the LPLS tires than in the slabs tested under the conventional tires. However, prior to this study no cracks had developed in the sections that were tested under LPLS tires.

Pumping had developed during the main Road Test only in the sections tested under conventional tires, and it continued to progress more rapidly during this special test than did the pumping in the adjoining sections. Progression of pumping once started, however, was also observed during the main Road Test.

In this study it was noted that reinforced pavements performed appreciably better than nonreinforced pavements of the same slab thickness.

TIRE PRESSURE—TIRE DESIGN

The objective of this program was to investigate the possible effects of changes in tire pressure and design on the dynamic effects associated with pavement structures and bridges. The tests were conducted on pavement sections in Loops 4 and 6 which had survived over a million applications of either 18,000-lb or 30,000-lb single-axle loads and on bridges that had been subjected to over 500,000 vehicle passages.

In the flexible pavements tire inflation pressure changes in the order of 50 psi accompanied by a limited tire design change had little effect on the dynamic deflections of the pavement sections and little or no effect on the pressure transmitted to the embankment.

In the rigid pavements, changes in tire pressure or tire design produced no noticeable effect on the dynamic edge strain or deflection measurements. However, had instrumentation been available to measure strain or deflection in the pavement surface at points other than at the edge, some effect might have been found.

In the test bridges under study the strain and deflection amplification factor (dynamic strain or deflection as a ratio of static strain or deflection) relationships in this study agreed with those given in Road Test Report 4; that is, an increase in speed was associated with larger amplification factors, and the amplification factors for single-axle vehicles were generally greater than those for the tandem-axle vehicles. No effects of tire pressure or design were noted.

COMMERCIAL CONSTRUCTION EQUIPMENT

The objective of this study was to determine the dynamic effect on bridges and pavements of commercial construction equipment and, insofar as possible, to relate the dynamic effects of these vehicles to those observed for conventional dual-tire truck units. One medium and one small two-axle tractor scraper units were operated over pavement sections on which dynamic measurements were made of strain, deflection, transmitted embankment pressure, and dynamic load effect. In the flexible pavements, the relationships between deflection and wheel load for the two scraper units agreed with the relationships for conventional truck units. The rate of increase of deflection with wheel load for the medium scraper was considerably lower than the rate for the conventional units.

With the instrumentation available the study of the effect of a change in tire pressure on pavement deflection failed to indicate any trend at any wheel load or inflation pressure tested.

For both units, deflection decreased as vehicle speed increased; however, the effect of vehicle speed was more pronounced for the small than for the medium scraper. In addition, the speed effect was greater at the higher wheel loads.

As vehicle speed increased there was a decrease in pressure transmitted to the embankment by both scrapers at all levels of wheel load and tire inflation pressure tested. However, changes in inflation pressure did not noticeably affect the transmitted pressure.

In the rigid pavement study, for both scrapers, compressive edge strains increased with wheel load but were affected very little by vehicle speed or tire inflation pressure. Tensile strains (measured at the pavement edge) were not noticeably affected by wheel load, vehicle speed or inflation pressure.

In the bridge tests, although the trend was not consistent for all bridges tested, the mean strain and deflection amplification factors for both scraper units were lower than those for the single-axle conventional vehicles but greater than those for the tandem-axle vehicles.

SPECIAL SUSPENSION SYSTEMS

This study was concerned with the dynamic effects on pavements and bridges of vehicles equipped with special suspension systems and comparison of these effects with the dynamic effects of conventional vehicles having similar axle loads and tire pressures. The instrumentation available at the time of the study made possible the measurements of strain, deflection, transmitted embankment pressure, and dynamic load. Included in the study were a tandem-axle semitrailer equipped with combination fluid and air suspension system; a semitrailer equipped with a unique staggered wheel suspension system in which no axle is common to any two wheels; a tandem tractor equipped with a variable single-spring suspension system with rear-axle drive; a tandem tractor equipped with standard Hendrickson walking-beam-type suspension with rubber load cushions; a tandem tractor equipped with similar walking-beam suspension with steel leaf springs; and a military tractor semitrailer equipped with LPLS tires. Conventional Road Test tractor semitrailers were also included in the study.

In the flexible pavement studies, the changes in deflection for the several designs of suspension systems were less than the difference attributed to experimental error. An increase in vehicle speed caused a comparable decrease in pavement deflection for all special suspension and conventional vehicles. The pressure transmitted to the embankment soil was generally lower for the special suspension units, with little variation among the several types, than for the conventional units. The effects of vehicle speed on the transmitted pressure were uniform for all special suspension and conventional units.

In the rigid pavement study the decrease in edge strain and corner deflection caused by an increase in vehicle speed was reasonably uniform for the several special suspension systems. Similar relationships for the conventional units showed no appreciable differences that could be associated with the changes in the suspension systems.

In the bridge studies the mean amplification factors for the conventional single-axle vehicles were higher than those for the tandem-axle vehicles, both conventional and special. However, the mean strain amplification factors for all the special vehicles were appreciably higher than the factors for the conventional units at 30 mph. At speeds of 15 mph this was not true for either strain or deflection amplification factors.

MILITARY VEHICLES WITH TIRES

The objective of this study was to investigate the dynamic effects on pavements and bridges of specialized units of military highway and off-highway equipment and to compare these effects where possible with those for conventional units at several axle loads and vehicle speeds. The vehicles tested are shown in Figure 53. Strain, deflection and embankment pressures were measured as in the previously described studies.

As was true for the other special studies, the large number of indeterminate variables and vehicle characteristics limit the findings of this program to general trends and indicate the need for further research.

In the flexible pavement, for all the military units in the study, the effect of vehicle speed on the deflection and transmitted embankment pressure agreed with the relationships found for the conventional units. For two of the heavy-duty transporters (GOER and HETAG) the rate of increase in pavement deflection with increase in wheel load was greater than for the conventional units.

In the rigid pavement studies the rate of decrease of edge strain and corner deflection with increase in vehicle speed for the military vehicles was of the same order of magnitude as that observed for the conventional units. The values of strain and deflection at several axle loads for the military equipment were slightly lower than the values for the conventional units at the same wheel loads. Some of this difference, however, was a result of pavement temperature differential.

Compressive edge strains recorded for the GOER and HETAG were found to be slightly lower than those for equivalent axle loads on conventional vehicles at all levels of speed and load included in this study. However, the corner deflection values for the HETAG were higher, and for the GOER were lower than those recorded for the conventional units.

In the studies on bridges, the relationships of amplification factors to vehicle speed and vehicle class reported in the report of the other special studies were found to exist for this study as well.

The amplification factors for the HETAG and GOER were found to be appreciably higher than those for any of the conventional vehicles tested.

MILITARY TRACKED VEHICLES

The objective of this study was to investigate the dynamic effects on pavements of track-laying military equipment and to compare the effects to those of conventional equipment. It was evident after conducting this study and reviewing the data that the instrumentation available at the Road Test was not adaptable to the track-laying equipment as far as the determination of the dynamic effects on the pavements and bridges were concerned. In general, the relationships between vehicle speed and deflection in both rigid and flexible pavement and between vehicle speed and edge compression strains for the track equipment indicated the same trend as for conventional units.

BRAKING, IMPACT AND ACCELERATION

This study was designed to investigate means of determining the dynamic effects on pavements, bridges, and in the cargos of a selected

(K–1) HETAG
Tank Transporter

K–3 GOER
(Shown with dynamic load recording trailer)

K–5 and K–6
Rolling Fluid Transporter

K–7 and L–1
Off-Road Train Trailers

L–3
Heavy-Duty Tank Transporter

M–52
Tractor-Semitrailer

Figure 53. Military vehicles (tire) used in Special Study Program.

group of vehicles when subjected to external accelerations.

An early pilot study developed the fact that it would not be possible with the instrumentation available to draw any conclusions concerning the effect of braking forces.

Each of the several vehicles selected for this study was operated over ramps so that its wheels dropped onto the pavement. Simultaneously, pavement strains, deflections and embankment pressures and vehicle and cargo accelerations were recorded.

In general an increase in height of ramp caused an increase in deflection and embankment pressure at creep speeds. It did not, however, cause an appreciable increase in edge strains. The rate of increase in either deflection or embankment pressure was not uniform for increase in height of ramp or vehicle speed.

A summary of the analog acceleration records shows that the magnitude of either the vehicle or cargo accelerations was such that the significance of the vehicle speed, tire pressure, or tire design could not be determined. Vehicle and cargo acceleration recorded during the impact study indicated a definite relationship between vehicle speed and height of ramp. An increase in speed and ramp height was associated with an increase in load cargo and vehicle accelerations. Figure 54 shows some of the ramps used in these studies.

SPECIAL STUDIES DURING RESEARCH PHASE

This section is included to call attention to several experiments conducted at the AASHO Road Test but not related directly to the project's major objectives. Some of these experiments were conducted by Road Test personnel, others by outside agencies at the request of and with the cooperation of Road Test personnel, and still others by outside agencies primarily for their own benefit. The existence of the Road Test physical plant constructed under highly-controlled conditions and subjected to exactly known traffic loadings made it an ideal testing ground for these side studies. Nearly all of these side studies were large enough to warrant independent publication. Where this was the case, references are given in Chapter 10 of AASHO Road Test Report 6.

In this summary statement, no attempt is made to report findings. Only a simple listing of the projects is included.

1. Development of nuclear testing equipment. The project staff undertook an extensive instrumentation development program for measurement of in-place density of the various layers of the pavement structure at the Road Test.

2. Volumetric determination of Westergaard foundation modulus. The U. S. Army Corps of Engineers, Ohio River Division Laboratories, conducted several tests on Road Test pavements in accordance with a procedure developed at their laboratories for the determination of the Westergaard *k*. In this procedure, measurements are made from the top of the rigid pavement slab.

3. Frost depth determination. A device was developed at the Road Test by which determination of depth of frost could be made without disturbing the pavement.

4. Driver behavior studies. The U. S. Army Personnel Research Office conducted several studies of the alertness of personnel engaged

Figure 54. GOER operated over ramps in drop tests at rigid pavement instrumentation van.

in the fatiguing and monotonous job of driving test vehicles.

5. Dynamic testing—Shell road vibration machine. Measurements were made with the Shell Oil Company road vibration machine on selected Road Test sections to investigate seasonal variation in stiffness of the pavements and to attempt to relate stiffness to pavement performance.

6. Dynamic testing—U. S. Army Corps of Engineers. A dynamic road testing device developed by the Waterways Experiment Station, U. S. Army Corps of Engineers, was also used for some special studies at the Road Test.

7. Skid studies. A major side study of the resistance to skidding of wet and dry flexible and rigid type pavements was conducted at the Road Test during the traffic phase of the main test. The skid trailer, developed and owned by the General Motors Corporation was used in these studies. At the beginning of test traffic, coefficients of friction averaged 0.72 and 0.63 for wet flexible and rigid pavements, respectively. After two years of test traffic and 1,100,000 axle applications, these coefficients had been reduced to averages of 0.44 and 0.42 for flexible and rigid pavements, respectively.

8. Relaxation tests. Samples of prestressing wire and strand used in prestressed concrete bridges were tested for up to 12,600 hours to determine their stress-relaxation characteristics.

9. Creep and shrinkage tests. Concrete cylinders were observed for over 2.5 years to determine the creep and shrinkage characteristics of the concrete used in prestressed concrete beams.

10. Fatigue studies. Laboratory fatigue tests of prestressing strand and wire were carried out at Lehigh University and laboratory fatigue tests of reinforcing bars were made at the Portland Cement Association Laboratories. The samples tested were from the materials used in the construction of the test bridges.