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THE AASHO ROAD TEST

Report 5

Pavement Research

Chapter 1

General Information

1.1 BACKGROUND AND OBJECTIVES

1.1.1 History

The events leading to the three most recent large-scale highway research projects, Road Test 1–MD, the WASHO Road Test and the AASHO Road Test, are described in detail in ASHO Road Test Report 1, "History and De-ription 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 common 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 1–MD was conducted in 1950. An existing concrete pavement in ryland was tested under repeated applica-n 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 Institute, while 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, Ill., in July 1955; and in August a task force of the Illinois Division of Highways moved to the site 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.

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 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.

1.1.2 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.

1.1.3 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 thick-

nesses 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.

This report deals primarily with work done in connection with Objectives 1 and 5 and with some of the special studies mentioned in Objective 3. 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.

1.1.4 Objectivity of Findings

Discussion of the results given in this report 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 select variables nor levels for variables to be included in the Road Test. This was the responsibility of the National Advisory Committee, acting upon the recommendations of the original AASHO Transport Committee's Working Committee. The Statistical Panel played an important role in influencing the experimental layout through its recommendations for complete factorial designs, randomization, and replication. Its recommendations, accepted by the Advisory Committee, made possible effective studies of the relationships sought by the objectives.

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 used to represent associations among experimental variables, then statistical methods were employed to determine constants for the models as well as 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 for other factors that were either held constant or that varied in an uncontrolled fashion, for example, embankment soil, strength of materials, and environmental conditions. Although estimates were obtained for the effects of axle load and axle configuration, it was not possible to determine the statistical significance of these effects because replication of load or configuration was not provided. Nevertheless, particularily in the cases of load effect on both pavement types and axle configuration effect on rigid pavement the differences observed were so great as to leave practically no doubt that the effects were significantly greater than zero.

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

1.1.5 Applicability of Findings

The findings of the AASHO Road Test, as stated in the relationships shown by formulas, graphs, and tables throughout this report, 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 that occurred 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 variations in climate, soil type, materials, construction practices and traffic.*

1.2 FACILITIES AND OPERATIONS

1.2.1 Site Location

The location of the AASHO Road Test was near Ottawa, Ill., in LaSalle County, about 80 mi southwest of Chicago (Fig. 1). The test

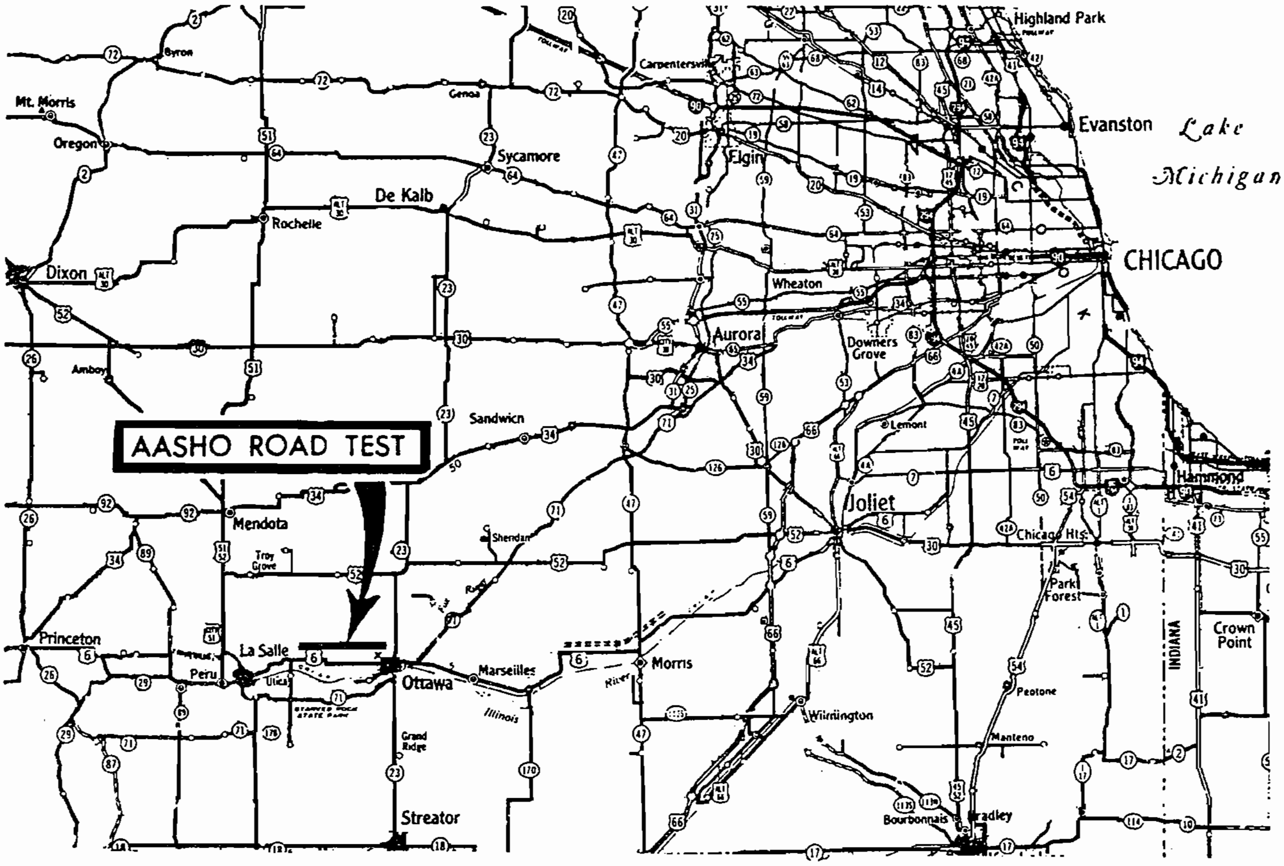

Figure 1. Site location.

facility was constructed along the alignment of Interstate Route 80. The site was chosen because the soil within the area was uniform and of a type representative of that found in large areas of the country, because the climate was 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.

1.2.2 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 2.

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 3 shows the layout of two typical test loops and locations of the test bridges.

Details of the experiment designs are given in Report 1 and are summarized in Sections 2.1.1 and 3.1.1 of this report. Details concerning all features of bridge research are given in Road Test Report 4.

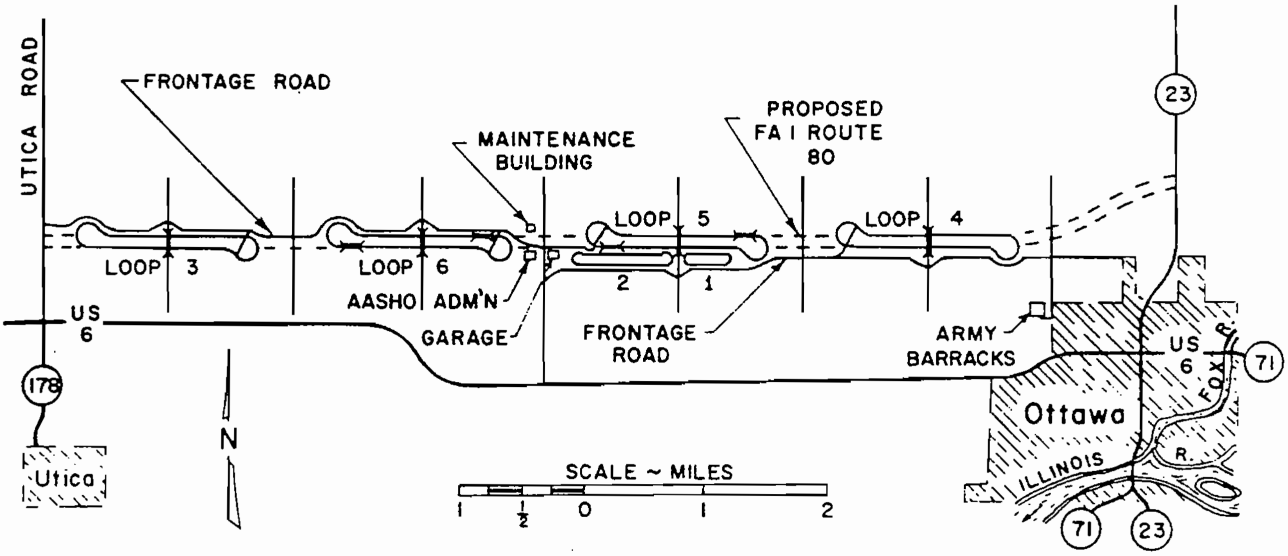

Figure 2. Layout of AASHO Road Test.

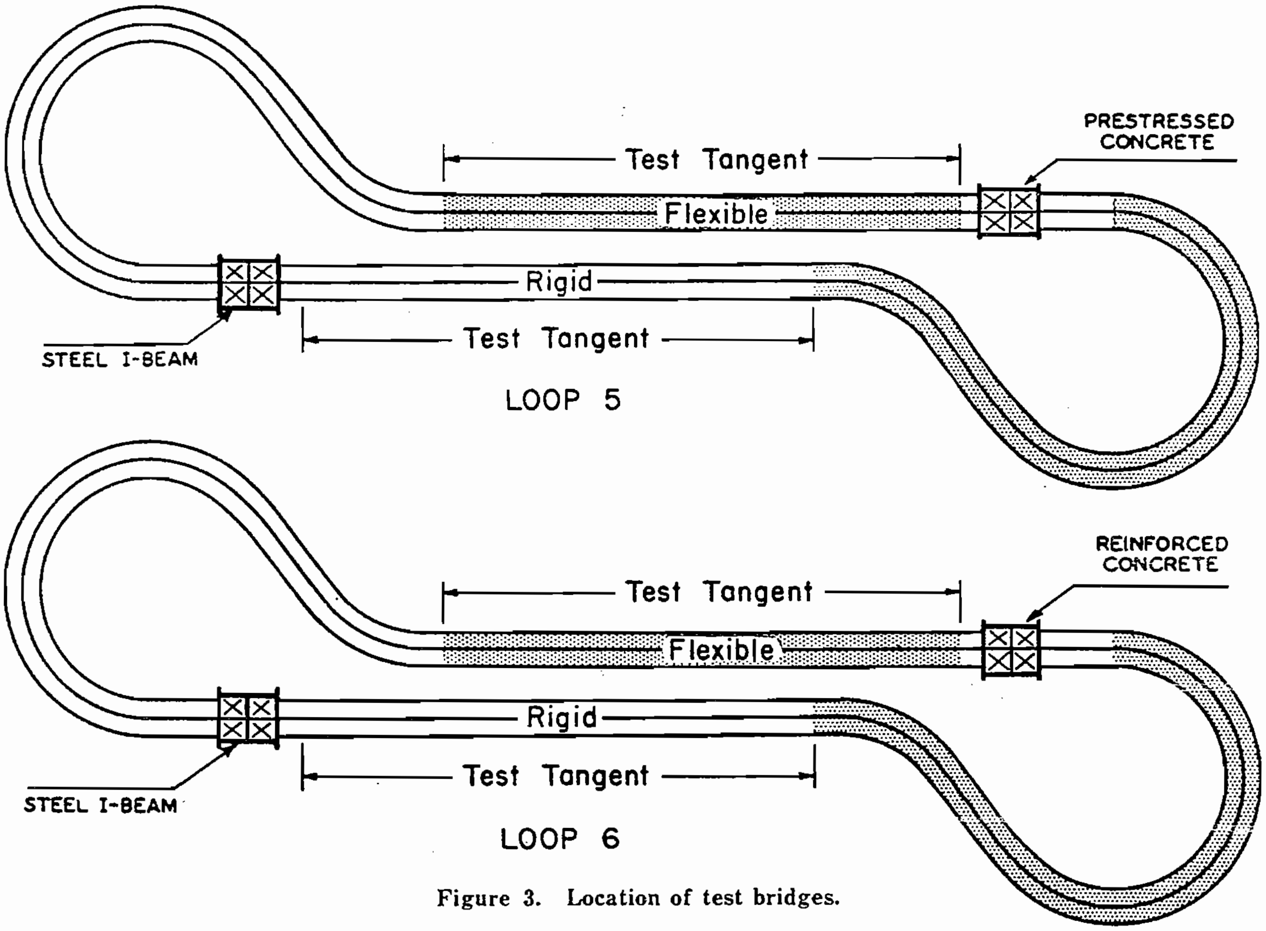

Figure 3. Location of test bridges.

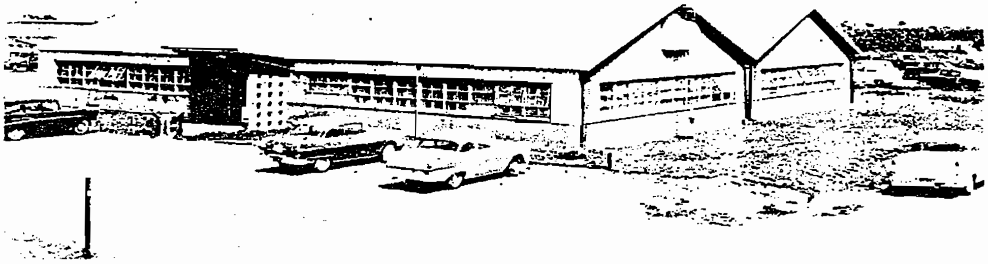

Figure 4. Administration building.

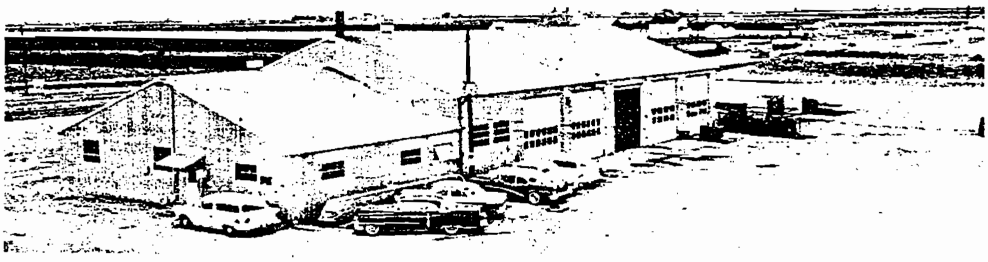

Figure 5. Vehicle maintenance garage.

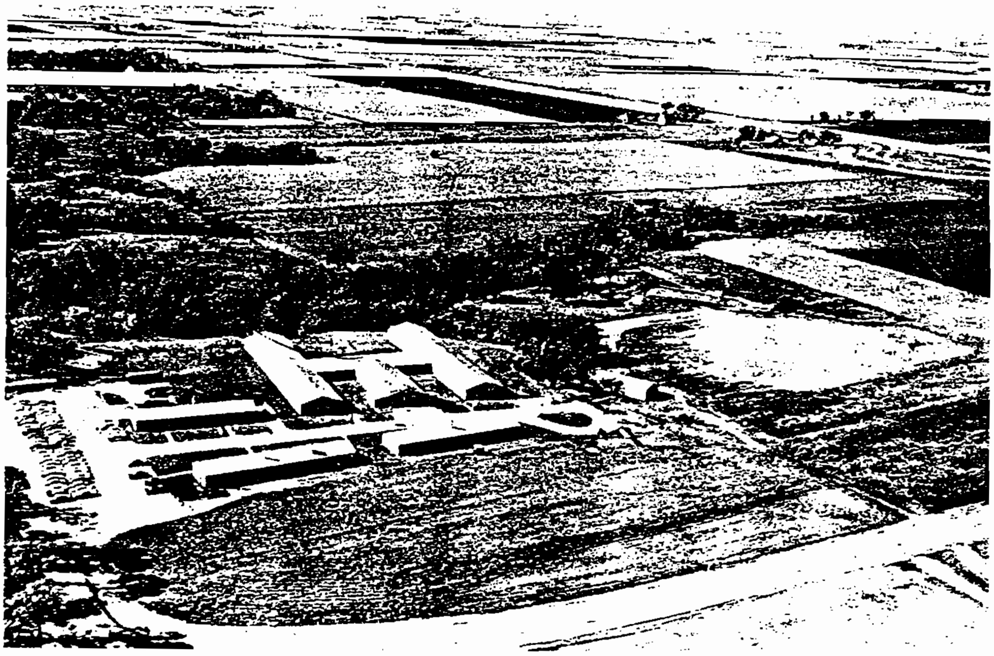

Figure 6. Army driver quarters (Wallace Barracks).

An administrative area was located at the center of the project. Laboratories and offices were located in the building shown in Figure 4. Shop facilities for vehicle maintenance were provided in the building shown in Figure 5. A military installation called Wallace Barracks (Fig. 6) was provided by the National Academy of Sciences to house the Army Transportation Corps Road Test Support Activity.

1.2.3 *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 used except that 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 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.

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

1.2.4 *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 7.

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 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. In January 1960, the traffic was increased 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.

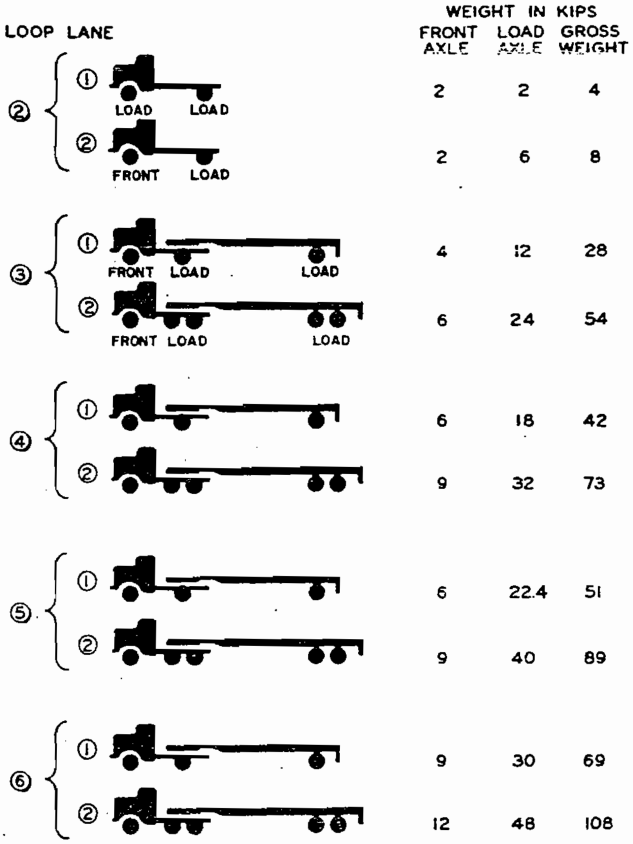

Figure 7. Typical test vehicle axle loadings.

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, 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 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.

1.2.5 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 a limited amount of additional information which might contribute to a better understanding of pavement mechanics.

Programs falling 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 falling 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 of 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 majority of the data were 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 lists major Road Test data systems concerned with pavement research and notes how the systems may 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. 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 Parts 2 and 3.

1.2.6 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 Section 1.3) 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 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.

1.2.7 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, how-

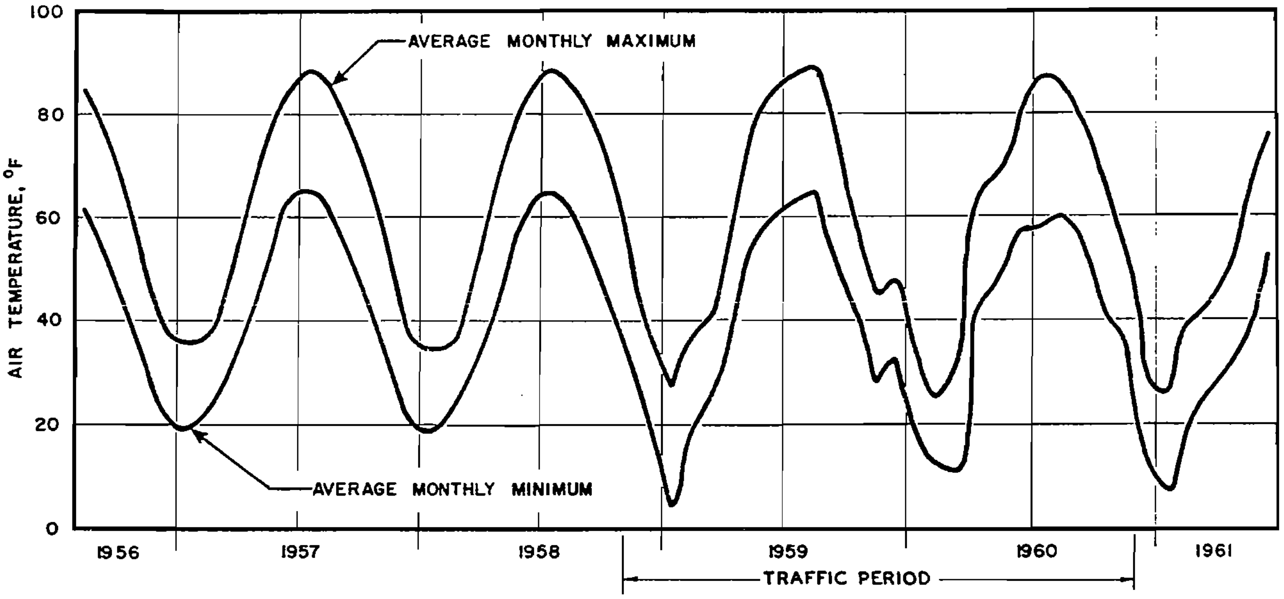

Figure 8. Average monthly air temperature at project.

ever, 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 a post-glacial period and were reasonably uniform in the area of the project. Soil drainage is generally poor. Bed rock 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. Substratum layers were usually represented by samples exhibiting A–6 characteristics.

In the interest of uniformity, soil making up the top 3 ft of embankment directly under the test pavements was taken 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, 58-70 percent finer than 0.02 mm and 34-40 percent finer than 0.005 mm. Maximum dry densities were in the range 114 to 118 lb per cu ft and optimum moisture contents in the range of 14 to 16 percent when compacted in accordance with standard procedure, AASHO T99–49.

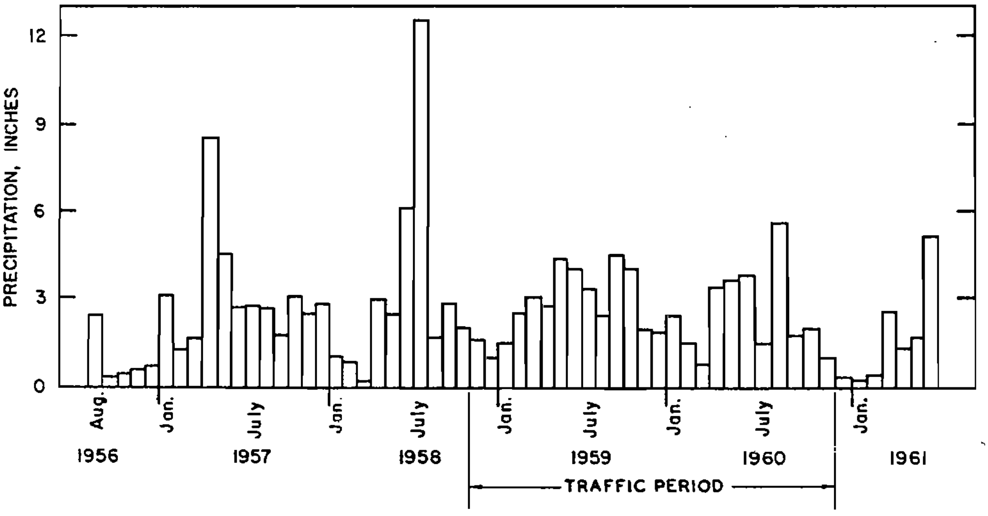

Figure 9. Precipitation at project.

The climate of the Road Test area is temperate with an average annual precipitation of 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 with 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 8 through 10 and frost depth information in Figure 11. 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 12 summarizes the observations made at the project on the elevation of the water table under the test pavements and adjacent natural ground.

1.3 PAVEMENT SERVICEABILITY AND PERFORMANCE

1.3.1 Relation to Objectives

The first objective of the Road Test (see Section 1.1.3) asks for 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. Briefly, it was considered that a pavement which maintained a high level of ability to serve traffic over a period of time was 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 represent 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 is given in the next two sections. 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.

1.3.2 Rating of Pavements in Service

Serviceability was found to be influenced by longitudinal and transverse profile as well as the extent of cracking and patching. The amount of weight to assign to each element in

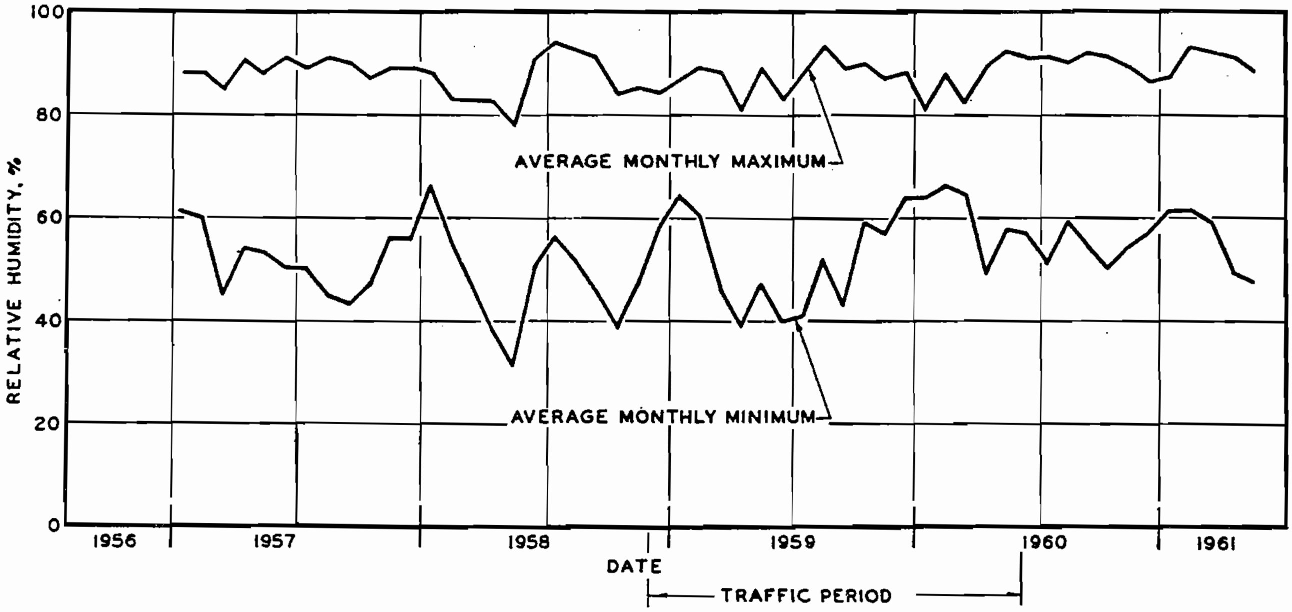

Figure 10. Relative humidity, weather station at Peoria, Ill.

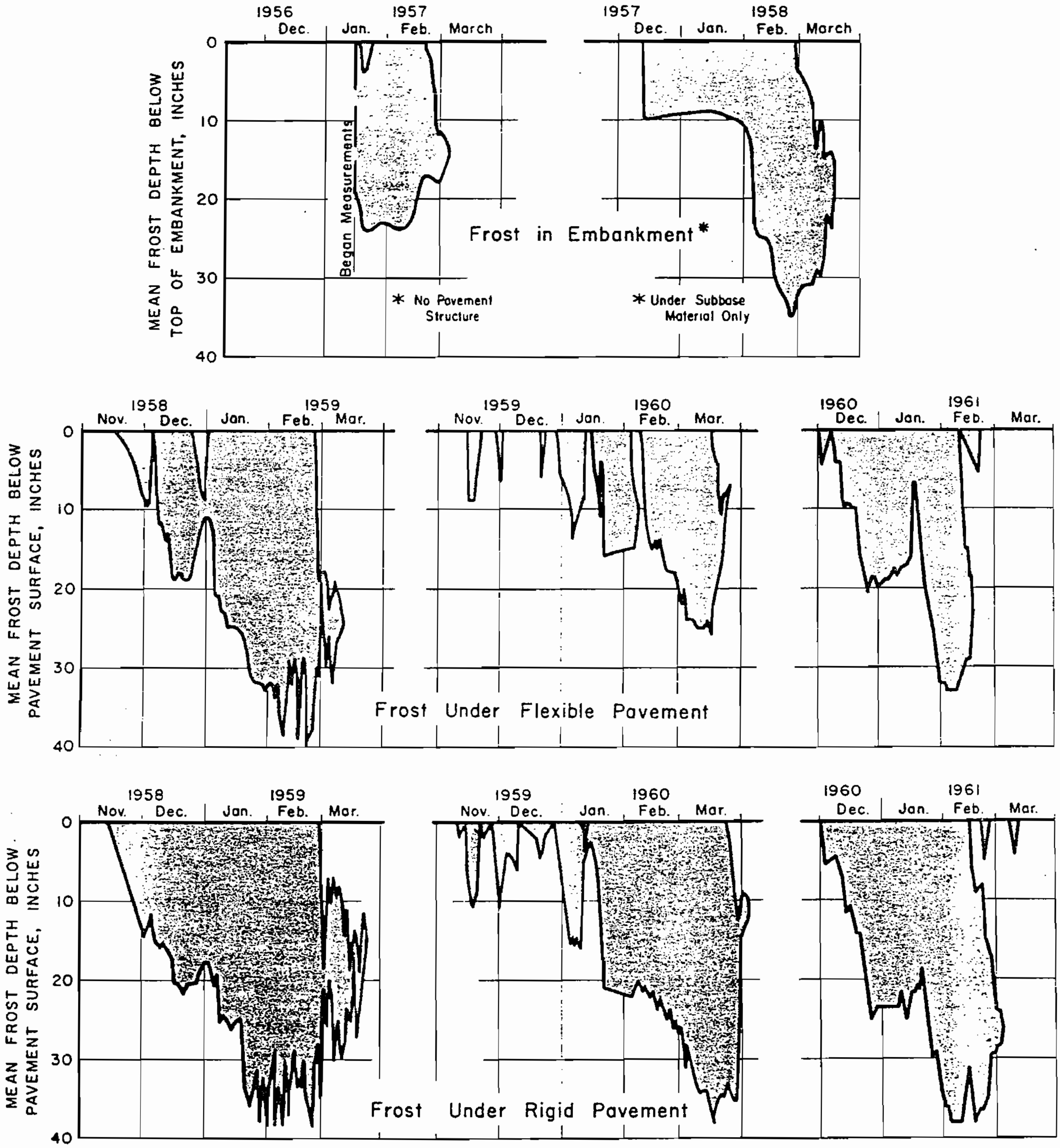

Figure 11. Frost depth.

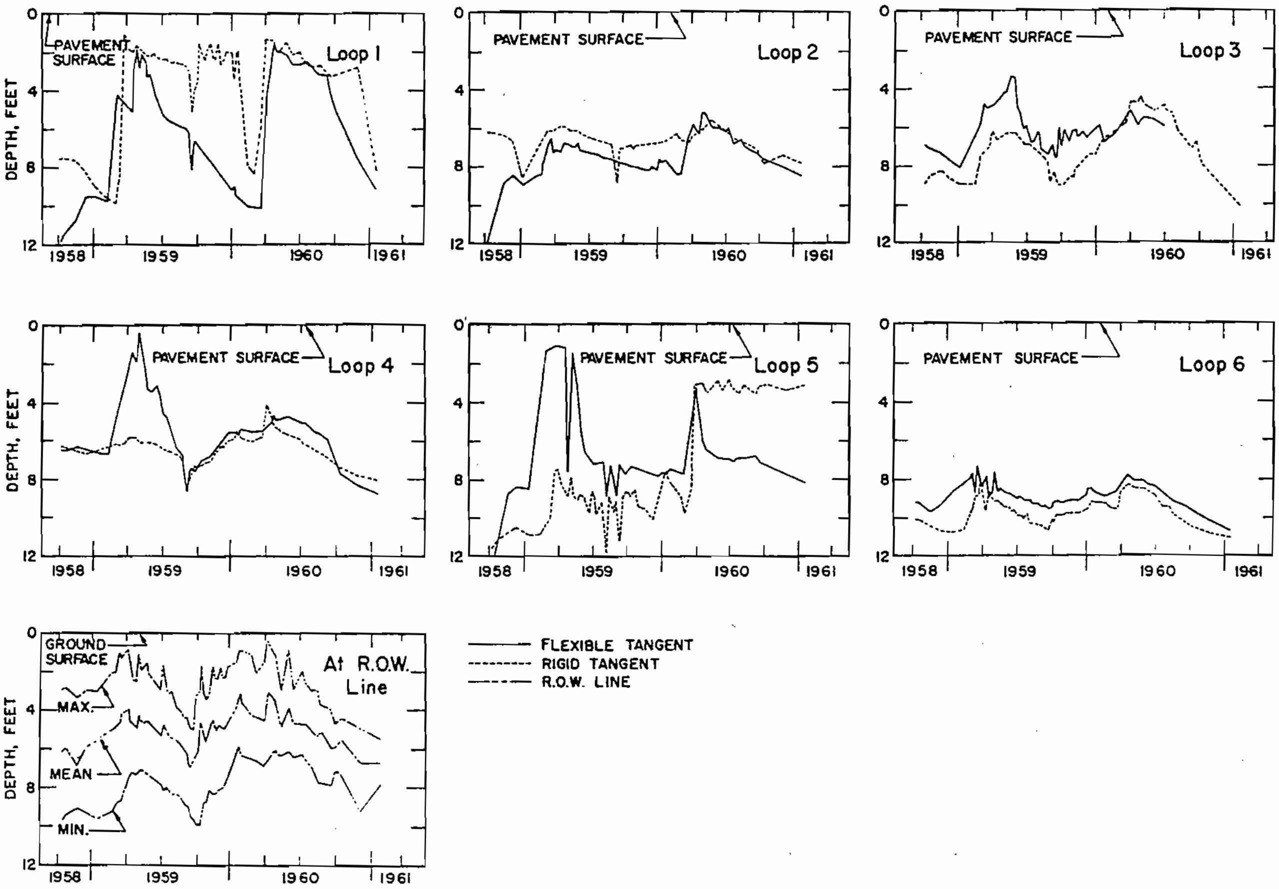

Figure 12. Water table data.

the determination of the over-all serviceability 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 men, 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. The members were instructed to use whatever system they wished in rating each pavement and to indicate their opinions of the ability of the pavement to serve traffic at the time of rating on a scale ranging from 0 to 5 with adjective designations of very poor (0–1), poor (1–2), fair (2–3), good (3–4), and very good (4–5). For each section the mean of the independent ratings of the individual panel members was taken as the section's present serviceability rating. Some of the sections were rated more than once in order to determine the ability of the panel to repeat itself. Road Test field crews then measured variations in longitudinal and transverse profiles, as well as the amount of cracking and patching of each section.

1.3.3 Present Serviceability Index

Through a conventional statistical procedure (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 either type of pavement this analysis resulted in a formula that used pavement measurements to compute a "present serviceability index" which closely approximated the mean rating of the panel.* The necessary measurements and serviceability index compu-

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* A detailed discussion of the work of the Rating Panel, including the ratings, the data obtained in the measurements of the sections that were rated, and the derivation of the present serviceability indexes is presented in Appendix F.

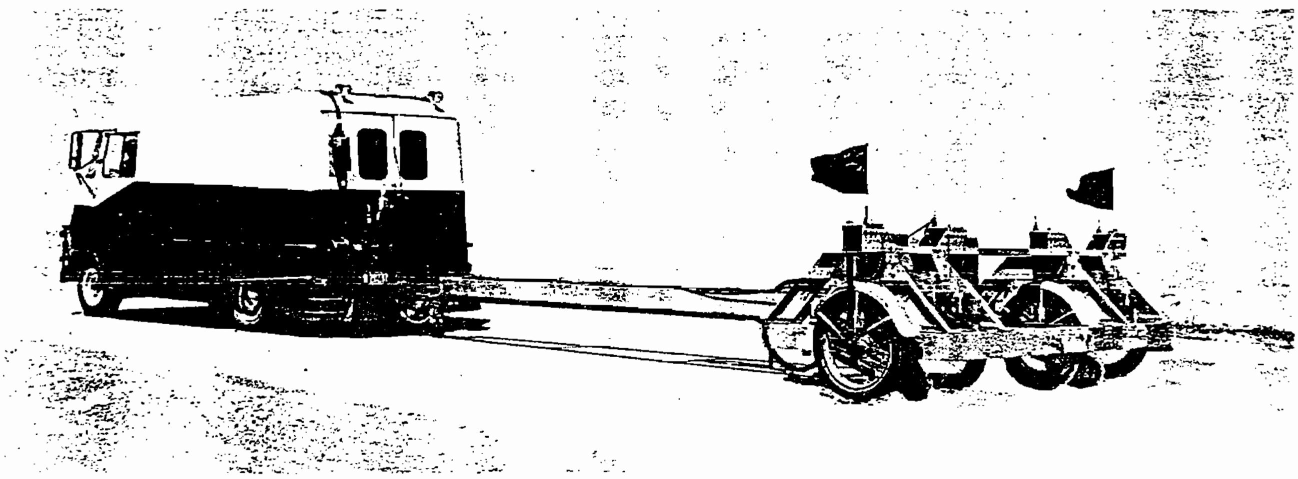


Figure 13. Longitudinal profilometer.

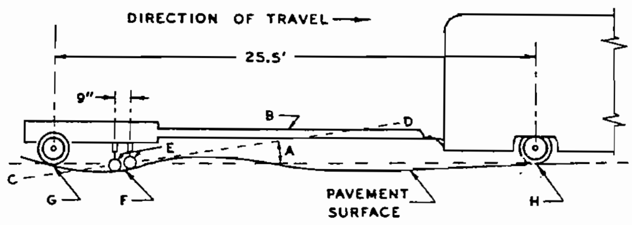


Figure 14. Schematic of longitudinal profilometer.

tations were made for each Road Test section at two-week intervals throughout the traffic phase.

Formulas for the present serviceability index, together with descriptions of the measurements entering into them, will be found in Chapters 2 and 3 for flexible and rigid pavement, respectively. 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 13 and shown schematically in Figure 14. This instrument, moving at a speed of 5 mph, recorded continuously the angle, A, formed by the line of the support wheels G and H, and the line CD that connects the centers of two small (8-in. diameter) hard-rubber tired wheels, E, arranged in tandem. One pair of these wheels traveled in the center of each wheelpath.

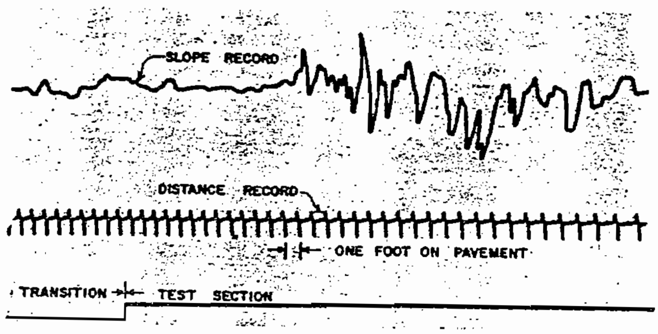
Since the distance between the centers of the wheels, E, was small (9 in.) the line, CD, was assumed to be approximately parallel to the tangent to the road surface at the point, F, midway between the wheels.

The distance between the supports, G and H, of the tongue being relatively large (25.5 ft), the line GH was regarded as being approximately parallel to the pavement surface had it been perfectly smooth. Thus, the angle, A, between CD and GH represents a departure from a smooth pavement surface and variations in A represent variations in the longitudinal profile. It was this angle that the instrument was designed to measure. The effect of vibration of the tires and springs at G and H was held to a low level by restricting the operating speed and by electrically filtering out high frequencies so that they did not appear on the record.

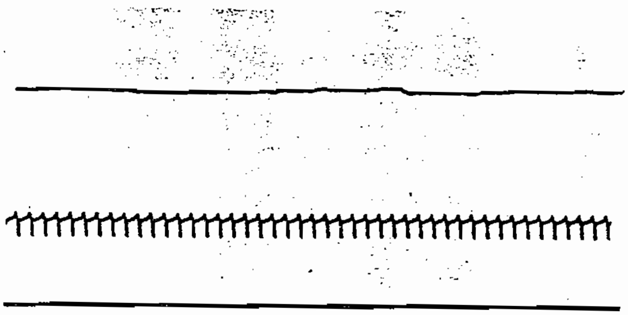
It was recognized that line GH was not a stable reference and that as a consequence the instrument could not respond correctly to gradual changes in the true pavement slope occurring over relatively long distances. Therefore, considerable effort was expended to develop a means to detect and correct for rotations of the line GH with respect to a horizontal reference. An inertial reference system was devised that would accomplish this purpose for short runs (that is, 2,000 ft). But tests of the effectiveness of the instrument with and without the reference indicated that the inconvenience of operation with the reference far outweighed the small increases in the over-all system effectiveness. Consequently, the inertial reference was abandoned.

The angle A rarely exceeded 3 deg even on rough pavements. Within the range of ±3 deg, the tangent of an angle is virtually equal to the radian measure of the angle, and thus the record of angle A could be interpreted as the slope of the pavement. In this report the profilometer output will be referred to as the pavement slope.

The instrument output on paper tape 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. 15). The tapes were fed into an automatic electronic chart reader (Fig. 16) which measured the ordinate of the chart at intervals equivalent to



For Rough Pavement



For Smooth Pavement

Figure 15. Typical longitudinal profilometer record.

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 statistic intended to represent the roughness of the section. Investigation of several alternative statistics led to the choice of the variance of the slope measurements computed from:

$$SV = \frac{\sum_{i=1}^{n} X_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} X_i\right)^2}{n-1} \qquad (1)$$

in which

SV = slope variance;
X_i = the i^{th} slope measurement; and
n = total number of measurements.

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. 17), designated the CHLOE Profilometer, whose

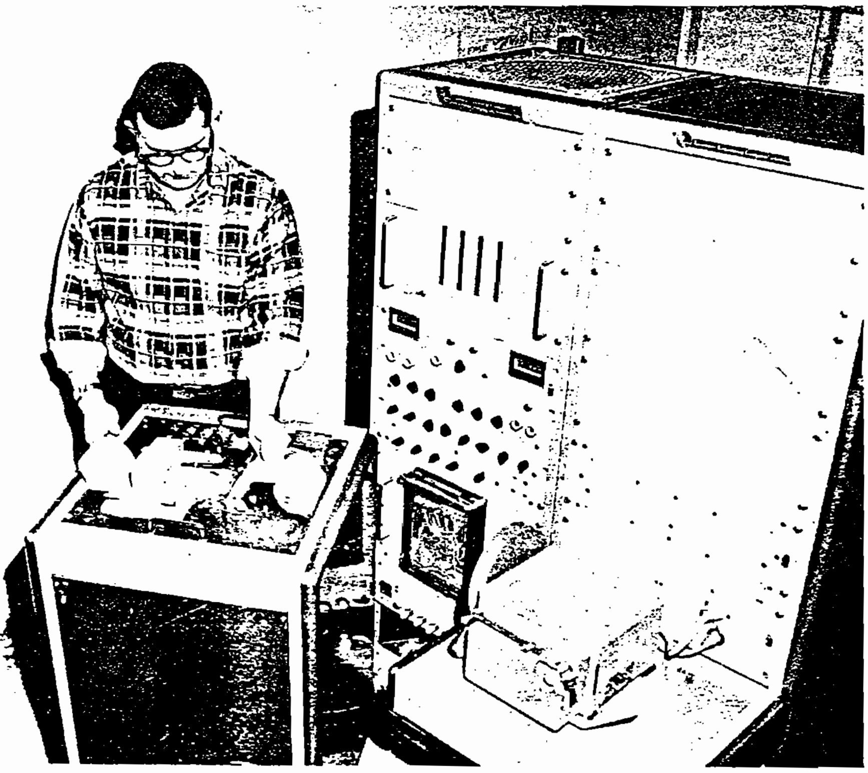


Figure 16. Electronic analog chart reader.

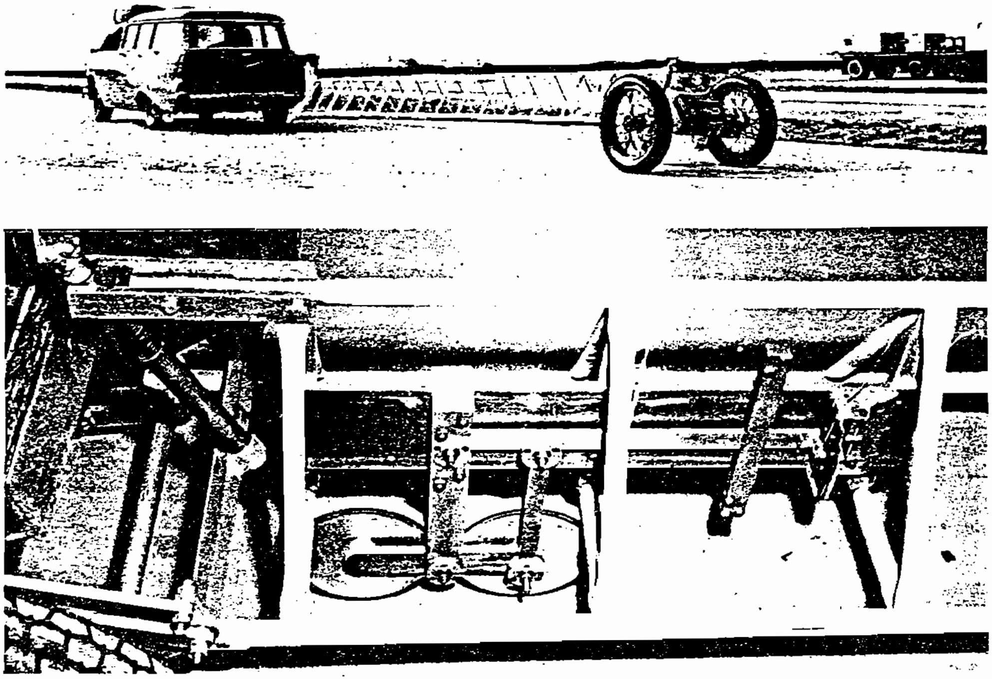


Figure 17. CHLOE profilometer.

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.

1.3.4 Pavement Performance Data

As stated in Section 1.3.1, 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. Prior to use in the analyses, performance data were identified and processed.

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 3, 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 was equivalent to specifying the serviceability index corresponding to a given number of axle applications. The symbol p_t' was used to represent the serviceability index of any section as determined by measurements made on the t^{th} index day, and the plot of p_t' versus time was termed the "serviceability history" of a section. (Usually the last three days of an index period were required to make the measurements on all sections for determining p_t'.)

The serviceability history of each section was converted to a "smoothed serviceability history" by a moving average that included at least three (generally five) successive index values except that the end values for the history were sometimes taken as end values for the smoothed history. Typical serviceability data and smoothed serviceability histories are shown in Figure 18.

The number of axle applications applied during the t^{th} index period, averaged over the ten traffic lanes, was represented by n_t, and the total number accumulated through that period by N_t; thus,

$$N_t = n_1 + n_2 + \ldots + n_t \qquad (2)$$

It was observed early in the traffic phase of the Road Test, confirming experience elsewhere, that for sections of insufficient design relative to load, the rate at which pavement damage accumulated with applications of load was affected by seasonal changes, especially 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 various seasons since sections which 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 the 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

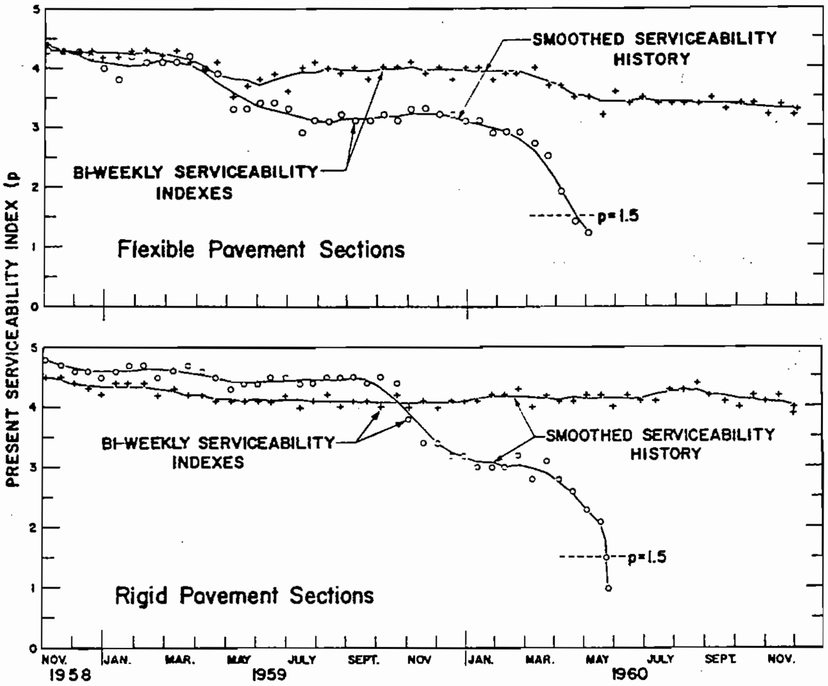


Figure 18. Typical serviceability histories.

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.

suggested the use of a "seasonal weighting function," q_t, to be multiplied by the number of load applications made during each index period, with the value of q_t depending on some measurement designed to reflect the general variation above and below a "normal" value in the strength of the test sections. The function q_t presumably would take on values greater than unity during periods when the pavement was weaker than normal, and between 0 and 1 when stronger than normal. The product, $q_t n_t$, would then yield "weighted applications," w_t, corresponding to the actual application, n_t, made on each test section during an index period. The total number of weighted applications, W_t, would be given by

$$W_t = q_1 n_1 + q_2 n_2 + \ldots + q_t n_t \qquad (3)$$

Weighted application, W_t, could then be substituted for actual applications, N_t, in the performance analyses. (Hereafter W will be used to represent either weighted or unweighted axle applications, the meaning of the symbol being specified wherever used.)

A seasonal weighting function, dependent on the periodic measurement of flexible pavement deflections in Loop 1, was developed and used in an analysis of flexible pavement performance described in Section 2.2. In the case of rigid pavements, although all rigid pavement distress was associated with pumping and although pumping must be associated with periods of high rainfall, the seasonal variations in damage rate were less pronounced, and no effective function was developed.

For the analyses of pavement performance it was assumed that the trend of serviceability, p, with increasing axle application, W, could be satisfactorily represented by five pairs of coordinates. For sections that failed during the test period, simultaneous values of p and W were taken at $p = 3.5$, 3.0, 2.5, 2.0 and 1.5. For sections that survived the traffic testing period, the coordinates were chosen from the smoothed serviceability history at 11, 22, 33, 44 and 55 index days. Sets of coordinates from the serviceability trend, that is, performance data, for each Road Test section are given in Appendix A.

1.3.5 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 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.

There are many different mathematical forms that could 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 consideration 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

$$p = c_0 - (c_0 - c_1)\left(\frac{W}{\rho}\right)^{\beta} \qquad (4)$$

in which

$c_1 \leqq p \leqq c_0$;

p = the serviceability trend value;

c_0 = the initial serviceability trend value (for the Road Test $c_0 = 4.5$ 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. Rearranging Eq. 4 in logarithmic form, and defining G, a function of serviceability loss, as $\log (c_0 - p)/(c_0 - c_1)$ gives

$$G = \beta (\log W - \log \rho) \qquad (5)$$

Plotting G against $\log W$ for Eq. 5 gives a straight line whose slope is β and whose intercept on the $\log W$ axis is $\log \rho$. For each Road Test section the performance data given in Appendix A were converted into values for G and $\log W$ and a straight line was fitted to the G, $\log W$ points. From these straight lines, estimates of β and $\log \rho$ were obtained for each test section. For the cases where the serviceability loss was very small over the traffic testing period β may be nearly zero and $\log \rho$ extremely large. Special rules were applied for these cases in order to obtain logical values of β and $\log \rho$ (see Appendix G).

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

$$\beta = \beta_0 + \frac{B_0 (L_1 + L_2)^{B_2}}{(a_1D_1 + a_2D_2 + a_3D_3 + a_4)^{B_1} L_2^{B_3}} \qquad (6)$$

in which

β_0 = 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. 6 are positive constants whose values were either to be assigned as was done for β_0 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 flexible pavement data, respectively.

The analysis rationale assumes that estimates for β from the equation are better than estimates based only on the individual section performance data. Consequently, the values of β estimated from the equation were used in conjunction with the data to obtain new estimates of log ρ for every test section.

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

$$\rho = \frac{A_0 (D + a_4)^{A_1} L_2{}^{A_3}}{(L_1 + L_2)^{A_2}} \tag{7}$$

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. 6, 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. 6 and 7 is reported in Section 2.2.2 for flexible and 3.2.2 for rigid pavements.

Eqs. 6 and 7 when evaluated and used in conjunction with Eq. 5 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 after presentation of derived equations in Sections 2.2.2 and 3.2.2.

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.

1.4 NEEDED RESEARCH—GENERAL

1.4.1 Modification of Performance Relationships

Any further effort by the Highway Research Board to fit a mathematical model to the Road Test performance data will likely involve modifications either in the basic models for p, β, and ρ, or in the fitting procedures, or in both. It is the purpose of this section to mention several possibilities for both types of modification that are contemplated in further work with the performance data.

Even if no changes are made in Eq. 4, it is possible to modify the formulas for β and ρ. For example, it might be assumed that β is a constant,

$$\beta = b_0 \tag{8}$$

or that β is a simple function of ρ, for example,

$$\beta = b_0 + \frac{b_1}{\rho\, b_2} \tag{9}$$

The concept of a thickness index for flexible pavements might be generalized after further research to a "structural index," S, where S would account for all pavement layers (their thicknesses and strengths) as well as the embankment soil. A single index for vehicle load, L, might be introduced so that L could account for all axle loads (including steering axles) and their spacing. Then it might be assumed that

$$\rho = \left(\frac{S}{\sqrt{L}}\right)^{A} \tag{10}$$

so that the structural index is squared relative to the load index. It may be noted that the ratio of A_1 to A_2 in Eqs. 18 and 21 (see Section 2.2) is already of the order two to one, so that Eq. 10 appears to be a reasonable assumption at least for flexible pavements.

As is explained in Appendix G, performance equations developed for the present report result from a step-by-step fitting procedure where the results of one step are used as input for the next step. Modification of the fitting procedures will likely take the form of an over-all procedure that determines all unassigned constants simultaneously as a particular residual criterion is minimized. Once the over-all fitting procedure is developed, the residual criterion can include both residuals from log W estimates and residuals from p estimates. Moreover, performance data from experiments that have been analyzed separately in this report may be combined in an effort to obtain a more general analysis.

Although it was not possible to investigate modifications of the type just described in time for inclusion in this report, the Highway Research Board will undertake these studies. It is hoped that further effort will produce modified equations that can represent all the Road Test performance data with at least the same precision as given in this report and that simplifications can be introduced with little sacrifice in precision over the equations reported herein.

1.4.2 Generalization and Extension of Relationships

Discussion in the preceding subsection relates to the need for additional study of the data obtained in the Road Test. A larger area for future research, involves the extension of the performance equations to include parameters that were not varied in the project. It is important to know, for example, the effects on pavement performance of variations in the characteristics of the soil and the materials used in the pavement structure. The effects of environment need study. Not only the differences in performance associated with the existence of heavy rainfall, desert conditions, frost, etc., must be considered, but also the differences that may be associated with different rates of traffic application and distribution of axle loads in the traffic stream. (For example, at the Road Test a million axle loads of one weight were applied in two years to each section. What would have been the situation had these loads, accompanied by several million lighter loads, been applied in 20 years?)

Studies designed to fill these gaps may fall in four categories: (1) theoretical studies, (2) major satellite studies, (3) field tests, and (4) laboratory tests.

There should be continuing encouragement of research into the mechanical and physical laws involved in pavement performance. Only through such theoretical work will there be developed rational mathematical models by which performance can be related to the fundamental properties of materials and to the dynamic characteristics of the loading.

Since the completion of such theoretical work appears to be years away, immediate attention should also be given to means for extending the empirical models developed at the Road Test to include additional important parameters. A most effective device for this purpose is the so-called satellite study. These studies have been described* as relatively small road tests in different parts of the country (and other countries) involving consideration of variables most of which were not included in the AASHO Road Test. A very important finding of the Road Test was that, within the range of precision of measurements systems and estimation techniques available, no significant interactions were found among the design variables. Therefore, in the design of satellite experiments where the variables are like those in the Road Test (structure thickness, base type, etc.) balance in the experiment can be attained through the use of partial rather than full factorials.** This means that to test a given number of variables any satellite experiment will require only a small fraction of the test sections that would have been required had the AASHO Road Test shown that significant interactions existed.

Such satellite experiments are also different from the Road Test in that traffic is not a variable. The test sections would be constructed as part of the regular highway system and their serviceability trends observed under the normal traffic using the facility. A careful record of the number and magnitudes of axle loads over the test sections would be required.

These experiments would provide for verification of the coefficients in the Road Test performance equations and for the inclusion of terms in the equations relating to variables that were not under study in the AASHO Road Test. More specific areas for study in the satellite experiments are discussed at the ends of Chapters 2 and 3.

Field tests would be simple pavement performance experiments, with 2 or 3 test sections each, constructed as part of normal highway construction in a large number of locations where only one or two variations from normal pavement design would be observed along with the normal design. These studies would prove very useful to engineers who must use judgment in the application of Road Test findings and in their attempts to evaluate new designs and new materials. However, the field tests would not be designed in such a way as to permit analyses that would result in important modification of the Road Test equations themselves. Many states have constructed test pavements in the field test category in the past. If traffic records are available, further study of these pavements would be extremely useful.

Laboratory tests are those needed in the study of materials characteristics as they might affect pavement performance. Here again more detailed recommendations are given at the ends of Chapters 2 and 3.

1.4.3 Serviceability of Pavements

It is believed that the serviceability-performance concept developed at the Road Test has added a new technique of value in the design and maintenance of highway pavement. It is emphasized, however, that the specific serviceability indexes developed for the Road Test, were based on very small samples of the American highway network by a very small group of highway engineers. There is no reason to think that more extensive sampling will result in major modification of these indexes, but if the system is to receive widespread use, it is imperative that other groups, working under the same rules as the Road Test Rating Panel, make subjective ratings of many sections of pavement over the entire country containing many types of distress leading to loss of serviceability. Accompanying these rating sessions should be objective measurements of those elements that may be involved in serviceability such as, slope variance (roughness), rut depth, cracking, faulting, patching, and slipperiness. Regression analyses of the ratings in terms of the objective measurement data will produce new more generally applicable serviceability indexes.

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* "Extending the Findings of the AASHO Road Test" before the Design Committee, AASHO, at the AASHO meeting in Denver, Colo., October 1961.

** See Hain, R. C., and Irick, P. E., "Fractional Factorial Analysis," HRB Road Test Conference, May 1962.