NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 7

COMPARISON OF DIFFERENT METHODS OF MEASURING PAVEMENT CONDITION

INTERIM REPORT

HIGHWAY RESEARCH BOARD NATIONAL ACADEMY OF SCIENCES - NATIONAL RESEARCH COUNCIL

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COMPARISON OF DIFFERENT METHODS OF MEASURING PAVEMENT CONDITION
INTERIM REPORT

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NATIONAL ACADEMY OF SCIENCES - NATIONAL RESEARCH COUNCIL 1964

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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

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

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

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

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

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

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FOREWORD

By Staff

Highway Research Board

Highway research engineers continue to seek methods for applying the AASHO Road Test findings to specific local conditions. Although the results of the Road Test have contributed much to the understanding of pavement design and performance, they are specifically applicable only to conditions comparable to those existing at the Road Test site. One of the more important concepts evolving from an analysis of these data has been that of evaluating pavement performance. This concept relates to a determination of road surface properties for the evaluation of pavement serviceability and to the serviceability changes throughout the life of the pavement. It is apparent to highway engineers that if measurement techniques for obtaining certain road surface properties can be developed, the pavement serviceability performance concept will become more widely applicable and increase the use of research findings from the Road Test. To this end, this study provides data on the comparison and correlation of several systems for measuring pavement roughness as one of the desired objective measurements in obtaining the present serviceability index of a pavement.

This has been essentially a field study involving eight different road roughness measurement devices and three rating panels consisting of individuals of different backgrounds. Data collection primarily consisted of field measurements with the equipment and subjective ratings by the panels. Data have been evaluated by a statistical approach somewhat similar to that used in the analysis of the AASHO Road Test data.

The measurement devices included the Bureau of Public Roads types of roughometers, four different types of profilometers, a texture meter, an accelerometer system, and an instrument for measuring variation in tire pressures. There were three rating panels, one consisting of housewives, farmers and other persons inexperienced in rating pavements; the second, referred to as the AASHO test panel, consisting of several members of the original AASHO Road Test rating panel. The third panel was made up of an HRB Committee of engineers. Forty-five pavement sections, including flexible, rigid, and overlay types of construction, were evaluated by the rating panels as well as by measuring devices. Information was analyzed to show correlations and contrasts among the three panels and also between the panels and the road roughness measuring devices. Data are also available which can be used to establish a correlation between roughometers and the slope profilometer. In addition, equations are provided for interpreting roughometer data in terms of serviceability indices.

This study, conducted by staff members at Purdue University, provides significant data which will make possible more effective use of equipment and rating panels for obtaining data on road surface properties. Of particular interest are the results which provide a correlation among several types of roughness measuring devices for obtaining objective measurements of pavement roughness. Basic data are presented for the comparison of road roughness equipment by agencies throughout the world which use the pavement serviceability concept for evaluating pavement performance. The correlation among the Bureau of Public Roads type rough-ometers will be particularly beneficial in that a number of agencies have such equipment.

Although this study is an interim report, it contains the major portion of the data developed. An extension of the study will continue into more detailed analysis of road loading mechanisms as measured through automobile tire pressures. The power spectrum analysis technique is being used in the continuation phase. Pavement data for the continuation phase were obtained in the initial research, but will receive analysis in the next phase.

CONTENTS

ACKNOWLEDGMENTS

The research project reported herein was conducted under the terms of a contract between the Purdue Research Foundation and the National Academy of Sciences. The work was made possible through the cooperation of many individuals in governmental and state agencies.

The equipment used in the study, with one exception, was loaned to this project at no cost to the project itself. The names of the states cooperating in the work are given throughout the report; each piece of equipment is identified by the name of the state which operated the instrument.

The Purdue Tire Pressure Measuring Device was developed by Professor B. E. Quinn. In addition, he supervised a major portion of the field work which involved operation of the roughometers and profilometers. W. J. Head was in charge of the field performance surveys. T. W. Williamson assisted materially in laying out the test sections. A. Y. Casanova, Bureau of Public Roads, gave major assistance during the field testing program.

The analysis of the data was based upon concepts presented by Carey and Irick. Liberal use was made of the data obtained in connection with the AASHO Road Test. In addition, use was made of data obtained at Purdue University for the Indiana State Highway Commission. This later work was reported to the Highway Research Board by Miss Velma Nakamura and Professor H. L. Michael.

The Bureau of Public Roads made a major contribution to the study by furnishing personnel to operate the AASHO Slope Profilometer. Personnel from the Texas Highway Department operated the CHLOE Profilometer.

COMPARISON OF DIFFERENT METHODS OF MEASURING PAVEMENT CONDITION—INTERIM REPORT

SUMMARY

As a part of the National Cooperative Highway Research Program, a study was conducted in 1963 to develop serviceability equations which relate road user opinion and data obtained using various roughometers and profilometers. The work was patterned after that developed by Carey and Irick in connection with the AASHO Road Test.

Forty-five pavement sections of three types (rigid, flexible, and overlay) were rated by a lay panel, the AASHO Road Test panel and the Highway Research Board Committee on Pavement Condition Evaluation. The extent of cracking and patching was determined for each section. Roughness and profilometer measurements were made using roughometers from eight different agencies, the AASHO Slope Profilometer, CHLOE Profilometer, Kentucky acceleration device, Texas Texture Meter, University of Michigan Truck Mounted Profilometer, General Motors Corporation device and the Purdue University tire pressure instrument.

Regression equations which relate pavement rating and objective measurements are presented in the report for each instrument. The conclusions in the report were based largely upon comparisons of the correlation coefficients and standard errors of estimate obtained for the regression equations. Tables are presented which summarize the regression analysis.

The rating data showed that the lay panel tended to rate pavements higher than the professional panels. Data from this study suggested lower ratings for acceptable pavements than the AASHO data.

The study indicated that, from the standpoint of predicting serviceability, little difference existed among the instruments. The authors suggest that choice of instrument to use should depend upon instrument costs, cost of data reduction and availability of the instrument. Thus, the BPR-type roughometers and CHLOE profilometers have high potential for obtaining serviceability data.

CHAPTER ONE

INTRODUCTION AND BACKGROUND

This report summarizes research carried out under terms of a contract between the Purdue Research Foundation and the National Academy of Sciences on various methods of measuring pavement condition. This project is a part of an overall study to extend the results of the AASHO Road Test.

One of the most significant findings of the AASHO Road Test dealt with serviceability of pavements and methods of measuring pavement condition. Specifically, serviceability has been referred to as the Present Serviceability Index (PSI). These concepts were first reported by Carey and Irick (*2*).

Briefly stated, the concepts were constructed on the premise that the road user should determine whether or not a pavement is satisfactory. Thus, the Present Serviceability Index was obtained by correlating user opinions with measurements of road roughness (as measured by the AASHO slope profilometer) and the extent of cracking, patching and rutting.

The Present Serviceability Index was established from regression equations which related user opinions with objective measurements. A panel drove over selected pavements and rated the pavements using an appropriate scale. The rating scale for this study ran from 0 to 5. A rating of zero denoted an impassable pavement whereas a rating of 5 indicated a perfectly smooth pavement. The raters were asked to mark on the scale the number which indicated their opinion of the road at the time that it was rated. In addition, the raters were asked to give their opinions relative to the objective features (*i.e.*, rutting and cracking) of the pavement which influenced their rating and were asked to state whether the road was acceptable for Interstate traffic.

Ratings vary because of human nature and differences of opinion; thus, the rating numbers assigned to a pavement by panel members were averaged and designated the Present Serviceability Rating (PSR).

The Present Serviceability Rating was correlated with the objective measurements previously mentioned by means of regression equations. The rating then calculated by these equations was termed the Present Serviceability Index.

Since its original development, the Present Serviceability Index concept has been adopted by many paving engineers. Specifically, several state highway departments have adopted these concepts for setting up maintenance programs, road life studies and priority ratings.

AASHO SERVICEABILITY EQUATIONS

The original serviceability equations took into account cracking, patching, rut depth and slope variance. The AASHO equations for rigid and flexible pavements are as follows:

Rigid Pavements:

$$p = 5.41 - 1.78 \log (1 + SV) - 0.09\sqrt{C + P} \quad (1)$$

Flexible Pavements:

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

in which

SV = Slope variance;
C = Major cracking, in ft per 1,000 sq ft of area;
P = Bituminous patching in sq ft per 1,000 sq ft of area; and
RD = Average rut depth of both wheelpaths in inches measured at the center of a 4-ft span in the most deeply rutted part of the wheelpath.

Slope variance (SV) is a statistical term which indicates the variation of slope of a pavement from the mean slope value. The slope variance is computed by

$$SV = \frac{\sum Y^2 - \frac{1}{n}(\Sigma Y)^2}{n - 1} \quad (3)$$

in which

Y = Difference between two elevations 1 ft apart; and
n = Number of elevation readings.

Slope variance was measured on the AASHO Road Test by means of the slope profilometer designed specifically for this test road (see Fig. 10). This particular instrument as well as others that can be used for this type of work is discussed in greater detail subsequently.

It must be emphasized that the rating given by the AASHO rating method is a condition rating at the time that the rater travels over the pavement surface. No indication is given as to the structural adequacy of the pavement or to the probable behavior of the pavement in the future.

The key word in the definition is "present." In fact, the raters are asked to look at nothing but the pavement and in addition are asked to rate the pavement as it is now without being influenced by such factors as potential behavior, pavement width, shoulder width, condition of shoulders, grade, alignment, structural adequacy, traffic, and climate. Thus, to relate the serviceability index with pavement life, it becomes necessary to rate the pavement over a period of time to give a rating history. This is termed performance. This performance concept was used in the evaluation of the AASHO Road Test by relating PSI with number of load applications (*5, 6*).

FACTORS AFFECTING THE INDEX

There is widespread agreement among engineers that the present serviceability concept makes available a tool which has been needed for a long time. Several items concerning this point follow, although this list is by no means complete.

1. The Present Serviceability Rating permits rating of pavements on a common basis. A serviceability rating of a certain number, for example, has specific meaning to engineers regardless of their location.
2. It permits the formulation of priority and maintenance program in a logical manner.
3. The Present Serviceability Index establishes relationships between objective pavement measurements and subjective ratings of the road user.
4. The method permits obtaining measurements at various times and the establishment of a parameter which defines pavement condition in design equations. Histories of pavement performance can be related to changes in serviceability with time.

There is little doubt that the present serviceability concept materially assisted analysis of the AASHO Road Test data; however, it should be recognized that the concept is based on a statistical approach. Since the completion of the AASHO Road Test, engineers have raised several questions which need clarification. For example, can data obtained by various pieces of road roughness equipment be used to establish regression equations? Which instrument gives the most reliable results? One of the purposes of this research project is to shed light on these questions.

The following briefly outlines several factors which affect the serviceability index and points out how these factors were interpreted in this study.

PSR Based on Average Values

The term PSR refers to Present Serviceability Ratings given by a panel of raters. For correlation purposes, the average (mean) rating by a panel is used. By its nature, variation among individual pavement raters exists. One of the functions of the PSR is to take individuality out of the assigned rating.

As a general rule, mean ratings are used in the regression analysis. This assumes that variation among raters is independent of the rating number itself. This assumption is not necessarily true since at the extreme ends of the rating scale there may be good agreement among raters, whereas in other portions of the scale there may be disagreement.

Variation Among Panels

In the original work done on the AASHO Road Test, consideration was given to differences of opinion among various sociological groups. This was studied further by Nakamura (*10*), who showed that, in general, lay panels rated pavements higher than panels consisting of highway engineers.

Pavement Acceptability

Several investigators have studied the relation between pavement rating and pavement acceptability. Nakamura indicates that lower ratings are acceptable for secondary pavements than for primary pavements. Carey and Irick point out that a rating of about 2.5 or higher indicates an acceptable pavement.

Presumably pavement acceptability should depend to some extent on the intended function of the pavement. This again is a subjective matter and could conceivably depend also upon location, economics and other geographic and sociological factors.

Number of Raters Required

Since variation among raters exists, it becomes necessary to use large panels to obtain accurate data. Nakamura, however, has suggested that if an error of 1.0 can be permitted, just two or three raters are required. She indicated further that, as a rule, it is necessary to send out a panel of 5 to 10 members.

Equipment

The original AASHO method is based upon the use of the Slope Profilometer. Data obtained in Indiana, however, have suggested that the Bureau of Public Roads roughometer is satisfactory when evaluating rigid pavements but not flexible pavements (*10*).

Housel (*7*) has correlated serviceability rating with data obtained by the University of Michigan profilometer. Scrivner and Hudson have suggested that surface texture can be an important factor in pavement rating (*14*) and have developed a Texture Meter which can be used in pavement evaluation.

To be of most use, the instrument used to evaluate a pavement must be economical; but on the other hand, it must obtain significant data. This leads to the need for studying various pieces of equipment to determine which instrument gives the most satisfactory answers in light of time and cost of obtaining the data.

Miscellaneous Factors Affecting Rating

Investigators on the AASHO Road Test have shown that the primary factors (other than surface roughness) which affect pavement rating appreciably are rutting, patching and cracking. The results of a study conducted in Indiana, however, have suggested that other factors may affect opinions of road users (*10*). These include grade, alignment, esthetic features, bleeding, raveling and slipperiness.

Here again, to be of most use to the engineer the regression analysis should include a minimum number of variables. Thus, there is a need to determine with accuracy which factors affect rating.

Mathematical Models

The model used at the AASHO Road Test was additive of the form

$$p = A_0 + A_1 f_1 + A_2 f_2 \ . \ . \ . \qquad (4)$$

in which

p = Serviceability index;
A_0, A_1, etc. = Coefficients; and
f_1, f_2, etc. = Objective measurement data.

Painter (*11*) has suggested that a model of the following form is better than the additive model:

$$\log p = \log a_0 + a_1 f_1 + a_2 f_2 \ . \ . \ .$$

or

$$p = a_0 \, 10^{a_1 f_1 + a_2 f_2} = a_0 \, 10^{a_1 f_1} \, 10^{a_2 f_2} \ . \ . \ . \qquad (5)$$

Engineers at the Road Test investigated both models and adopted the first for their use for several reasons. Eq. 4 has advantages when relating PSI with traffic history, which in itself is justification for its use.

Generalized Equations

Logically, any agency using the serviceability concept should establish its own regression equations to fit its particular conditions. However, a considerable amount of effort could be expended by state highway departments to carry this to fulfillment. It therefore appears desirable to establish generalized regression equations which relate Present Serviceability Rating and objective measurements which are obtained using several techniques.

CHAPTER TWO

PROCEDURES, EQUIPMENT, AND PANELS

Briefly stated, the primary purpose of this research project was to make a study of several roughness measuring instruments and to determine which instrument or group of instruments is the most reliable for predicting serviceability. As a natural adjunct to this, a secondary purpose (perhaps just as important) was to study the physical features of a pavement which affect pavement rating.

This project compared conventional roughness measuring equipment. The pavement sections were selected so that surface texture was variable. It also included a study of physical features of the pavement which affect rating but did not include traffic data (such as number of coverages of a certain wheel load), thickness of pavement or strength of pavement components.

The study included evaluation of various pieces of equipment when used on three basic pavement types: rigid, flexible and overlay pavements. Overlay pavement as used throughout this report refers to portland cement concrete pavement resurfaced with bituminous concrete. The road roughness equipment used in this study included:

1. Bureau of Public Roads Roughometer (8 different roughometers from eight different agencies)
2. AASHO Slope Profilometer
3. CHLOE Profilometer
4. Texas Texture Meter
5. Kentucky Highway Department Accelerometer Device
6. University of Michigan Truck Mounted Profilometer
7. General Motors Corporation Profilometer
8. Purdue University Tire Pressure Instrument.

In addition to these instruments, the prospectus submitted to the Highway Research Board included the tire pressure measuring instruments mounted on a special test truck as used by the Michigan Highway Department and the instrument developed for the Air Force that utilizes a light beam for making the necessary measurements. These instruments were not available at the start of this project and thus were not included.

Actual work on the project was started in March 1963. At this time, preliminary arrangements were made to bring the equipment to Indiana. After consultation with personnel from the Highway Research Board, preliminary plans were laid for selecting panels to be used in the study.

LOCATION OF STUDY

Test pavements used in this study were located in the north-central section of Indiana in the vicinity of Lafayette. Figure 1 shows the location of the test pavements. Most of the test pavements were located on soils deposited by the latest advances of the Wisconsin Age glaciers; thus, the soils are typically silty clays with well-developed profiles. One test pavement was located on a granular terrace associated with the Wabash River.

Pavements on the primary system are essentially all portland cement concrete underlain with a granular base course. The secondary and county roads are nearly always built using flexible pavements although in some cases rigid pavements are to be found. The rigid pavements (with the exception of four pavement sections) were on the primary state highway system. The four exceptions included a section on a county road, a section on a state highway, and two sections which were initially in the primary state highway system but which were abandoned due to relocation.

In contrast to the above, flexible pavements with one exception were on the secondary state highway road system or in the Tippecanoe County highway system. The overlay pavements were all in the state highway system.

As a result, several unique features were associated with both the flexible and rigid sections. Since the rigid pavements were by and large on the primary system, grade and alignment, right-of-way widths, etc., were in accordance with standards used on the primary system, whereas these features for the flexible pavements were in accordance with the lower standards of the secondary highway system.

CHOICE OF PAVEMENT SECTIONS

Because it was the intent of this study to correlate objective measurements with pavement rating, it was decided at the outset to select the pavements so that a wide range of pavement ratings would be included. Initially, 150 pavement sections were tentatively selected and were rated by one individual using the AASHO rating scale.

On the basis of the preliminary rating the number of pavement sections was reduced to 75 by eliminating obvious duplications and sections unsuitable because of poor sight distance, accessibility and other factors.

The next step consisted of establishing a rating panel consisting of fifteen Purdue staff members. This rating panel rated each of the 75 pavement sections during the months of May and June 1963.

The ratings of the Purdue panel were averaged and, again through a process of elimination, the number of test pavements was reduced to approximately 50. At this stage, a conscientious effort was made to include a wide variation of pavements with a concentration of pavements having ratings ranging from 2.5 to 3.0.

Duplicate pavement sections were included wherever possible. Figure 1 shows the final selection of pavements used in this study. The test pavements were divided into two loops, one north and the other south of Lafayette. Duplicate sections were so chosen that a pavement of each type and rating was included in both loops. The final selection of test pavements was modified to minimize travel time around each loop.

Each pavement test section was approximately one-quarter mile in length. This was modified somewhat during the experiment layout due to restrictions imposed by

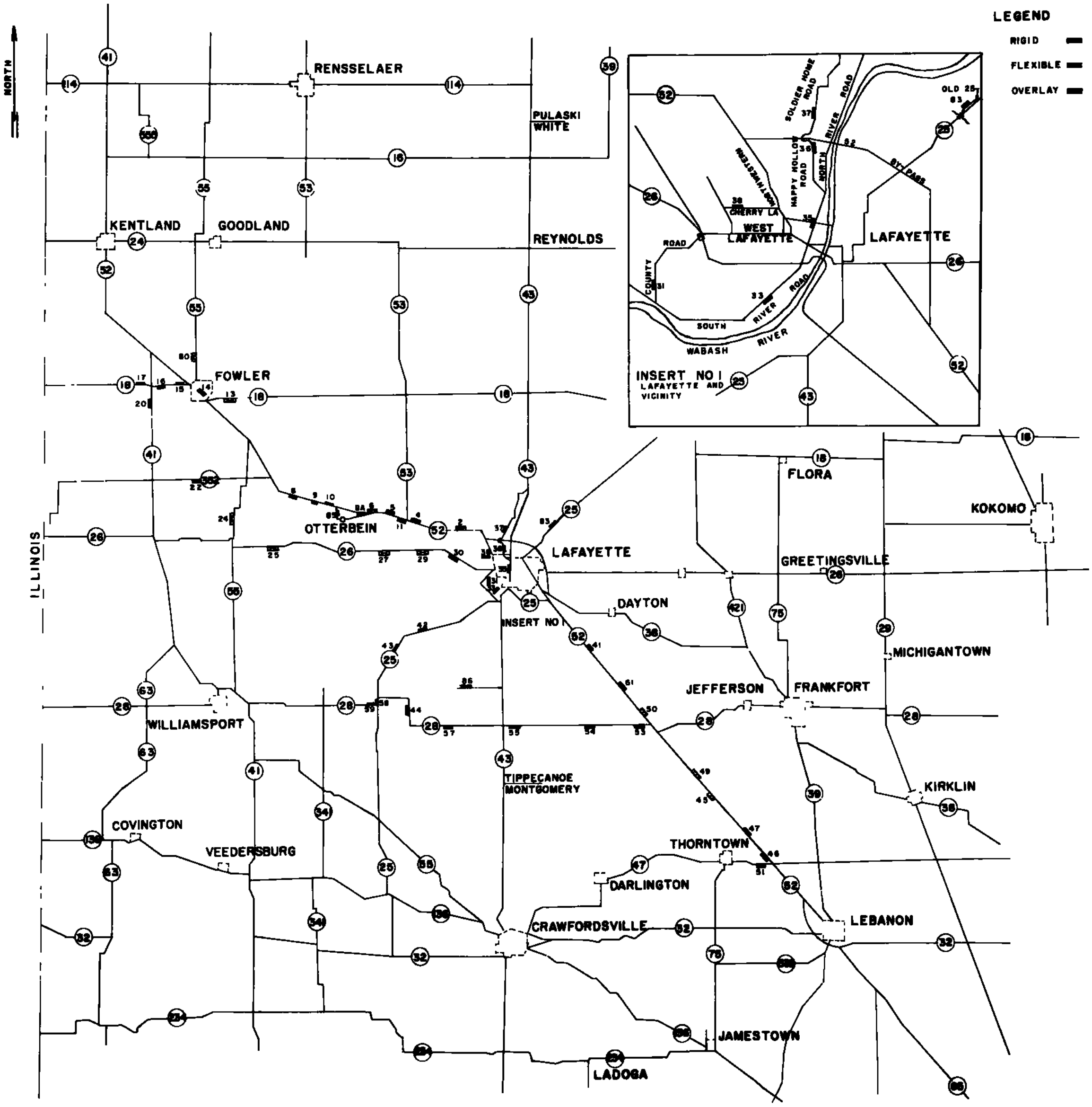

Figure 1. Location of test sections.

sight distance, grade and alignment. In each case, the test section was in one lane of the highway only. In the case of 4-lane divided pavements, the test section was always in the traffic lane (outside lane) while for 2-lane pavements, choice of lane depended upon route of travel. The majority of the rigid test sections were on 12-ft lanes, whereas most of the flexible and overlay sections were on 11-, 10- or 9-ft lanes.

CONDITION SURVEYS

The condition surveys of the pavement sections were conducted from June through August 1963. The survey party consisted of three men. Equipment included a standard roll tape, a measuring wheel calibrated in feet, a "faultmeter," a "rutmeter," and a still camera.

The purpose of the surveys was to record the physical condition of the pavement sections. In conducting the surveys the policy was to record as much information as possible on the field data sheets or "maps" (Fig. 2).

When conducting a field survey, the survey party walked the test section and noted the location and size of physical features of the pavement. Usually, one man served as flagman, one man operated the measuring wheel and faultmeter (or rutmeter) and made measurements, and the third man drew to scale the physical features of the pavement on the map.

Certain measurements were common to all sections including:

1. Width of pavement (usually 9, 10, 11, or 12 ft);
2. Length of section (usually 1,320 ft);
3. Width of shoulder;

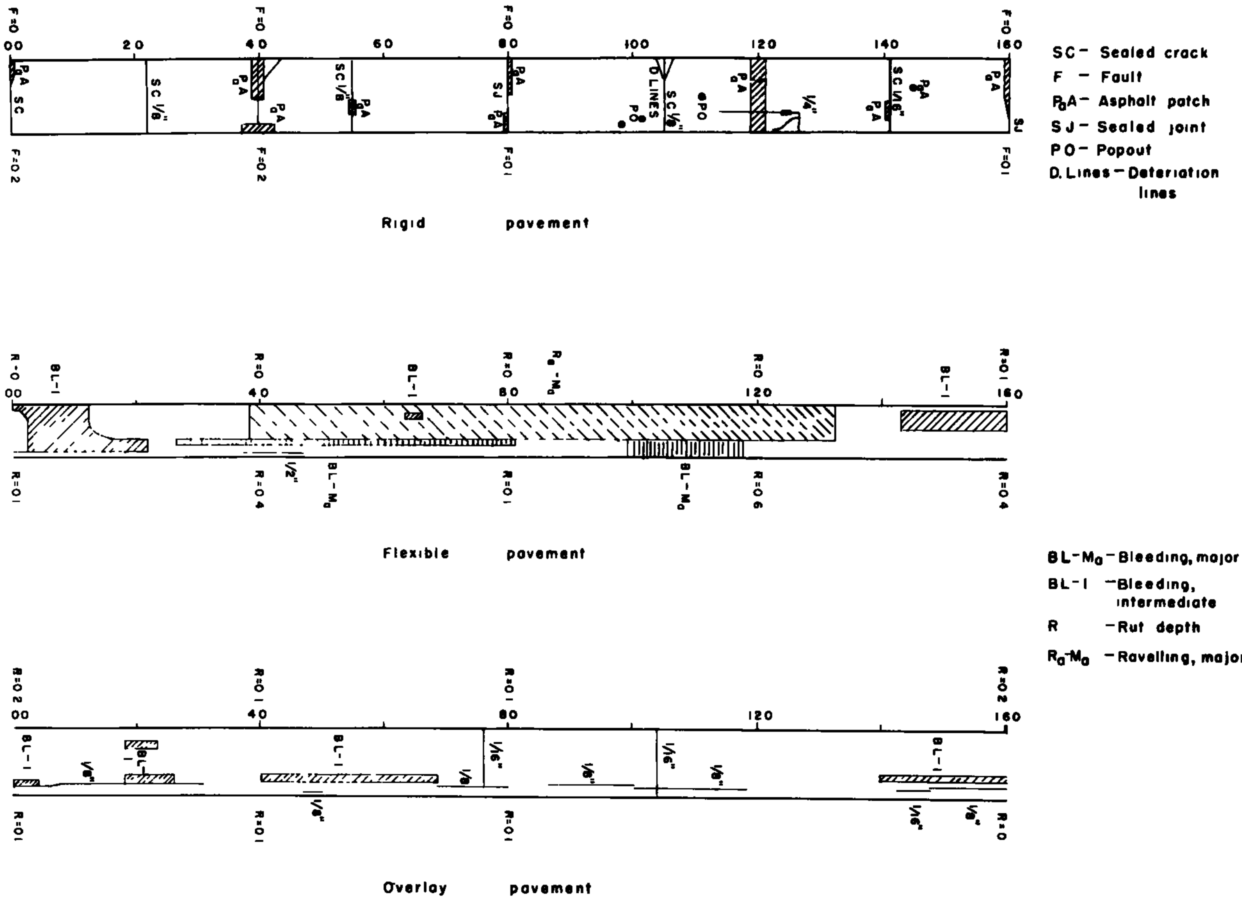

Figure 2. Portions of typical field maps.

4. Width of right-of-way (measured from edge of pavement to right-of-way line);
5. Location of cut, fill, and at-grade sections;
6. Time of day;
7. Prevailing weather conditions; and
8. General condition of pavement surface.

Rigid Pavements

CRACKS

Cracks were classified on the basis of type and size. Most of the cracks observed were essentially transverse or longitudinal, sealed or unsealed. Crack size ranged from less than 1/32 in. to more than 1 in. (considering joints as "cracks"). Difficulty was frequently encountered in choosing a crack size, for many cracks were spalled over a portion of their length. In such situations, the survey party exercised its judgment and estimated the average width of the crack including the spalled portions.

FAULTING OF CRACKS AND JOINTS

A "faultmeter" was devised to measure relative differences in slab elevations. This instrument consisted of metal pipe, a metal rod riding in the vertical pipe, and a scale calibrated in tenths of an inch. The operation of the faultmeter involved placing the meter on the higher portion of the slab, allowing the rod to come in contact with the lower portion of the slab, and reading the difference in elevation (*i.e.*, the fault) directly on the scale. Fault readings were taken at every joint in both wheelpaths. Additional readings were taken at transverse cracks at the discretion of the survey party and at all longitudinal cracks.

PATCHING

Only bituminous patching was observed in the field surveys. Patched areas were considered rectangular and the length and width of the patch were measured and noted on the field map.

BLOWUPS

Pavement blowups, sometimes associated with patching, were measured on an area basis by considering the disrupted areas as rectangles, measuring lengths and widths, and computing areas of the blowups.

OTHER DEFECTS

The location and extent of other pavement defects, such as corner breaks, D-lines, large popouts, scaling, and spalling were noted during the field surveys and appear on the maps.

Flexible Pavements

CRACKS

Cracks were classified on the bases of type and size. Most cracks were essentially transverse or longitudinal; no sealed cracks occurred.

PATCHING

Only bituminous patching was observed; areas of patching were computed on the same basis as in rigid pavements.

RUTTING

A "rutmeter" was devised to measure the depth of longitudinal depressions in the wheelpaths. This instrument consisted of a metal pipe, a metal rod riding in the vertical pipe, and a scale calibrated in tenths of an inch. Operation of the rutmeter involved centering the meter in a wheelpath, allowing the rod to come in contact with the surface, and reading the depth of the rut directly on the scale. Rut readings were taken at 40-ft intervals in both wheelpaths.

BLEEDING

Bleeding was measured on an area basis. Patches of bleeding were considered to be rectangular and length and width measurements were taken. Areas of bleeding were computed from these measurements.

Bleeding was visually classified into three types; major (Fig. 3), intermediate (Fig. 4), and minor (Fig. 5). In spite of the arbitrary nature of the system, it was felt that the survey party, after gaining some experience, was relatively consistent in its classifications of bleeding areas.

RAVELING

Raveling was also measured on an area basis. Raveling was considered to be of three types: major (Fig. 6), intermediate (Fig. 7), and minor (Fig. 8).

Overlay Pavements

CRACKS

Cracks were treated in essentially the same manner as they were in rigid pavements; some sealed cracks were present.

FAULTING

Fault readings were taken at the discretion of the survey party. Fault readings were very difficult to obtain on rough-textured pavements; in some cases, the survey party was compelled to make arbitrary decisions as to the values assigned.

BLEEDING, RUTTING, AND RAVELING

Bleeding, rutting and raveling were treated in the same manner as on flexible pavements.

PATCHING, BLOWUPS

Patching and blowups were treated in the same manner as they were on rigid pavements.

EQUIPMENT AND EQUIPMENT SURVEYS

An effort was made to include a variety of road roughness measuring devices available at the time of this study. The instruments were run over the test pavements during the latter half of July 1963. The one exception to this was the BRP Roughometer owned and operated by the Minnesota State Highway Department which was used during the month of September.

The slower moving pieces of equipment (AASHO Slope Profilometer, CHLOE Profilometer and University of Michigan Profilometer) were run over the test pavements in a train to facilitate traffic control. Operators for the remaining equipment were given a map showing location of pavements and were permitted to test the pavements using a schedule established by each operator. In general, the roughometers required from 2 to 3 days to complete

Figure 3. Major bleeding (paper on pavement is approximately 11 in. long).

Figure 4. Intermediate bleeding, discontinuous and non-uniform.

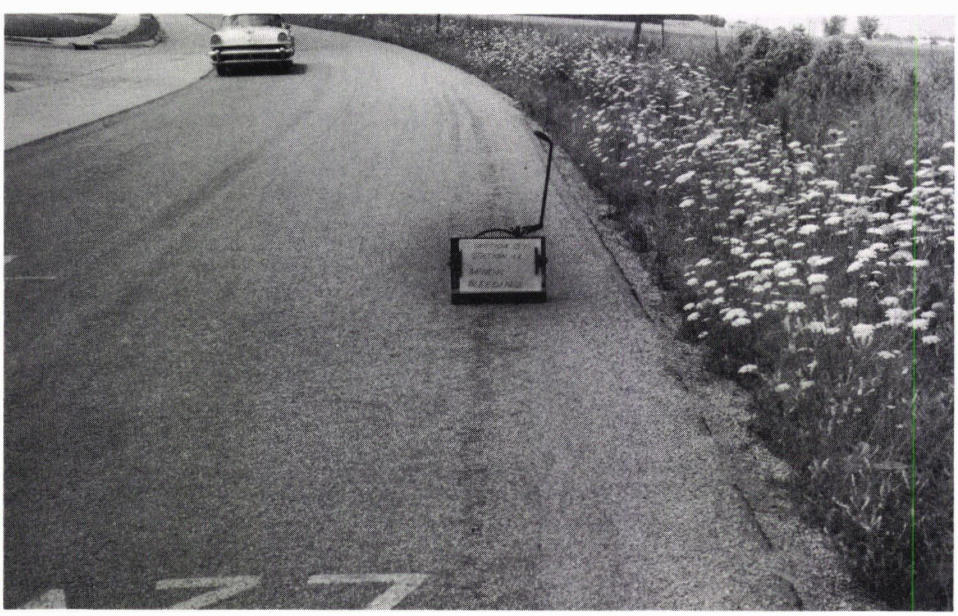

Figure 5. Strip of minor bleeding in center foreground.

Figure 6. Major raveling.

the testing program while approximately two weeks were required by the profilometers.

BPR Roughometers

The Bureau of Public Roads Roughometer (Fig. 9) needs no description here since it is a device well known to the highway profession. Roughometers owned and operated by each of the following were included in the study: Indiana, Illinois, Tennessee, New York, South Dakota, Minnesota, Michigan, and the Bureau of Public Roads.

Some of the roughometers had both electronic and mechanical recording devices. Where this was the case, the results obtained by each method were included in the analysis. The roughometer owned by the Michigan State Highway Department, in addition, has been modified to include accelerometers mounted on the roughometer frame.

AASHO Slope Profilometer

The AASHO Slope Profilometer (Fig. 10) is described in detail in the final report of the AASHO Road Test (*5*). This instrument utilizes two small wheels in each wheelpath and measures slope variance as given in Eq. 3. This instrument was operated by personnel from the Bureau of Public Roads.

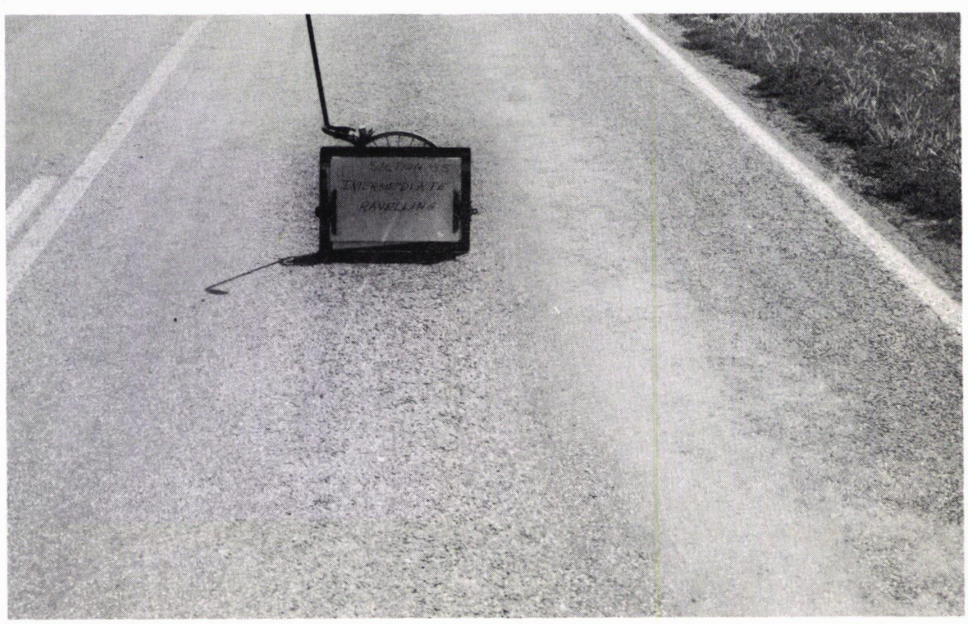

Figure 7. Intermediate raveling in center and along right edge of pavement.

Figure 8. Minor raveling of a rough-textured flexible pavement.

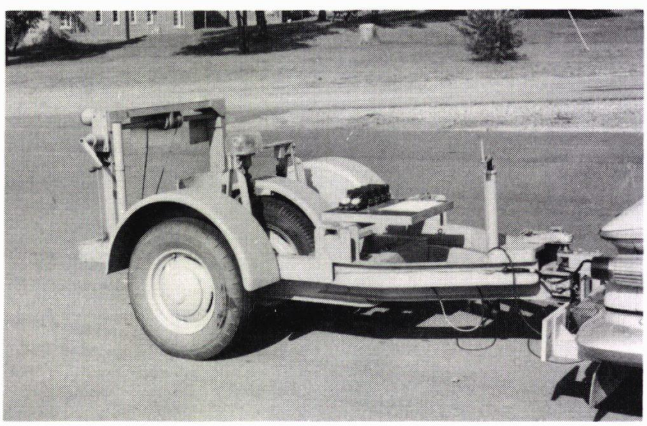

Figure 9. Bureau of Public Roads Roughometer.

CHLOE Profilometer

The CHLOE Profilometer (Fig. 11) is a modification of the AASHO Slope Profilometer and is also described in detail in the final report of the AASHO Road Test (*5*). The CHLOE Profilometer digitizes slope variance electronically at 6-in. intervals along the pavement surface. This profilometer has slope wheels in one wheelpath and to obtain slope variance in two wheelpaths, it is necessary either to rerun the profilometer over the test pavement, or to alternate between the left and right wheelpaths at intervals along the pavement.

For this study, the CHLOE Profilometer was towed alternately in the outer and inner wheelpaths and the slope variance obtained by this instrument thus is an average of the two wheelpaths. This is in contrast to the roughometers, which were towed over the outer wheelpath only.

The CHLOE Profilometer was the property of the Bureau of Public Roads but was operated by personnel from the Texas Highway Department.

Texas Texture Meter

The texture meter (Fig. 12) developed by Scrivner and Hudson (*14*) was used on each of the test pavements. This instrument gives a measure of the micro relief of the pavement by means of a series of prongs which give an indication of the indentations and surface roughness of the pavement. Engineers in Texas have found that slope variance as measured by the CHLOE Profilometer may be in error when considering rough-textured surface treatments. Although the texture meter was developed primarily for use on flexible pavements, it was used in this study on all test pavements.

Kentucky Accelerometers

Engineers for the State Highway Department of Kentucky have devised an instrument for measuring pavement roughness based upon the acceleration experienced by a passen-

Figure 10. AASHO Slope Profilometer with double set of wheels to measure slope variation and calibrated odometer wheel.

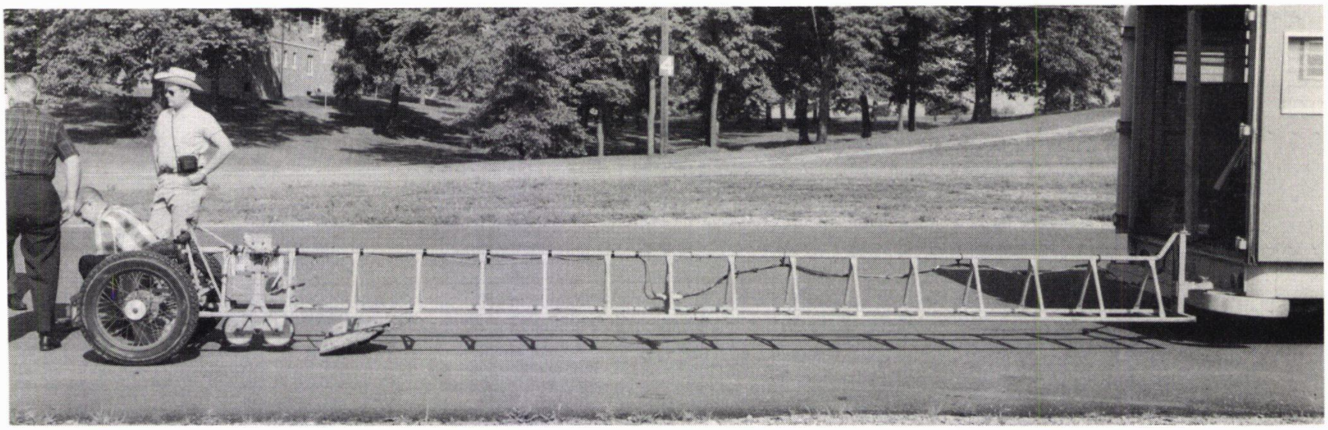

Figure 11. CHLOE Profilometer with single set of wheels to measure slope variation.

ger in an automobile. This instrument (Fig. 13) is described by Gregg and Foy (*4*) and Rizenbergs (*13*).

Since the Kentucky accelerometer device measures acceleration that a passenger in a vehicle experiences as a function of distance, there arises a need for determining a single number which describes the characteristics of a pavement surface. It would be possible, for example, to perform a double integration and obtain displacement of the passenger. Another approach would be to obtain an arbitrary measure of the total acceleration. This latter method is that adopted by the Kentucky engineers and roughness index is expressed as average acceleration in the vertical direction. The total acceleration is determined by obtaining the area under the acceleration-distance curve and dividing this area by the length of the chart (with appropriate scale factors) to yield the average acceleration in the vertical direction.

Tests are performed with the Kentucky accelerometer

Figure 12. Texture meter.

Figure 13. Kentucky Accelerometer mounted on passenger's chest.

Figure 14. University of Michigan Profilometer.

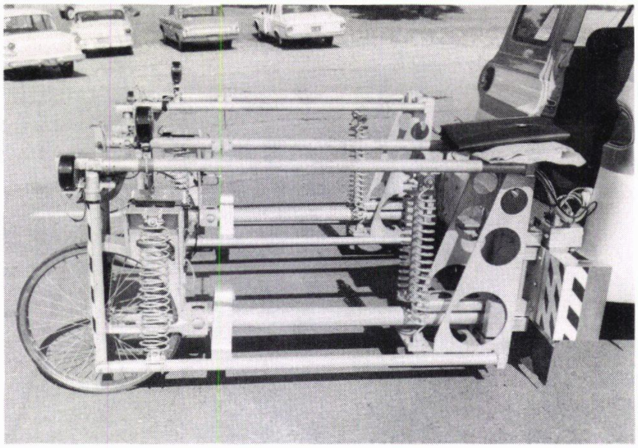

Figure 15. General Motors device.

device by driving the test vehicle over the test pavements at three different vehicle speeds.

University of Michigan Profilometer

The University of Michigan developed a truck-mounted profilometer (Fig. 14), described by Housel (*8*), to measure and record pavement profiles.

The truck is equipped to trace and record a profile in each wheel track of the pavement. Two sets of bogey wheels, located in front and in back of the truck, 30 ft apart, provide reference points from which vertical displacement is measured by a recording wheel midway between the reference wheels. The instrument is similar to that developed by engineers for the State Highway Department of California (*9*).

Pavement profiles are recorded on a continuous chart permitting analysis of detailed profiles in both wheelpaths. The cumulative vertical displacement in each mile is called the roughness index. The index is obtained directly from records obtained by the truck without analyzing the detailed charts of the pavement profiles.

General Motors Device

The General Motors instrument (Fig. 15) has been described by Spangler and Kelly (*15*). This instrument determines pavement profile by referencing a pavement follow wheel to an inertial platform. Accelerometers mounted on the platform indicate the movement of the platform relative to the pavement surface. The platform maintains a relative fixed position by means of an electrohydraulic valve and hydraulic actuator. By means of a system involving double integration, the pavement profile is placed on magnetic tape. No single roughness index is obtained from the method; rather, the road amplitude may be plotted as a function of distance along the pavement.

Purdue Tire Pressure Measurement Device

A technique for determining the dynamic wheel load by measuring the change in the inflation pressure of the tire is described by Boswell and Hopkins (*1*). A similar procedure developed by the Michigan State Highway Department laboratories in Lansing has also been successfully used for this purpose. The equipment (Fig. 16) used by Purdue University in these tests was virtually identical to that developed by the investigators in Michigan except for a few minor changes.

This equipment measures and records the change in tire inflation pressure as the vehicle is traveling over the pavement section. Through appropriate calibration procedures, it is then possible to convert records of change in tire pressure, p, to records of dynamic tire force, F.

The magnitude of the dynamic tire force is affected by the velocity of the vehicle. Since some test sections were on primary roads in open country and others were located within city limits, it was not feasible to conduct all tests at the same speed. Accordingly, a typical vehicle velocity, suitable to the location of the test section, was used in an attempt to simulate the conditions experienced by the rating panel.

PANELS

Type and Composition

Three different rating panels were used in this study. The lay panel was composed of 10 citizens from the Lafayette

Figure 16. Purdue tire pressure device mounted on test vehicle.

area and was selected so that a general cross-section of occupations was achieved. The lay panel was composed of a retired shop foreman, a Scout executive, three housewives, two firemen, a minister, a grade school teacher and an industrial engineer. The only restriction placed upon panel members was that they operate their own vehicles and travel alone during their rating sessions to minimize bias.

Two professional panels were used in the study including a portion of the original AASHO Road Test Rating Panel and a panel consisting of members of the Highway Research Board Pavement Condition Evaluation Committee. The six-man AASHO panel was composed of an engineer, three state highway engineers, and two research engineers. The HRB Committee panel had nineteen members and was composed of a consulting engineer, seven research engineers, two paving engineers, two automotive engineers, an airport engineer, a maintenance engineer, a design engineer, a state highway engineer, a research statistician, and two research administrators.

Mechanics of Rating

The rating card (Fig. 17) used in this study is nearly identical to the one used on the AASHO Road Test with the exception that pertinent information relative to the specific pavements was accounted for on the card. Each panel member was instructed to rate the pavement sections by making a mark on the scale and to give his opinion relative to the acceptability of the pavement depending upon whether the section was on a secondary or primary pavement. Rating was intended to be independent of classification of pavement. The raters were instructed to consider classification only in deciding whether the pavement was acceptable for its given classification.

Members of the lay panel rated the pavements while driving their own vehicles. The professional panels, on the other hand, made their ratings as passengers. In addition, some of the professional panel members rode in the rear seat, whereas others rode in the right-hand front seat.

Position of passenger within the vehicle as well as type of rater (passenger or driver) may have influenced the

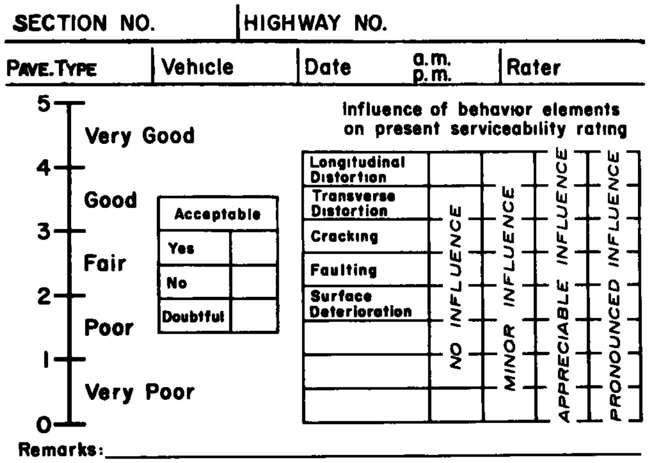

Figure 17. Rating card.

ratings of the passenger to some extent, but it is believed that this was nominal.

Schedules of Rating

To avoid bias as much as possible, the lay panel was split into two groups. Each group was instructed to start rating on the northern loop or the southern loop. The panel members were also instructed to rate over a period of two days and in no case were they to rate pavements in both loops in any one day. They were further instructed to rate the pavements over as long a period as possible, preferably over three or four days.

The HRB Committee panel was also split into two groups. One-half of the panel started rating on the northern loop, whereas the other half started on the southern loop. In addition, the panel rated one-half the pavements during an afternoon and the other half during the following morning.

It was not possible for the AASHO panel to rate over a 2-day period due to time limitations; thus, the panel members rated the pavements in one day. However, an effort was made to start rating alternately on the two loops.

CHAPTER THREE

RESEARCH RESULTS

The primary objectives of this research project were to make a study of several roughness measuring instruments and to determine which instrument or group of instruments is the most reliable for predicting serviceability. In order to achieve these objectives, a series of pavements was rated by three panels and the panel ratings were compared with objective measurements obtained from the roughness equipment and with physical data pertaining to the highway.

The primary objectives led to other studies. For example, comparisons were made of the ratings of the three panels and relationships existing between various roughness measuring instruments were examined. The discussion

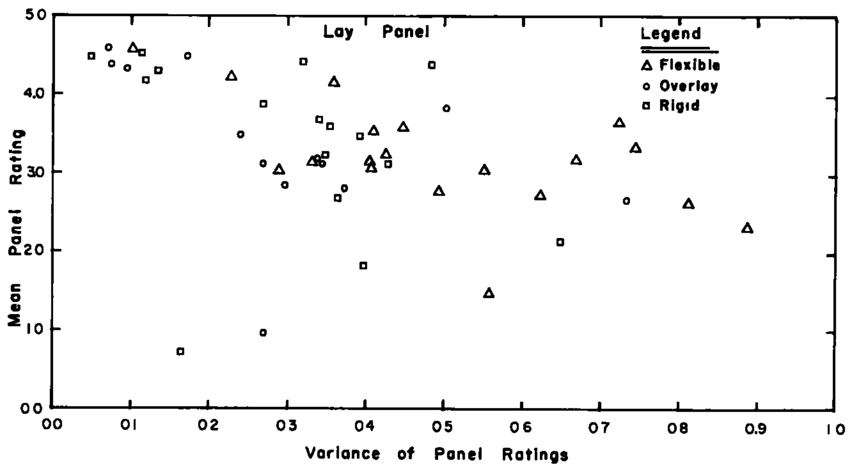

Figure 18. Variance of mean panel ratings.

which follows, then, includes data which do not pertain specifically to the objectives of the project. Nevertheless, the data should be of general interest. For the sake of completeness, some figures and tables are redundant in that results obtained by individual panels as well as average values representing all panels are shown. Also included are comparisons of data obtained in this study with data reported in the AASHO Road Test Report (*5*) and data obtained by Nakamura (*10*).

PANEL RATING

The combination of the Highway Research Board Committee panel and the AASHO panel was termed "professional panel" while the combination of the lay panel, Highway Research Board Committee panel, and AASHO panel was termed "overall" panel.

The analysis of data and discussion which follows in this section also includes data obtained by Nakamura (*10*) and Carey and Irick (*2*) in previous studies. Objectives of the analysis were (a) to determine variation within a panel, (b) to establish relationships among panels, and (c) to study pavement acceptability (*i.e.*, what rating indicates an acceptable pavement?).

Variation Within Panels

Variability of panel members was determined by computing variance of panel ratings about the mean rating. Variance is defined

$$S_x^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1} \qquad (6)$$

in which

S_x^2 = Variance of x;
x = Value of one observation;
$\bar{x}$ = Mean of n observations;
n = Number of observations; and
S_x = The standard deviation.

Figure 18 depicts variance of panel ratings about their mean for the lay panel and indicates that variance is a function of the mean rating itself.

Linear regression equations were fitted to each set of data and the resulting equations, standard errors of estimate, correlation coefficients, and critical correlation coefficients for the sample size and a 99 percent level of confidence, are given in Table 4. The critical correlation coefficients are those given by Crow, Davis, and Maxfield (*3*).

The absolute value of the calculated correlation coefficient must be larger than the critical value in order to reject the null hypothesis that variance is not influenced by the mean panel rating. Data in Table 1 indicate that the null hypothesis is rejected in all cases; hence, variance is a function of mean panel rating.

Figure 18 indicates low variance for high mean panel ratings. Conceivably, a "perfect" pavement and an impassable pavement would be rated as such by all raters. The "true" relation between variance of panel ratings and mean panel rating would probably indicate a peak variance at mean ratings of 1 to 3 and zero variance for mean ratings of 0.0 and 5.0. Data obtained in this study were not sufficient to validate this observation.

Variance is apparently a negative function of mean rat-

TABLE 1

VARIANCE REGRESSION EQUATIONS

PANEL	EQUATION	STD. ERROR OF ESTIMATE	CORR. COEF.	CRITICAL VALUE OF CORR. COEF.
Lay	$S_x^2 = 0.0708 - 0.0099$ (PSR)	0.0189	—0.433	0.363
HRB Comm.	$S_x^2 = 0.0246 - 0.0032$ (PSR)	0.0055	—0.409	0.360
AASHO	$S_x^2 = 0.0997 - 0.0205$ (PSR)	0.0216	—0.638	0.360
Overall	$S_x^2 = 0.0164 - 0.0022$ (PRS)	0.0029	—0.529	0.360

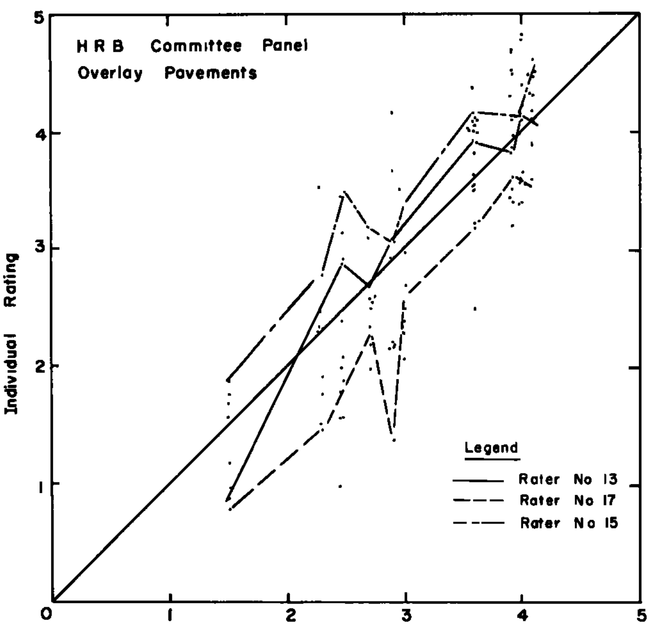

Figure 19. Example of individual ratings vs mean panel ratings.

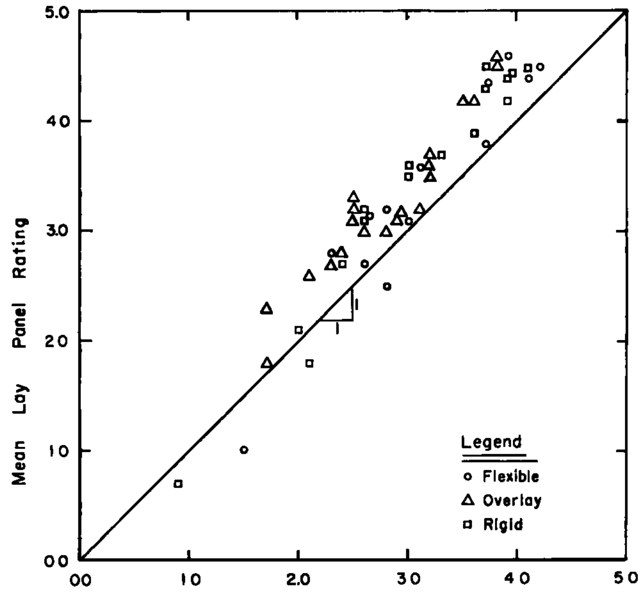

Figure 20. Comparison of professional and lay panels.

ing; thus, larger panels are required to estimate the rating of pavements in poor condition as compared to pavements in good condition. The data substantiate the observation of many engineers that greatest variation in opinion occurs for mean ratings of 2.0 or less. As stated previously, however, panel variation is a minimum for both very good and very poor pavements.

Figure 19 shows the variability of individual ratings as a function of mean rating for the overlay pavements, and also the ratings for three individuals selected at random. The data, considered typical of the data obtained, illustrate that some of the individuals rated pavements consistently higher than the average, whereas others rated pavements consistently lower. In several instances, individual raters were essentially average inasmuch as their ratings consistently were close to the mean for the panel. On the other hand, some raters tended to be erratic, rating some pavements higher and some lower than the mean for the group.

Relationships Among Panels

A comparison of mean lay panel ratings and mean professional panel ratings is shown in Figure 20. In general, the lay panel tended to rate pavements higher than the professional panel. Data did not disclose why this trend was reversed on the poorer pavements.

Correlation coefficients among panels are given in Table 2. The coefficients indicate excellent correlation between ratings of any two panels. Subsequent regression analysis which relate panel rating and objective measurements utilize the overall panel rating. A uniform, normal distribution of mean panel ratings about a gross mean is assumed; moreover, the distribution is assumed independent of type of panel. The high correlation between panels indicates that the distribution is probably both uniform and normal.

Pavement Acceptability

Each rater was asked to indicate whether the pavements being rated were acceptable, unacceptable or of doubtful acceptability. Typical results are shown in Figures 21 and 22.

The data indicated no significant differences among panels in determining acceptability. Thus Figures 21 and 22 which compare primary and secondary pavements are based on overall panel data. Nakamura (*10*) found that

TABLE 2

CORRELATION COEFFICIENTS AMONG RATING PANELS

PANEL	LAY	HRB	AASHO	PROFESSIONAL	OVERALL
Lay	1.000	0.961	0.928	0.957	0.980
HRB	0.961	1.000	0.970	0.997	0.995
AASHO	0.928	0.970	1.000	0.982	0.973
Professional	0.957	0.997	0.982	1.000	0.994
Overall	0.980	0.995	0.973	0.994	1.000

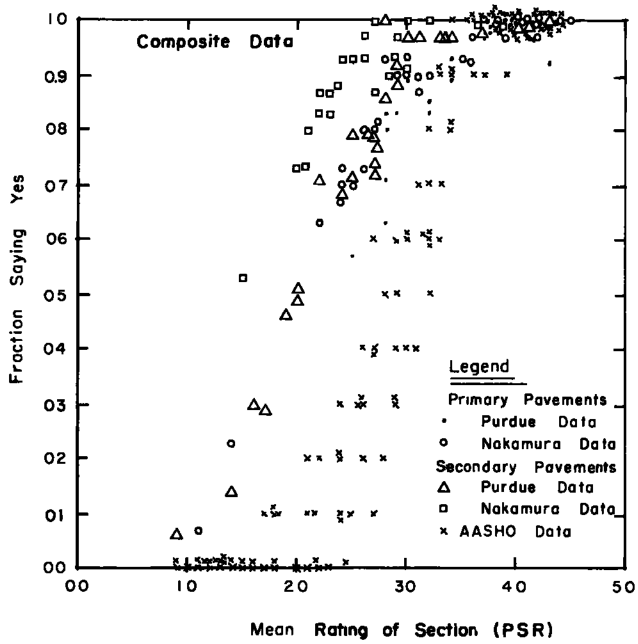

Figure 21. Acceptability vs mean rating.

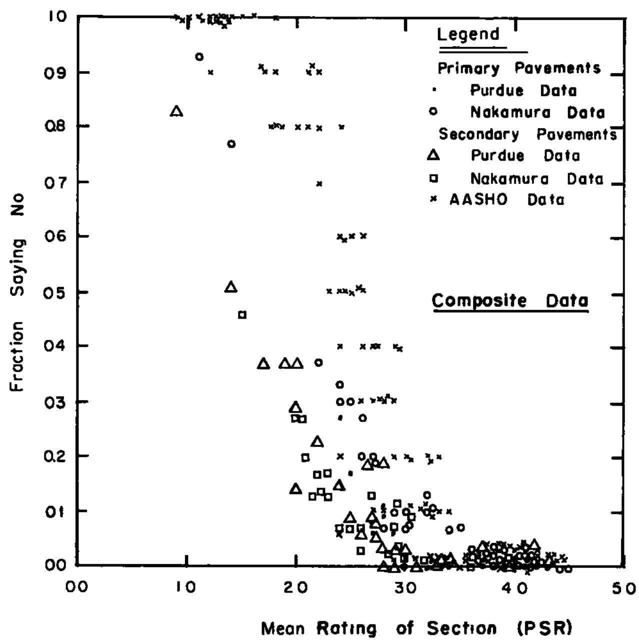

Figure 22. Unacceptability vs mean rating.

lower ratings were acceptable for secondary pavements than for primary pavements; Figures 21 and 22 indicate a similar trend in this study.

Figures 21 and 22 present comparisons of data obtained in this study, labeled Purdue Data (overall panel), with data obtained by Nakamura (*10*), and that obtained in connection with the AASHO Road Test (*2*).

Nakamura's study did not include a doubtful category; this may have affected her results. Figures 21 and 22 indicate that if raters in Nakamura's study were doubtful about the acceptability of a pavement but had to make a choice, they tended to rate the pavement acceptable.

In the AASHO study, data for overlay pavements were included with data for flexible pavements. The effect of this combining of data on Figures 21 and 22 is unknown.

Data such as shown in Figures 21 and 22 were used to estimate the rating at which 50 percent of the raters indicated an acceptable pavement (Table 3). Because of the lack of a doubtful category in the Nakamura study, these data were not analyzed for the fraction saying yes.

In general, Nakamura's data and Purdue data indicate lower ratings for acceptable pavements than the AASHO data. Pavement type probably was not a factor but the data apparently were influenced by differences in panels used in the three studies.

AASHO MODEL EQUATIONS

The equations developed by Carey and Irick are of the form shown in Eqs. 1 and 2. Equations, patterned after these equations, were developed from data obtained in this study and are henceforth termed "AASHO model equations."

Observation of the field data indicated that the slope variance measured by either the CHLOE Profilometer or AASHO Profilometer, for several sections of rigid pavement, did not fall in the same pattern as the data for rigid

TABLE 3

RATING AT WHICH 50 PERCENT OF PANEL INDICATED YES OR NO

	SECONDARY AND PRIMARY COMBINED						SEPARATE BUT PAVEMENT TYPE COMBINED			
	RIGID		OVERLAY		FLEXIBLE		SECONDARY		PRIMARY	
DATA SOURCE	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO
Purdue	2.2	1.5	2.2	1.5	2.2	1.7	2.0	1.5	2.4	—
AASHO Road Test	2.9	2.5	—	—	2.9	2.5	—	—	—	—
Nakamura	—	—	—	—	—	—	2.0[a]	1.5	2.5[a]	2.0
Combined[b]	—	—	—	—	—	—	—	1.5	—	1.9

[a] At 0.70 percentile.
[b] Nakamura and Purdue data combined.

pavement sections. Correlations established among the results of the various instruments used in this study, as well as correlations between slope variance and pavement rating, pointed up the probability that the CHLOE instrument did not function properly on sections 6, 9a and 43. Data on this point, however, were not sufficient to clarify this observation with certainty. Therefore, to avoid bias by arbitrarily discarding data for these sections, all equations were developed in which data from pavement sections 6, 9a and 83 were included in the analysis.

The general AASHO model equations are as follows:

Rigid pavements:

$$p = A_0 + A_1 F + A_2 \sqrt{C + P} \qquad (7)$$

Flexible and overlay pavements:

$$p = A_0 + A_1 F + A_2 \sqrt{C + P} + A_3 (\overline{RD})^2 \qquad (8)$$

The functions of equipment (F) measurement are as follows:

Equipment [1]	*Function F*
All roughometers	Roughness in inches per mile (for the Minnesota Roughometer, both the mechanical and electrical recorders)
Michigan Roughometer	Acceleration in g's per mile
Univ. of Mich. Profilometer	Roughness index in inches per mile
AASHO Profilometer	SV, $\sqrt{SV}$, and $\log (1 + SV)$
CHLOE Profilometer	SV, $\sqrt{SV}$, and $\log (1 + SV)$
Texture Meter	Texture in inches $\times 10^{-3}$
Kentucky Accelerometer	Acceleration index (for operating speed of 40, 51.5 and 60 mph)

Data obtained from the Kentucky Accelerometer are reported in terms of a roughness index. For purposes of this report, this roughness index has been designated accelerometer index to avoid confusion with data reported by other types of equipment.

Table 4 contains the results of a linear regression analysis for each piece of equipment for rigid, overlay and flexible pavements. Table 4 is based on Eqs. 7 and 8 with the following definitions for terms:

p = Present Serviceability Index;
A_0 = p intercept;
A_1 = Constant;
F = Function of equipment measurement;
A_2 = Constant;
$C + P$ = Cracking plus patching;
A_3 = Constant;
$\overline{RD}$ = Rut depth.

[1] The Texture Meter was not designed to measure pavement condition *per se,* but these data are analyzed here and in subsequent sections of this report for the sake of totality. Data for the General Motors device were not analyzed since there is no single number from this instrument representing roughness.

Only 14 pavement sections were tested by the Purdue tire pressure measuring device. The sample for this device was too small to allow a regression analysis to be made for each pavement type. A regression equation was obtained, however, which includes all pavement types:

$$\text{PSI} = 9.80 - 3.39 \log (\text{RMS Force}) - 0.06\sqrt{C + P} \qquad (9)$$

The standard error of estimate is 0.38; the multiple correlation coefficient is 0.94.

Several blank spaces appear in columns A_2 and A_3 in Table 4 for overlay and flexible pavements. The numbers in these instances were deleted because they indicated a positive correlation with the Serviceability Rating. In all cases, however, the plus values were very small.

Table 5 (Eq. 8) gives the AASHO model equations for the Purdue data for the combination of flexible and overlay pavements. The correlation coefficients are higher than those for the flexible pavements alone.

Table 6 gives a summary of the correlation coefficients and standard errors of estimate for the principal pieces of equipment used in the study. The standard error of estimate gives an indication of the vertical dispersion of the actual values of PSR about the regression line. The sample standard error of estimate is an indication of the true standard error of estimate. Approximately 68 percent of the estimated values are within ± 1 true standard error and 95 percent within ± 2 true standard errors of the true values of the PSR.

Observations drawn from these analyses must be qualified on the basis of the relatively small sample size used in the study. Nevertheless, several points of interest appear worthy of mention. First, the texture meter, although not intended to measure pavement condition *per se,* correlates very well with serviceability rating. This is believed to be due to the high degree of correlation between surface texture and other features of the pavement surface. For example, old concrete pavements used in this study were generally scaled because of deicing operations. Scaling of these pavements was correlative with other surface defects from the standpoint of pavement age.

Second, there is the apparent consistent accuracy of the majority of the instruments. The one exception to this is the CHLOE Profilometer used in this study on the rigid pavements. Third, the utility of the BPR-type Roughometer is readily apparent.

COMBINED EQUATIONS

Equations were derived from combining two sets of data. Sources of data were this project (Purdue data), the AASHO Road Test Report (*5*), and Nakamura (*10*).

The data were combined as follows: (1) Purdue-AASHO Road Test, and (2) Purdue-Nakamura. The simple correlation coefficients between items appearing in the equations and PSR are given in Table 7.

Equations derived from regression analysis of the combined Purdue-AASHO Road Test data are given in Table 8 (see Eq. 8). The equations employ a function of mean slope variance as measured by the AASHO Profilometer. In the analysis, two transformations of mean slope variance

TABLE 4

AASHO MODEL EQUATIONS (EQS. 7 AND 8)

		RIGID PAVEMENTS				
EQUIPMENT	FACTOR F	A_0	A_1	A_2	STD. ERROR	CORR. COEF.
Ind. Rough.	Roughness	6.33	—0.024	—0.08	0.41	0.92
Ill. Rough.	Roughness	6.09	—0.023	—0.08	0.38	0.93
BPR Rough.	Roughness	6.08	—0.021	—0.08	0.41	0.91
N.Y. Rough.	Roughness	5.88	—0.020	—0.09	0.39	0.92
Tenn. Rough.	Roughness	5.87	—0.021	—0.07	0.39	0.94
Mich. Rough.	Roughness	5.39	—0.0076	—0.06	0.28	0.96
Mich. Rough.	Acceleration	5.72	—0.0018	—0.09	0.45	0.90
Minn. Rough.	Roughness (E)	6.38	—0.023	—0.12	0.36	0.94
Minn. Rough.	Roughness (M)	6.47	—0.024	—0.11	0.41	0.92
S.D. Rough.	Roughness	6.11	—0.022	—0.08	0.41	0.91
U. of Mich. Prof.	Roughness	5.49	—0.012	—0.09	0.33	0.95
AASHO Prof.	SV	4.28	—0.032	—0.10	0.48	0.88
AASHO Prof.	$\sqrt{SV}$	5.16	—0.40	—0.10	0.33	0.95
AASHO Prof.	$\log(1+SV)$	5.68	—1.60	—0.14	0.53	0.91
CHLOE Prof.	SV	4.79	—0.054	—0.11	0.64	0.78
CHLOE Prof.	$\sqrt{SV}$	5.70	—0.45	—0.12	0.64	0.77
CHLOE Prof.	$\log(1+SV)$	6.37	—2.04	—0.13	0.67	0.75
Texas Texture	Texture	4.54	—0.34	—0.17	0.58	0.82
S.D. Texture	Texture	4.51	—0.28	—0.17	0.64	0.72
Ky. Accel.	Accel. Index (40)	6.89	—0.0068	—0.084	0.45	0.90
Ky. Accel.	Accel. Index (51.5)	6.34	—0.0052	—0.105	0.61	0.80
Ky. Accel.	Accel. Index (60)	6.65	—0.0047	—0.131	0.67	0.75
CHLOE Prof.*	SV	4.83	—0.005	—0.12	0.22	0.96
CHLOE Prof.*	$\log(1+SV)$	7.88	—1.74	—0.14	0.30	0.92

* Sections 6, 9a and 83 deleted from analysis of rigid pavements.

TABLE 5

AASHO MODEL EQUATIONS, FLEXIBLE AND OVERLAY PAVEMENTS (EQ. 8)

EQUIPMENT	FACTOR F	A_0	A_1	A_2	A_3	STD. ERROR	CORR. COEF.
AASHO Prof.	SV	3.72	—0.036	—0.027	—2.75	0.41	0.84
AASHO Prof.	$\sqrt{SV}$	4.35	—0.350	—0.018	—0.52	0.36	0.88
AASHO Prof.	$\log(1+SV)$	4.85	—1.670	—0.011	—0.51	0.35	0.89

TABLE 6

SUMMARY FOR AASHO MODEL EQUATIONS

	RIGID PAVEMENTS		OVERLAY PAVEMENTS		FLEXIBLE PAVEMENTS	
EQUIPMENT	STD. ERROR	CORR. COEF.	STD. ERROR	CORR. COEF.	STD. ERROR	CORR. COEF.
Roughometers [a]	0.41	0.92	0.13	0.99	0.30	0.91
U. of Mich. Profilometer	0.33	0.95	0.12	0.99	0.31	0.90
AASHO Profil.						
$\log(1+SV)$	0.53	0.96	0.29	0.96	0.39	0.84
$\sqrt{SV}$	0.33	0.95	0.19	0.98	0.40	0.84
CHLOE Profil.						
$\log(1+SV)$	0.67	0.75	0.18	0.98	0.35	0.87
$\log(1+SV)$	0.30 [b]	0.92 [b]	—	—	—	—
$\sqrt{SV}$	0.64	0.77	0.20	0.98	0.33	0.89
Kentucky Accel. (40 mph)	0.45	0.90	0.42	0.90	0.33	0.89
Purdue Tire Pressure [c]	0.37	0.95	—	—	—	—

[a] Average for all roughometers.
[b] Sections 6, 9a, and 83 deleted for analysis.
[c] For all pavements.

OVERLAY PAVEMENTS						FLEXIBLE PAVEMENTS					
A_0	A_1	A_2	A_3	STD. ERROR	CORR. COEF.	A_0	A_1	A_2	A_3	STD. ERROR	CORR. COEF.
5.35	−0.015	−0.11	—	0.09	0.99	4.78	−0.015	0.004	−0.26	0.30	0.91
4.92	−0.012	−0.10	−3.78	0.08	1.00	4.54	−0.014	−0.01	—	0.30	0.92
5.14	−0.014	−0.10	−4.21	0.09	0.99	4.67	−0.015	−0.0002	—	0.30	0.91
5.02	−0.014	−0.07	−2.30	0.20	0.98	4.71	−0.016	−0.0003	—	0.30	0.92
5.03	−0.013	−0.10	−2.60	0.11	0.99	4.64	−0.015	0.002	—	0.30	0.91
4.59	−0.004	−0.12	—	0.15	0.99	4.09	−0.0048	−0.003	—	0.30	0.91
4.87	−0.0012	−0.06	−16.64	0.19	0.98	4.40	−0.0014	—	−2.85	0.35	0.87
4.92	−0.012	−0.10	—	0.12	0.99	4.62	−0.014	—	—	0.31	0.90
5.03	−0.013	−0.12	−1.65	0.11	0.99	4.66	−0.015	—	—	0.33	0.89
5.00	−0.012	−0.11	—	0.15	0.99	4.83	−0.016	−0.004	—	0.32	0.89
4.64	−0.0071	−0.11	—	0.12	0.99	4.41	−0.008	−0.006	−0.11	0.31	0.90
4.24	−0.027	−0.13	−1.59	0.16	0.99	3.67	−0.04	−0.015	−1.14	0.41	0.82
4.62	−0.28	−0.09	−4.17	0.19	0.98	4.29	−0.36	−0.01	−0.33	0.40	0.84
4.92	−1.42	−0.05	−6.65	0.29	0.96	4.82	−1.70	−0.0077	—	0.39	0.84
4.29	−0.030	−0.13	−2.76	0.25	0.97	3.76	−0.03	−0.01	—	0.33	0.89
4.97	−0.34	−0.09	−8.09	0.20	0.98	4.52	−0.33	−0.01	—	0.33	0.89
5.81	−2.03	−0.04	−13.88	0.18	0.98	5.43	−1.87	−0.009	—	0.35	0.87
4.28	−0.048	−0.14	−17.45	0.59	0.82	3.18	−0.012	−0.03	−0.81	0.67	0.37
4.14	−0.074	−0.11	−15.59	0.54	0.83	3.23	−0.016	−0.03	—	0.64	0.46
5.49	−0.0048	−0.03	−25.14	0.42	0.90	5.08	−0.0047	—	−2.14	0.33	0.89
5.38	−0.0043	−0.04	−13.87	0.44	0.89	4.71	−0.0027	−0.009	−2.34	0.32	0.90
5.23	−0.0035	−0.10	—	0.51	0.85	4.53	−0.0018	−0.01	−1.40	0.35	0.88
—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—

were made: $\sqrt{SV}$ and $\log(1+SV)$. The equations for flexible-overlay pavements were derived on the basis of combined flexible and overlay pavement data because the AASHO Road Test Report listed overlay pavement data with flexible pavement data.

Equations derived from regression analysis of the combined Purdue-Nakamura data are given in Table 9.

$$p = A_0 + A_1 F \tag{10}$$

Terms are as previously defined. Nakamura did not obtain cracking and patching or rut depth data, hence these terms are dropped from Eq. 10.

The equations employ roughness as measured by the Indiana Roughometer. In Nakamura's study, section lengths varied from ¼ mile to 3 or 4 miles, whereas in this study the sections were essentially constant (¼ mile). The effects of variation in section length on results obtained from combining data from the two studies are unknown.

RELATIONSHIPS AMONG INSTRUMENTS

Equations which relate $\log(1+SV)$, as measured by the AASHO Profilometer, with measurements obtained by other instruments are given in Table 10.

$$\log(1+SV) = A_0 + A_1 F \tag{11}$$

in which

$\log(1+SV)$ = Data from AASHO Profilometer;
A_0 = Intercept;
A_1 = Constant; and
F = Function of equipment measurement.

Table 11 gives the comparison of standard errors and correlation coefficients of equipment equations for the CHLOE Profilometer and Roughometer.

TABLE 7

SIMPLE CORRELATION COEFFICIENTS

DATA SOURCE [a]	ITEM	PAVEMENT TYPE	SIMPLE CORR. COEF.
1	$\sqrt{SV}$	Rigid	−0.92
1	$\sqrt{SV}$	Flexible and overlay [b]	−0.89
1	$\log(1+SV)$	Rigid	−0.94
1	$\log(1+SV)$	Flexible and overlay [b]	−0.89
1	$\sqrt{C+P}$	Rigid	−0.83
1	$\sqrt{C+P}$	Flexible and overlay [b]	−0.56
1	$\overline{RD}^2$	Flexible and overlay [b]	−0.14
2	Roughness [c]	Rigid	−0.90
2	Roughness [c]	Overlay	−0.78
2	Roughness [c]	Flexible	−0.79
2	Roughness [c]	Flexible and overlay [b]	−0.81

[a] Data sources (1) Purdue and AASHO Road Test data combined and (2) Purdue and Nakamura data combined.
[b] Combination of flexible pavement and overlay pavement data.
[c] Measured by the Indiana Roughometer.

TABLE 8

COMBINED EQUATIONS—PURDUE AND AASHO ROAD TEST DATA (EQ. 8)

PAVEMENT TYPE	F	REGRESSION EQUATION COEFFICIENTS A_0	A_1	A_2	A_3	STD. ERROR OF ESTIMATE	CORR. COEF.
R [a]	$\sqrt{SV}$	4.81	—0.47	—	—	0.42	0.92
R	$\sqrt{SV}$	4.76	—0.34	—0.09	—	0.34	0.95
R	$\log(1+SV)$	5.79	—2.49	—	—	0.38	0.94
R	$\log(1+SV)$	5.51	—1.88	—0.08	—	0.31	0.96
F & O [b]	$\sqrt{SV}$	4.29	—0.40	—	—	0.42	0.88
F & O	$\sqrt{SV}$	4.39	—0.38	—0.01	—1.50	0.30	0.91
F & O	$\log(1+SV)$	4.89	—1.92	—	—	0.40	0.89
F & O	$\log(1+SV)$	4.95	—1.83	—0.01	—1.34	0.36	0.91

[a] Rigid pavements.
[b] Combination of flexible pavement and overlay pavement data.

TABLE 9

COMBINED EQUATIONS—PURDUE AND NAKAMURA DATA (EQ. 10)

PAVEMENT TYPE	F	REGRESSION EQUATION COEFFICIENTS A_0	A_1	STD. ERROR OF ESTIMATE	CORR. COEF.
R	Roughness	5.89	—0.024	0.42	0.90
O	Roughness	4.93	—0.018	0.43	0.78
F	Roughness	4.50	—0.015	0.39	0.79
F & O [a]	Roughness	4.76	—0.016	0.41	0.81

[a] Combination of flexible and overlay pavement data.

TABLE 10

EQUIPMENT EQUATIONS (EQ. 11)

EQUIPMENT	FACTOR F	RIGID PAVEMENTS A_0	A_1	STD. ERROR	CORR. COEF.	OVERLAY PAVEMENTS A_0	A_1	STD. ERROR	CORR. COEF.
Ind. Rough.	Roughness	—0.15	0.011	0.17	0.91	—0.12	0.010	0.20	0.91
Ill. Rough.	Roughness	—0.02	0.010	0.17	0.91	0.18	0.008	0.21	0.90
BPR Rough.	Roughness	0.01	0.009	0.20	0.88	0.005	0.009	0.19	0.92
N.Y. Rough.	Roughness	0.08	0.009	0.17	0.91	0.04	0.009	0.20	0.92
Tenn. Rough.	Roughness	0.08	0.009	0.17	0.91	0.09	0.009	0.19	0.91
Mich. Rough.	Roughness	0.29	0.0034	0.25	0.85	0.44	0.002	0.24	0.87
Mich. Rough.	Acceleration	0.13	0.0008	0.18	0.90	0.25	0.008	0.24	0.87
Minn. Rough.	Roughness (E)	—0.06	0.010	0.19	0.89	0.15	0.008	0.21	0.90
Minn. Rough.	Roughness (M)	—0.13	0.011	0.18	0.90	0.17	0.009	0.25	0.85
S.D. Rough.	Roughness	—0.005	0.010	0.19	0.88	0.14	0.008	0.24	0.87
U. of Mich. Prof.	Roughness	0.29	0.005	0.18	0.90	0.40	0.005	0.22	0.89
AASHO Prof.	SV	—	—	—	—	—	—	—	—
AASHO Prof.	$\sqrt{SV}$	—	—	—	—	—	—	—	—
AASHO Prof.	$\log(1+SV)$	—	—	—	—	—	—	—	—
CHLOE Prof.	SV	—	—	—	—	0.71	0.02	0.29	0.80
CHLOE Prof.	$\sqrt{SV}$	—	—	—	—	0.19	0.23	0.22	0.88
CHLOE Prof.	$\log(1+SV)$	—0.03	0.94	0.37	0.63	—0.42	1.31	0.17	0.94
Texas Texture	Texture	0.90	0.124	0.32	0.62	0.90	0.043	0.44	0.40
S.D. Texture	Texture	0.92	0.102	0.34	0.57	0.84	0.063	0.38	0.62
Ky. Accel.	Accel. Index (40)	—0.47	0.003	0.14	0.94	—0.14	0.003	0.31	0.76
Ky. Accel.	Accel. Index (51.5)	—0.14	0.002	0.25	0.79	—0.24	0.003	0.24	0.86
Ky. Accel.	Accel. Index (60)	—0.28	0.002	0.27	0.75	—0.20	0.002	0.28	0.81
CHLOE Prof.*	$\log(1+SV)$	0.32	0.68	0.16	0.87	—	—	—	—

* Sections 6, 9a and 83 deleted from analysis of rigid pavements.

TABLE 11

COMPARISON OF STANDARD ERRORS AND CORRELATION COEFFICIENTS OF EQUIPMENT EQUATIONS FOR CHLOE PROFILOMETER AND ROUGHOMETER

		RIGID		OVERLAY		FLEXIBLE		FLEXIBLE AND OVERLAY	
FUNCTION	INSTRUMENT	STD. ERROR	CORR. COEF.	STD. ERROR	CORR. COEF.	STD. ERROR	CORR. COEF.	STD. ERROR	CORR. COEF.
$\log(1+SV)$	CHLOE	0.37	0.63	0.17	0.94	0.10	0.95	0.17	0.94
		0.16[a]	0.87[a]	—	—	—	—	—	—
	Roughometer[b]	0.18	0.89	0.22	0.89	0.15	0.91	0.17	0.89
$\sqrt{SV}$	CHLOE	1.56	0.70	0.74	0.95	0.51	0.94	0.74	0.95
		0.53[a]	0.91[a]	—	—	—	—	—	—
	Roughometer[b]	0.93	0.90	0.63	0.96	0.67	0.89	0.72	0.91

[a] Sections 6, 9a and 83 were deleted from analysis.
[b] Average for all roughometers.

USING COMBINED EQUATIONS WITH EQUIPMENT EQUATIONS

It is believed that equations appearing in Tables 8 and 9 are the best available at the present time because they were obtained using data from two independent studies. Thus, use of these equations is to be recommended when it is desired to use general equations for predicting the Present Serviceability Index.

As an example of use, assume that it is desired to use a general equation for flexible-overlay pavements with data obtained from the University of Michigan Profilometer. From Table 8 the applicable equation is

$$p = 4.95 - 1.83\ \log(1+SV) - 0.01\ \sqrt{C+P} - 1.34\ \overline{RD}^2$$

From Table 10, line 11 for flexible and overlay pavements

$$\log(1+SV) = 0.42 + 0.004R$$

Thus the serviceability equation becomes

$$p = 4.95 - 1.83(0.42 + 0.004R) - 0.01\sqrt{C+P} - 1.34\ \overline{RD}^2$$

$$p = 4.18 - 0.0073R - 0.01\sqrt{C+P} - 1.34\ \overline{RD}^2$$

EQUATIONS USING ONLY EQUIPMENT MEASUREMENTS TO DETERMINE PSI

Regression equations were determined which relate PSR to the measurements obtained from each piece of equipment, omitting other physical measurements from the equations. The results are given in Table 12.

$$p = A_0 + A_1 F \tag{12}$$

The roughometers and profilometers, with the exception of the CHLOE profilometer on rigid pavement, predicted PSI with similar standard errors of estimate. Table 13 summarizes standard errors and correlation coefficients for equations using equipment only.

SLOPE VARIANCE AND ROUGHNESS COMBINED WITH TEXTURE

Table 14 gives serviceability equations (based on the AASHO model) but with texture added to the equations.

$$p = A_0 + A_1 F + A_2 \log(1+T) + A_3\sqrt{C+P} + A_4\overline{RD}^2 \tag{13}$$

Addition of the texture term raised the correlation coefficients a small amount and resulted in decreased errors of estimate. These changes, however, were in general small for the pavements included in this study.

FLEXIBLE PAVEMENTS				FLEXIBLE AND OVERLAY PAVEMENTS			
A_0	A_1	STD. ERROR	CORR. COEF.	A_0	A_1	STD. ERROR	CORR. COEF.
0.23	0.007	0.14	0.90	0.11	0.008	0.17	0.89
0.31	0.007	0.13	0.92	0.25	0.008	0.16	0.91
0.28	0.007	0.15	0.89	0.18	0.008	0.17	0.90
0.28	0.007	0.14	0.91	0.17	0.008	0.16	0.91
0.28	0.007	0.14	0.91	0.20	0.008	0.16	0.91
0.56	0.002	0.15	0.89	0.50	0.002	0.18	0.88
0.49	0.0006	0.19	0.82	0.38	0.0007	0.20	0.84
0.29	0.006	0.14	0.90	0.25	0.007	0.17	0.89
0.25	0.007	0.14	0.91	0.24	0.008	0.18	0.88
0.17	0.008	0.14	0.91	0.16	0.008	0.17	0.89
0.39	0.004	0.14	0.91	0.42	0.004	0.17	0.89
—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—
0.70	0.016	0.13	0.92	0.71	0.016	0.20	0.85
0.28	0.171	0.11	0.94	0.19	0.229	0.22	0.88
−0.23	0.994	0.10	0.95	−0.42	1.308	0.17	0.94
1.00	0.009	0.31	0.36	0.99	0.010	0.35	0.34
1.01	0.009	0.30	0.39	0.99	0.011	0.35	0.40
0.11	0.002	0.16	0.88	0.09	0.002	0.23	0.80
0.29	0.001	0.16	0.87	0.36	0.001	0.24	0.76
0.36	0.0009	0.17	0.86	0.52	0.0008	0.27	0.69
—	—	—	—	—	—	—	—

TABLE 12

EQUATIONS FOR PREDICTING SERVICEABILITY USING INSTRUMENT MEASUREMENTS ONLY

		RIGID PAVEMENTS			
EQUIPMENT	FACTOR F	A_0	A_1	STD. ERROR	CORR. COEF.
Ind. Rough.	Roughness	6.09	—0.025	0.42	0.90
Ill. Rough.	Roughness	5.81	—0.024	0.40	0.91
BPR Rough.	Roughness	5.78	—0.023	0.44	0.90
N.Y. Rough.	Roughness	5.56	—0.021	0.41	0.91
Tenn. Rough.	Roughness	5.61	—0.027	0.36	0.93
Mich. Rough.	Roughness	5.16	—0.0080	0.29	0.90
Mich. Rough.	Acceleration	5.39	—0.002	0.47	0.88
Minn. Rough.	Roughness (E)	5.93	—0.024	0.42	0.90
Minn. Rough.	Roughness (M)	6.05	—0.025	0.44	0.89
S.D. Rough.	Roughness	5.81	—0.023	0.44	0.89
U. of Mich. Prof.	Roughness	5.14	—0.013	0.36	0.93
AASHO Prof.	SV	3.80	—0.035	0.51	0.86
AASHO Prof.	$\sqrt{SV}$	4.73	—0.418	0.38	0.92
AASHO Prof.	$\log(1+SV)$	5.53	—2.163	0.41	0.91
CHLOE Prof.	SV	4.33	—0.058	0.66	0.74
CHLOE Prof.	$\sqrt{SV}$	5.25	—0.489	0.67	0.73
CHLOE Prof.	$\log(1+SV)$	5.88	—2.185	0.71	0.69
Texas Texture	Texture	3.72	—0.348	0.66	0.74
S.D. Texture	Texture	3.67	—0.290	0.72	0.68
Ky. Accel.	Accel. Index (40)	6.65	—0.007	0.47	0.88
Ky. Accel.	Accel. Index (51.5)	6.01	—0.006	0.63	0.77
Ky. Accel.	Accel. Index (60)	6.20	—0.005	0.70	0.70
CHLOE Prof.*	SV	4.36	—0.0059	0.34	0.89
CHLOE Prof.*	$\log(1+SV)$	7.60	—1.95	0.44	0.80

* Sections 6, 9a and 83 deleted from analysis of rigid pavements.

Table 15 gives equipment equations which relate $\log(1 + SV)$ with CHLOE and roughometer readings with the texture term added to each.

$$\text{AASHO} \log(1+SV) = A_0 + A_1 F + A_2 \log(1+T) \quad (14)$$

in which

$F = \log(1 + SV)$ from CHLOE, or the roughometer value from South Dakota instrument; and

$T =$ Texture reading from Texas instrument when combined with CHLOE and from South Dakota instrument when combined with roughometer.

TABLE 13

SUMMARY OF STANDARD ERRORS AND CORRELATION COEFFICIENTS FOR EQUATIONS USING EQUIPMENT ONLY

	RIGID		OVERLAY		FLEXIBLE	
EQUIPMENT	STD. ERROR	CORR. COEF.	STD. ERROR	CORR. COEF.	STD. ERROR	CORR. COEF.
Roughometers [a]	0.40	0.90	0.38	0.90	0.29	0.91
U. of Mich. Profilometer	0.36	0.93	0.40	0.89	0.30	0.90
AASHO Profil.						
$\log(1+SV)$	0.41	0.91	0.37	0.91	0.37	0.89
$\sqrt{SV}$	0.38	0.92	0.38	0.90	0.38	0.83
CHLOE Profil.						
$\log(1+SV)$	0.71	0.69	0.37	0.91	0.34	0.86
$\sqrt{SV}$	0.67	0.73	0.42	0.88	0.32	0.88
Kentucky Accel. (40 mph)	0.47	0.88	0.52	0.80	0.32	0.88

[a] Average for all roughometers.

OVERLAY PAVEMENTS				FLEXIBLE PAVEMENTS			
A_0	A_1	STD. ERROR	CORR. COEF.	A_0	A_1	STD. ERROR	CORR. COEF.
5.23	—0.019	0.40	0.89	4.76	—0.015	0.28	0.91
4.69	—0.015	0.40	0.89	4.55	—0.015	0.29	0.91
4.98	—0.017	0.39	0.90	4.67	—0.015	0.29	0.91
4.98	—0.018	0.32	0.93	4.71	—0.016	0.28	0.92
4.88	—0.017	0.37	0.90	4.64	—0.015	0.28	0.91
4.29	—0.005	0.42	0.88	4.10	—0.005	0.28	0.91
4.58	—0.002	0.42	0.88	4.28	—0.001	0.35	0.86
4.76	—0.015	0.37	0.90	4.62	—0.013	0.29	0.90
4.73	—0.016	0.46	0.85	4.66	—0.015	0.31	0.89
4.87	—0.015	0.38	0.90	4.84	—0.016	0.31	0.89
4.36	—0.009	0.40	0.89	4.41	—0.008	0.30	0.90
3.64	—0.004	0.46	0.85	3.59	—0.045	0.40	0.81
4.40	—0.350	0.38	0.90	4.27	—0.372	0.38	0.83
4.82	—1.621	0.37	0.91	4.83	—1.735	0.37	0.84
3.69	—0.038	0.50	0.83	3.74	—0.031	0.32	0.88
4.76	—0.431	0.42	0.88	4.52	—0.330	0.32	0.88
5.75	—2.326	0.37	0.91	5.44	—1.877	0.34	0.86
3.36	—0.073	0.82	0.35	3.05	—0.013	0.66	0.25
3.44	—0.102	0.75	0.52	3.10	—0.017	0.64	0.36
5.39	—0.006	0.52	0.80	5.01	—0.005	0.32	0.88
5.53	—0.006	0.46	0.85	4.65	—0.003	0.32	0.88
5.49	—0.005	0.53	0.80	4.49	—0.002	0.34	0.87
—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—

TABLE 14

SERVICEABILITY USING SLOPE VARIANCE AND ROUGHNESS COMBINED WITH TEXTURE (EQ. 13)

PAVE. TYPE	EQUIPMENT	F	A_0	A_1	A_2	A_3	A_4	STD. ERROR	CORR. COEF.	STD. ERROR [a]	CORR. COEF. [a]
R	AASHO	$\sqrt{SV}$	5.18	—0.34	—0.67	—0.10	—	0.31	0.96	0.33	0.95
R	AASHO	$\log(1+SV)$	5.72	—1.21	—1.53	—0.14	—	0.38	0.93	0.53	0.91
R	CHLOE	$\sqrt{SV}$	5.69	—0.31	—1.74	—0.12	—	0.50	0.88	0.64	0.77
R	CHLOE	$\log(1+SV)$	6.15	—1.38	—1.82	—0.14	—	0.51	0.87	0.67	0.75
R	Rough.[b]	Roughness	6.08	—0.019	—0.91	—0.09	—	0.33	0.95	0.41	0.91
O	AASHO	$\sqrt{SV}$	4.63	—0.28	—0.05	—0.08	— 4.31	0.21	0.98	0.19	0.98
O	AASHO	$\log(1+SV)$	4.91	—1.43	0.06	—0.05	— 6.49	0.31	0.96	0.29	0.96
O	CHLOE	$\sqrt{SV}$	5.09	—0.34	—0.49	—0.07	— 8.60	0.12	0.99	0.20	0.98
O	CHLOE	$\log(1+SV)$	5.88	—2.01	—0.38	—0.03	—14.29	0.14	0.99	0.18	0.98
O	Rough.[b]	Roughness	4.99	—0.012	—0.02	—0.11	2.28	0.15	0.99	0.15	0.99
F	AASHO	$\sqrt{SV}$	4.27	—0.36	0.02	—0.01	— 0.38	0.41	0.84	0.40	0.84
F	AASHO	$\log(1+SV)$	4.76	—1.79	0.15	—0.008	— 0.008	0.40	0.84	0.39	0.84
F	CHLOE	$\sqrt{SV}$	4.39	—0.35	0.25	—0.01	+ 1.58	0.33	0.90	0.33	0.89
F	CHLOE	$\log(1+SV)$	5.39	—2.18	0.42	—0.009	+ 1.36	0.34	0.89	0.35	0.87
F	Rough.[b]	Roughness	4.87	—0.016	—0.11	—0.004	+ 0.25	0.33	0.90	0.32	0.89

[a] Standard error and correlation coefficient for similar AASHO model equation but without the texture term.
[b] South Dakota Roughometer.

TABLE 15

AASHO PROFILOMETER IN TERMS OF TEXTURE READINGS PLUS CHLOE OR ROUGHOMETER READINGS (EQ. 14)

PAVE. TYPE	F [a]	A_0	A_1	A_2	STD. ERROR	CORR. COEF.	STD. ERROR [b]	CORR. COEF. [b]
Rigid	log $(1 + SV)$	0.019	0.79	0.41	0.36	0.66	0.37	0.63
	Roughness	0.021	0.010	0.04	0.30	0.87	0.19	0.88
Overlay	log $(1 + SV)$	—0.49	1.24	0.31	0.14	0.96	0.17	0.94
	Roughness	0.15	0.006	0.54	0.21	0.91	0.24	0.87
Flexible	log $(1 + SV)$	—0.22	1.06	—0.08	0.10	0.95	0.10	0.95
	Roughness	0.11	0.007	0.14	0.13	0.93	0.14	0.91
Flexible and Overlay	log $(1 + SV)$	—0.20	1.11	—0.12	0.15	0.92	0.17	0.94

[a] CHLOE or roughometer.
[b] Standard error and correlation coefficient for similar equation but without the texture term.

CHAPTER FOUR

INFLUENCING FACTORS

The primary purposes of this research project were to study the precision of various road roughness measuring devices and to evaluate their applicability for measuring pavement condition. During the course of the study various analyses were made relative to factors which affect pavement rating; the following discussion deals in part with general concepts of pavement condition rating.

FACTORS INFLUENCING SERVICEABILITY RATING

A question often posed by paving engineers is "What factors should be considered when setting up serviceability equations?" Carey and Irick (*2*) pointed out that longitudinal and transverse distortion are primary factors which affect user opinions.

Three methods of measuring pavement condition are available to the engineer.

1. Use an instrument such as the profilometer or roughometer to measure the distortion of the pavement surface.
2. Measure the physical condition of the pavement including such factors as area of patching, extent of cracking, faulting and other features which are apparent to the eye.
3. Use the equipment measurements in conjunction with physical measurements (the technique adopted by Carey and Irick).

At first thought a large number of variables should be measured in great detail so that all of the factors which affect serviceability ratings are included in the analysis. However, from a practical standpoint it is desirable to include a minimum of variables to minimize the cost of obtaining field data. Therefore, it becomes necessary to measure only those factors which significantly influence user opinions.

A factor analysis was performed on simple correlation matrices of all the data as a whole (*i.e.*, irrespective of pavement type). Orthogonal factors were obtained using the principal axes solution. A summary of the significant factors is shown in Table 16.

The factors listed in Table 16 were identified by assigning to each a descriptive name. It was difficult to interpret the maintenance factor; however, the remaining factors were readily identified. Longitudinal and transverse distortion, and micro-roughness were found to be significant factors in terms of the pavement serviceability rating.

Roughness (both macro-roughness and micro-roughness) is a major factor which was found to influence rating. Its rating has the same algebraic sign as bleeding and bituminous patching and the opposition sign of the roughometer, profilometer and texture readings. It is apparent that "smoothness" (both macro and micro) is a desirable property insofar as the pavement user is concerned.

A general picture of the factors which influence serviceability rating for each pavement type can be obtained by observing the simple correlation matrices. The minimum values of correlation coefficients, for the hypothesis that the true correlation coefficients are non-zero with a 90 percent probability, are given in Table 17. Correlation coefficients (correlative and Present Serviceability Rating) which are greater than these minimum values are also given.

In Table 16, as well as in the correlation matrices, it is significant that the major factors which influence serviceability rating are longitudinal distortion and transverse distortion. This observation is in line with the reasoning presented by Carey and Irick. The results of this study have indicated that the mathematical models proposed by Carey and Irick include the major factors which influence

TABLE 16

SUMMARY OF FACTOR ANALYSIS

FACTOR	LATENT ROOT	ELEMENT	FACTOR LOADING
Longitudinal distortion (flexible pavements)	13.7410	Roughometer	0.8935
		U. of Mich. Prof.	0.8876
		Ky. Accel.	0.8649
		AASHO Prof.	0.7040
		Texture	0.5970
		Rating	—0.8481
		Flex. pave.	0.5556
Longitudinal distortion (rigid pavements)	9.3556	Roughometer	0.5022
		U. of Mich. Prof.	0.3360
		Ky. Accel.	0.5622
		AASHO Prof.	0.4097
		Rating	—0.3075
		Long. fault	0.6570
		Trans. fault	0.8260
		Rigid pave.	0.7674
Maintenance	3.5149	Roughometer	—0.1414
		Texture	0.4219
		Avg. fault	0.4319
		Rating	0.1192
		Rigid pave.	0.0622
		Overlay pave.	—0.6587
		Flex. pave.	0.5268
Transverse distortion	2.6093	Avg. rut depth	0.5157
		Roughometer	0.0288
		Rating	—0.2223
		Avg. long. fault	0.4178
Micro-roughness	2.2198	Rating	—0.1019
		Major bleeding	—0.5127
		Bit. patching	—0.5634
		Sealed cracks	—0.2789
		Un-sealed cracks	0.4516
		Texture reading	0.2984

serviceability rating. There are, however, several other factors, of lesser importance, which appear to influence rating but which are not presently included in the serviceability equations. Magnitude of faulting had its influence on the rating of rigid pavements and bleeding appeared to influence the serviceability rating of flexible pavements to a minor degree.

Faulting and number of blowups showed negative correlation with serviceability rating. These features are measured by the roughness measuring instruments and, therefore, it can be reasoned that it is not necessary to include these terms in the regression analysis.

Pavement distortion, except for that at faulted joints, shattered slabs, large chuck holes, etc., may not be readily detected by the eye. Thus, the user's reaction to pavement condition is largely influenced by his response to vibrations and other accelerations of the vehicle, but he is no doubt influenced by other features he sees (cracks, patches, etc.). Data obtained in this study did not shed light on this latter point with certainty. An attempt was made to include a variety of extrinsic features attendant to the pavement (*i.e.*, right-of-way width, condition of shoulder, and pavement color) in the variables under study. No significant effects of these variables were apparent.

TABLE 17

SUMMARY OF SIMPLE CORRELATION COEFFICIENTS

PHYSICAL MEASUREMENT	COEFFICIENTS		
	RIGID	OVERLAY	FLEXIBLE
Avg. trans. fault	—0.80	—	—
Blowups	—0.74	—	—
Bit. patching	—0.65	—	—
Joints (no.)	0.65	—	—
Max. trans. fault	—0.61	—	—
Avg. long. fault	—0.40	—	—
Crack. and patch.	—0.37	—0.63	—
Max. rut depth	—	—0.90	—0.74
Bit. patching	—	—0.69	—0.57
Avg. rut depth	—	—0.63	—
Bleeding [a]	—	—	—0.69
Absolute min. value [b]	**0.35**	**0.37**	**0.30**

[a] Sum of major, intermediate and minor bleeding.
[b] Minimum correlation coefficient for 90 percent probability that coefficient is non-zero.

Table 18 gives the mean rating of individuals who rode in the rear seat of the automobile compared to the mean rating of those who rode in the front seat. Inasmuch as there is little difference among ratings assigned from various positions in the automobile, it appears that the rater's ability to see the pavement had little, if any, influence on his rating.

The major importance of slope variance (or roughness) is further demonstrated in Table 19. Bleeding, for example, had little effect on rating (compare columns 2 and 5 for the flexible pavements). Likewise, texture as measured by the texture meter had little effect on the precision of the prediction equations (columns 3 and 4 vs columns 1 and 2 for flexible pavements).

Regression equations were established which predict the Present Serviceability Index in terms of physical measurements made on the pavement surface exclusive of slope variance or roughness (Table 19, Col. 7). In addition, data appearing in Table 12 permit calculation of the index without any objective measurements other than slope variance or roughness.

Considering the data as a whole, there appears to be no need to change the mathematical models originally proposed by Carey and Irick (Table 20, also Tables 14, 15 and 19). The one possible exception to this is the Texture

TABLE 18

MEAN RATINGS VS POSITION OF RATER IN AUTOMOBILE [a]

POSITION	MEAN PAVEMENT RATINGS		
	RIGID	OVERLAY	FLEXIBLE
Right-front	3.02	3.11	2.71
Right-rear	3.06	3.12	2.71
Left-rear	3.00	2.90	2.70
All positions	3.03	3.05	2.71

[a] HRB Committee panel.

Meter used in conjunction with the CHLOE Profilometer. Data from this study, however, indicate that there is little need to use the Texture Meter with the AASHO Profilometer and the BPR-type Roughometer. The need for its use is apparently unique to the correlations between the CHLOE and AASHO Profilometers. Even so the texture term did not increase these later correlations a significant amount.

COMPARISON OF EQUIPMENT

From previous discussions it is apparent that good correlations can be obtained between rating and a variety of physical measurements. Tables 6 and 13 indicated that, for the serviceability correlations obtained on the pavements in this study, there was little if any difference in the precision of one instrument over the other instruments. The roughometers yielded consistently good results on all types of pavement. This observation, together with the general widespread use of the roughometer and its rugged construction, points up its applicability to establishing serviceability equations.

The AASHO Slope Profilometer performed very well throughout the testing program. The results obtained by this instrument were consistent and little difficulty was experienced with the functional operation of the instrument.

The University of Michigan Profilometer produced excellent results throughout the testing program. Records which show change in pavement profile as a function of

TABLE 19

COMPARISON OF VARIOUS EQUATION MODELS WITH THE AASHO MODEL

	REGRESSION COEFFICIENTS						
	AASHO MODEL						
TERM	(1)	(2)	(3)	(4)	(5)	(6)	(7)
RIGID PAVEMENT:							
Intercept	5.16	6.33	4.24	4.53	—	—	4.13
Roughness	—	—0.024	—	—0.0051	—	—	—
$\sqrt{SV}$	—0.40	—	—0.62	—	—	—	—
$\sqrt{C+P}$	—0.10	—0.08	—	—	—	—	—
$\sqrt{P}$	—	—	—0.16	—0.14	—	—	— 0.17
$\sqrt{\text{Blowups}}$ [a]	—	—	—0.58	—0.61	—	—	— 0.68
Avg. tran. fault	—	—	—3.69	—3.33	—	—	— 4.36
Avg. long. fault	—	—	—1.17	—1.30	—	—	— 0.91
Standard error	0.33	0.41	0.16	0.15	—	—	0.16
Corr. coefficient	0.95	0.92	0.99	0.99	—	—	0.99
OVERLAY PAVEMENT:							
Intercept	4.62	5.35	4.32	4.90	—	—	3.64
Roughness	—	—0.015	—	—0.01	—	—	—
$\sqrt{SV}$	—0.28	—	—0.26	—	—	—	—
$\sqrt{C+P}$	—0.09	—0.11	—	—	—	—	—
$\sqrt{P}$	—	—	—0.11	—0.16	—	—	— 0.43
$\overline{RD}^2$ [b]	—4.17	—	—4.49	—2.59	—	—	—22.0
Standard error	0.19	0.09	0.31	0.31	—	—	0.46
Corr. coefficient	0.98	0.99	0.95	0.95	—	—	0.86
FLEXIBLE PAVEMENT:							
Intercept	4.29	4.78	4.27	4.87	4.60	4.03	3.34
Roughness	—	—0.015	—	—0.016	—0.01	—	—
$\sqrt{SV}$	—0.36	—	—0.36	—	—	—0.28	—
$\sqrt{C+P}$	—0.01	0.004	—0.01	—0.08	—	—	—
$\sqrt{P}$	—	—	—	—	—0.04	—0.08	— 0.11
$\overline{RD}^2$ [c]	—0.33	—0.26	—0.38	—4.31	—1.52	—	— 2.81
Texture log $(1+T)$	—	—	0.02	—0.05	—	—	—
$\sqrt{\text{Bleeding}}$ [a]	—	—	—	—	—0.001	—	— 0.03
Standard error	0.40	0.30	0.41	0.33	—	0.35	0.41
Corr. coefficient	0.84	0.91	0.84	0.90	0.92	0.87	0.83

[a] Blowups and bleeding are in square feet of area per 1,000 sq ft of pavement, faults are in inches and other terms are same as for AASHO equations.

[b] Average of rut depth in right and left wheelpaths.

[c] Average of rut depths in right and left wheelpaths for AASHO model (Cols. 1 and 2); for the equations in Cols. 3 through 7, rut depth in right wheelpath only.

TABLE 20

EXAMPLES OF POSSIBLE TRANSFORMATIONS

EQUATION	EQUIPMENT FUNCTION F	FUNCTION OF p	PAVEMENT TYPE	A_0	A_1	A_2	A_3	STD. ERROR	CORR. COEF.
Combined serviceability [a]	AASHO	p	Rigid	5.51	−1.88	−0.08	—	0.31	0.96
	log $(1 + SV)$	log p	Rigid	0.89	−0.35	−0.01	—	0.07	0.93
		p	F & O	4.95	−1.83	−0.01	−1.34	0.36	0.89
		log p	F & O	0.79	−0.32	−0.002	+0.20	0.07	0.90
p vs function of roughness (R) as measured by Ind. Roughometer [b]	R	p	Rigid	6.09	−0.025	—	—	0.42	0.90
	log R		Rigid	17.71	−7.13	—	—	0.43	0.90
	R	p	Overlay	5.23	−0.019	—	—	0.40	0.89
	log R		Overlay	14.09	−5.41	—	—	0.40	0.91
	R	p	Flexible	4.76	−0.015	—	—	0.28	0.91
	log R		Flexible	11.58	−4.20	—	—	0.29	0.90
Equipment [c] using R to predict log $(1 + SV)$ as measured by AASHO Prof.	R	y-value	Rigid	−0.15	0.011	—	—	0.17	0.91
	log R	is log $(1 + SV)$	Rigid	−5.40	3.2	—	—	0.25	0.85
	R		Overlay	−0.12	0.010	—	—	0.20	0.91
	log R		Overlay	−5.59	3.38	—	—	0.14	0.96
	R		Flexible	0.23	0.007	—	—	0.14	0.90
	log R		Flexible	−3.11	2.05	—	—	0.13	0.91

[a] Table 8 for definition of coefficients.
[b] See Table 12.
[c] See Table 10.

distance were obtained by this profilometer. These data, however, were not analyzed in detail other than to obtain the roughness index.

The Kentucky accelerometer device gave excellent results throughout the study. Some difficulty was encountered in maneuvering several of the sections (near horizontal curves) at high speed.

The CHLOE Profilometer yielded variable results. For the rigid pavements, the correlation coefficients obtained by the CHLOE instrument were lower, and the errors of estimate were higher than corresponding values for the roughometers. This was thought to be due to several erratic readings of the CHLOE. Exclusion of these erratic readings raised the correlation coefficients for this instrument a significant amount. For rigid and flexible pavements the roughometers generally yielded higher correlation coefficients and lower standard errors of estimate than the CHLOE instrument used in conjunction with the Texture Meter.

It should be recognized that the AASHO Profilometer and the University of Michigan Profilometer yield basic data which cannot be obtained by the roughometer. For example, charts showing slope variance, elevation of pavement surface, and approximations of the pavement profile as a function of distance can be obtained by both of these instruments.

Table 8 presents equations which were obtained by combining data from this study with data from the AASHO Road Test. Since these equations were developed using a large sample, general use of these equations is to be recommended. However, since these equations are based upon slope variance measured by the AASHO Slope Profilometer, it becomes necessary to rely on correlations between this instrument and other profilometers or roughometers.

Table 11 compares correlation coefficients and standard errors for the CHLOE Profilometer and roughometer when the results of these instruments were correlated with results given by the AASHO Slope Profilometer. For these correlations, the CHLOE Profilometer and roughometers yielded, in general, about the same precision.

The Kentucky Accelerometers yielded excellent correlations with pavement rating. This is also true for correlation of results from this instrument with the results of the AASHO Slope Profilometer.

The results of this study have indicated that for the pavements tested, the correlations between the AASHO Profilometer and the CHLOE Profilometer and BPR-type Roughometers were not significantly improved by adding the texture term to the equations.

CHAPTER FIVE

SUMMATION OF FINDINGS

It is recognized that the number of pavements included in the study was relatively small and, thus, the limitations inherent to sample size must be kept in mind by the reader. For example, on the basis of these tests alone, the serviceability equations (in some instances) indicated that the rut depth term added to the equations. On the other hand, considering the data from this study combined with the AASHO Road Test results, the reverse was found to be true. Also, correlations between data from the CHLOE instrument and other data for the rigid pavements depended upon whether several data points were included in the analysis.

The report presents equations for each piece of equipment used in the study (with the exception of the General Motors instrument). This large number of equations was developed so that each state cooperating in the study could compare its own instrument with those from other agencies.

RATING PANELS

1. A study of variance rating within a panel suggested that variance is a function of the mean rating. Variation within a panel was greatest for mean ratings of from 2 to 4 (approximately).
2. The lay panel, on the average, rated the pavements higher than the professional panels.
3. The data from this study indicated lower ratings for acceptable pavements than the AASHO data (Table 3); the reasons for this are unknown.

SERVICEABILITY EQUATIONS

1. Serviceability equations using the AASHO mathematical model were developed for each piece of equipment (Table 4). Except for the CHLOE instrument on rigid pavements, these equations indicated no significant differences in the precision of the major instruments for predicting serviceability. Exclusion of three data points for the rigid pavements resulted in no significant differences among any of the instruments.
2. Equations were developed which permit prediction of serviceability using only equipment measurements (Table 12). These equations showed, in general, lower correlation coefficients and higher errors of estimate than the AASHO model equations.

COMBINED AASHO MODEL AND EQUIPMENT EQUATIONS

1. Data from this study were combined with data obtained in connection with the AASHO Road Test (Table 8). Equations comparing measurements by each instrument with a function of slope variance determined by the AASHO Slope Profilometer were developed.
2. The combined Purdue-AASHO serviceability equations are for two pavement types: (a) rigid and (b) flexible and overlay pavements combined.
3. The relatively large number of pavements used in developing the AASHO combined equations leads to the conclusion that these are the best available at the present time. These equations plus the equipment equations permit use of various instruments for predicting the Present Serviceability Index.

COMBINED ROUGHOMETER AND EQUIPMENT EQUATIONS

1. Data obtained with the Indiana Roughometer in this study were combined with those previously reported by Nakamura and Michael (Table 9).
2. These equations were developed to assist those desiring to obtain the Present Serviceability Index without making other objective measurements (cracking, patching and rut depth).
3. These data should also be useful to engineers who have past records of roughometer readings on highway pavements and who would like to interpret these data in terms of Present Serviceability Indices.

EQUATION MODELS

1. The desirability of transforming the serviceability index term in the AASHO model equations to the logarithm of serviceability index was investigated. The results indicated that this transformation did not increase the precision of prediction significantly (Table 20).
2. For the flexible pavements tested in this study, introduction of a texture term into the AASHO model equations did not increase the correlation coefficients a significant amount.

EQUIPMENT

1. The field test results indicated that, from the standpoint of precision of predicting serviceability, little difference existed among the various instruments.
2. On this basis, it is suggested that choice of instrument to use should depend upon instrument costs (including initial, maintenance and operating costs), ease of data reduction and availability of the instrument. Thus, the roughometers and CHLOE profilometers should have high potential for obtaining serviceability data.
3. If in addition to serviceability data, detailed records of pavement slope, pavement profile and pavement-vehicle response are desired, other considerations overshadow the element of cost. The AASHO Slope Profilometer measures slope variance but it will also measure pavement profile if the horizontal reference system is used. The University of Michigan Profilometer measures relative pavement profiles and can (by computation) yield data on true pavement profile and/or slope variance. The Kentucky Accelerometer and the Purdue tire pressure device give basic data relative to pavement-vehicle response. Hence, the value of each of these instruments as a research tool is apparent.

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