COMPARISON OF DIFFERENT
METHODS OF MEASURING
PAVEMENT CONDITION

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PURDUE UNIVERSITY
LAFAYETTE INDIANA

by

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and

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Technical Paper

COMPARISON OF DIFFERENT METHODS OF MEASURING PAVEMENT CONDITION

TO: K. B. Woods, Director
Joint Highway Research Project

February 4, 1965

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 9-10-1

The attached technical paper "Comparison of Different Methods of Measuring Pavement Condition" is presented to the Board as information. It resulted from research performed under a National Cooperative Highway Research Program (NCHRP) contract and was presented at the recent meeting of the Highway Research Board.

The paper has been authored by E. J. Yoder and R. T. Milhous of our staff and will be published by the Highway Research Board. The study results indicate that the BPR type roughometer can be used successfully for predicting serviceability.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Secretary

HLM:bc

Attachment

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COMPARISON OF DIFFERENT METHODS OF MEASURING PAVEMENT CONDITION

(NCHRP 1-2)

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ACKNOWLEDGEMENTS

The research project reported herein was conducted under the terms of a contract between the Purdue Research Foundation and the Highway Research Board. 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 Quinn. In addition, he supervised a major portion of the field work which involved operation of the roughometers and profilometers.

Mr. W. J. Head was in charge of the field performance surveys.

Mr. T. C. Williamson assisted materially in laying out the test sections. Mr. 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.

Professor J. C. Oppenlander gave invaluable assistance in the statistical analysis of the data.

COMPARISON OF DIFFERENT METHODS OF MEASURING PAVEMENT CONDITION

SUMMARY

This report presents the results of a field study of the precision of various roughometers and profilometers for predicting serviceability. Forty-five pavement sections of three types (flexible, rigid and overlay) were rated by a lay panel, the AASHO Road Test panel and the Highway Research Board Committee on Pavement Condition Evaluation. These same pavements were evaluated using the roughness and profilometer equipment. Statistical relationships, following techniques adopted at the AASHO Road Test, were developed between rating and objective measurements.

The lay panel tended to rate the pavements higher than the professional panels. The results indicated little difference regarding the precision of the various instruments in so far as predicting serviceability is concerned. The data suggest that the BPR type roughometer can be used successfully for predicting serviceability.

Data from this study were combined with those from the AASHO Road Test and serviceability equations were developed for these combined data on the basis of the Slope Profilometer. Correlations between roughometers and the Slope Profilometer were presented. Equations are presented which should permit engineers who have past records of roughometer readings to interpret these data in terms of Present Serviceability Indices.

COMPARISON OF DIFFERENT METHODS OF MEASURING PAVEMENT CONDITION

INTRODUCTION

This report summarizes research carried out under terms of a contract between the Purdue Research Foundation and the Highway Research Board on various methods of measuring pavement condition. This project is NCHRP 1-2 and 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. These concepts were first reported by Carey and Irick (2).

Briefly stated, the concepts proposed by Carey and Irick 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 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.

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 reproduced below.

Rigid Pavements:

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

Flexible Pavements:

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

where:

SV = Slope Variance

C = Major cracking in feet per 1000 sq. ft. of area

P = Bituminous patching in sq. ft. per 1000 sq. ft. of area

RD = Average rut depth of both wheel paths in inches measured at the center of a 4-ft. span in the most deeply rutted part of the wheel path.

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 means of equation 3.

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

where:

Y = Difference between two elevations, one foot apart

n = Number of elevation readings.

Slope variance, as used in these equations, was measured on the AASHO Road Test by means of the slope profilometer designed specifically for this test road (see Figure 3*). This particular instrument as well as others that can be used for this type of work will be discussed in greater detail in later paragraphs.

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, climate, etc. Thus, it can be seen that 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).

Mathematical Models

The model used at the AASHO Road Test was additive of the form shown in equation 4.

$$p = A_0 + A_1 f_1 + A_2 f_2 \dots\dots\dots 4.$$

* All figures are in the appendix.

where:

p = Serviceability index

A_0, A_1 etc. = Coefficients

f_1, f_2 etc. = Objective measurements

Painter (11) has suggested that a model of the form shown in equation 5 is better than the additive model.

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

or

$$p = a_0 10^{a_1 f_1 + a_2 f_2} = a_0 10^{a_1 f_1} \times 10^{a_2 f_2} \times \dots \quad 5.$$

Engineers at the Road Test investigated both models and adopted the first for their use for several reasons. Equation 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 their own regression equations to fit their 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.

PURPOSES OF THIS RESEARCH PROJECT

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.

SCOPE

The scope of this project included comparisons of conventional roughness measuring equipment. The pavement sections were selected so that surface texture was variable.

The scope 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 nor 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 8 different agencies were used in this study.)
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 (data were not analyzed)
8. Purdue University Tire Pressure Instrument.

PROCEDURE

Location of Study

Test-pavements used in this study were located in the north-central section of Indiana in the vicinity of Lafayette, Indiana. Pavements on

both the primary and secondary highway systems were included in the study. Several county roads were also studied.

Pavements on the primary system in the study area 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 included in this study (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 of the above, 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

Since 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 month 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. The test pavements were divided into two loops, one north of Lafayette and the other south of Lafayette. Duplicate sections were so chosen that a pavement of each type and rating was included in both the northern and southern 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 sight distance, grade and alignment. In each case, the test section was in one lane of the highway only. In the case of four lane divided pavements, the test section was always in the traffic lane (outside lane) while for two lane pavements, choice of lane depended upon route of travel. The majority of the rigid test sections were on 12 foot lanes whereas most of the flexible and overlay sections were on 11, 10 or 9 foot lanes.

CONDITION SURVEYS

General

The condition surveys of the pavement sections in this project were conducted from June through August 1963. The survey party consisted of three men. Equipment utilized 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" (Figure 1) since it was not known initially what factors would effect pavement rating.

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 feet)
2. Length of section (usually 1320 feet)
3. Width of shoulder
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
8. General condition of pavement surface

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 $1/32$ " to more than 1" (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 of rigid and overlay pavements. This instrument consisted of a metal rod riding in a 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 wheel paths. 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 (rigid and overlay pavements), 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.

Miscellaneous Defects of Rigid Pavements

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.

Rutting

A "rutmeter" consisting of a metal pipe with a metal rod riding in a vertical pipe, and a scale calibrated in tenths of an inch was used. Operation of the rutmeter involved centering the meter in a wheel path, allowing the rod to come in contact with the surface, and reading the depth of the rut directly on the scale. Rut readings were generally taken at forty feet intervals in both wheel paths.

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.

Severity of bleeding was visually classified into three types; major, intermediate, and minor. 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.

Ravelling

Ravelling was also measured on an area basis. Ravelling was also considered to be of three types; major, intermediate and minor.

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 described in subsequent paragraphs were run over the test pavements during the latter half of July, 1963. The one exception to this was the BPR 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 the testing program while approximately two weeks were required by the profilometers.

BPR Roughometers (Figure 2)

The Bureau of Public Roads Roughometer needs no description here since it is a well known device to the highway profession. Roughometers owned and operated by each of the agencies listed below were included in the study.

1. Indiana
2. Illinois
3. Tennessee
4. New York

5. South Dakota
6. Minnesota
7. Michigan
8. Bureau of Public Roads

Some of the roughometers listed above 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 (Figure 3)

The AASHO Slope Profilometer is described in detail in the final report of the AASHO Road Test (5). This instrument utilized two small wheels in each wheel path and measures slope variance as given in Equation 3. This instrument was operated by personnel from the Bureau of Public Roads.

CHLOE Profilometer (Figure 4)

The CHLOE Profilometer 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 inch intervals along the pavement surface. This profilometer has slope wheels in one wheel path and therefore, to obtain slope variance in two wheel paths, it is necessary either to rerun the profilometer over the test pavement, or to alternate between the left and right wheel paths at intervals along the pavement.

For this study, the CHLOE Profilometer was towed alternately in the outer and inner wheel paths and the slope variance obtained by this instrument thus is an average of the two wheel paths. This is in contrast

to the roughometers which were towed over the outer wheel path only.

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

Texas Texture Meter (Figure 5)

The texture meter 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 (Figure 6)

Engineers for the State Highway Department of Kentucky have devised an instrument for measuring pavement roughness based upon the acceleration experienced by a passenger in an automobile. This instrument 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 later 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 device when the test vehicle was driven over the test pavements at three different vehicle speeds.

University of Michigan Profilometer (Figure 7)

The University of Michigan has built a truck mounted profilometer, described by Housel (8), to measure and record pavement profiles. The instrument is similar to that developed by engineers for the State Highway Department of California (9).

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 feet apart, provide reference points from which vertical displacement is measured by a recording wheel midway between the reference wheels.

Pavement profiles are recorded on a continuous chart permitting analysis of detailed profiles in both wheel paths. 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 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 electro-hydraulic 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. Since there is no single index produced by this instrument, the results from this instrument are not included herein.

Purdue Tire Pressure Measurement Device (Figure 3)

A technique for determining the dynamic wheel load by measuring the change in the inflation pressure of the tire is described in reference (1). A similar procedure, developed by the Michigan State Highway Department Laboratories in Lansing, Michigan has also been successfully used for this purpose. The equipment 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 the tire inflation pressure as the vehicle is traveling over 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 while 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 citizens from the Lafayette area and were selected so that a general cross section of occupations was encompassed. Several housewives were included in the panel. 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. It will be noted that panel sized varied with the Highway Research Board Committee Panel being the largest.

Mechanics of Rating.

Figure 9 shows the rating card used in this study. This card is nearly identical to the one used on the AASHO Road Test with the exception that pertinent information relative to the specific pavements of this study 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. 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 rater within the vehicle as well as type of rater (passenger or driver) may have influenced the ratings 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, preferable 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 two 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.

RESULTS

General

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 are the most reliable for predicting serviceability. In order to achieve these objectives, a series of pavements were 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 among various roughness measuring instruments were examined. The discussion which follows, then, includes data which do not pertain specifically to the objectives of the project; nevertheless, the data should be of general interest. 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

General

For purposes of this study, 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 "Over-All" 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: (1) to determine variation within a panel, (2) to establish relationships among panels and (3) to study pavement acceptability (i.e. what rating indicates an acceptable pavement?)

Variation Within Panels

Figure 10, which depicts typical variance of panel ratings about their mean for the Lay panel, indicates that variance is a function of the mean rating itself.

Figure 10 indicates low variance for both high and low 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.

Figure 11 shows the variability of individual ratings as a function of mean rating for the overlay pavements. This figure also shows the ratings for three individuals selected at random. The data on this figure, 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 than the average. In several instances, individual raters were essentially average in as much 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. The above serves to emphasize the necessity for using relatively large panels.

Relationships Among Panels

A comparison of mean Lay panel ratings and mean Professional panel ratings is shown in Figure 12. In general, the Lay panel tended to rate pavements higher than the Professional panel. Data obtained in this study did not disclose why this trend was reversed on the poorer pavements.

Correlation coefficients among panels are shown in Table 1. The coefficients indicate excellent correlation between ratings of any two panels. Subsequent regression analysis which relate panel rating and objective measurements utilize the Over-all 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.

Table 1 Correlation Coefficients Among Rating Panels

Panel	Lay	HRB	AASHO	Professional	Over-All
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
Over-All	0.980	0.995	0.973	0.994	1.000

Pavement Acceptability

Each rater was asked to indicate whether the pavements being rated were acceptable, unacceptable or of doubtful acceptability. The composite data are shown graphically in Figure 13.

The data indicated no significant differences among panels in determining acceptability. Thus, the Purdue data which compare primary and secondary pavements are based on Over-all panel data. Nakamura (10) found that lower ratings were acceptable for secondary pavements than for primary pavements; the data from this study indicated a similar trend.

Figure 13 presents comparisons of data obtained in this study, labeled "Purdue Data Over-all Panel", with data obtained by Nakamura (10), labeled "Nakamura Data, Over-all Panel", and data obtained in connection with the AASHO Road Test (2), labeled "AASHO Data".

In the AASHO study, data for overlay pavements were included with data for flexible pavements. The effect of this combining of data in Figure 13 is unknown.

The data were analyzed to estimate the rating at which 50 percent of the raters indicated an acceptable pavement. The results are summarized in Table 2. 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 the data obtained in this study (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.

Table 2 Rating at Which 50 Percent of Panel Members
Indicated Yes or No

a) Secondary and Primary Pavements Combined.

	Rigid		Overlay		Flexible	
	Yes	No	Yes	No	Yes	No
Purdue Data	2.2	1.5	2.2	1.5	2.2	1.7
AASHO Road Test	2.9	2.5	---	---	2.9	2.5

b) Secondary and Primary Pavements Separate but Pavement Types Combined.

	Secondary		Primary	
	Yes	No	Yes	No
Purdue Data	2.0	1.5	2.4	---
Nakamura	2.0*	1.5	2.5*	2.0
Nakamura and Purdue Data Combined	---	1.5	---	1.9

* At 0.70 percentile

AASHO Model Equations

The equations developed by Carey and Irick are of the form shown in equations 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 suggested 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 the remainder of the rigid 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 section 6, 9a and 43. Data on this point, however, were not sufficient to clarify this observation for certain. Therefore, to avoid bias by arbitrarily discarding data for these sections, all equations were developed in which data from pavement sections 6, 9a and 43 were included in the analysis.

The general AASHO model equations are as follows:

rigid pavements:

$$p = A_0 + A_1 f(\text{equipment measurement}) + A_2 \sqrt{C + P} \quad 6.$$

flexible and overlay pavements:

$$p = A_0 + A_1 f(\text{equipment measurement}) + A_2 \sqrt{C + P} + A_3 (\overline{RD})^2 \quad 7.$$

The functions of equipment measurement are as follows:

<u>Equipment*</u>	<u>Function F</u>
All Roughometers	Roughness in inches/mile (for the Minnesota Roughometer, both the mechanical and electrical recorders)
Michigan Roughometer	Acceleration in g's/mile
University of Michigan Profilometer	Roughness Index in inches/mile
AASHO Profilometer	SV, $\sqrt{SV}$, and $\log (1 + SV)$
CHLOE Profilometer	SV, $\sqrt{SV}$, and $\log (1 + SV)$
Texture Meters	Texture in inches $\times 10^{-3}$
Kentucky Accelerometer	Acceleration Index (for operating speeds of 40, 51.5 and 60 MPH)

Data obtained from the Kentucky Accelerometer is 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.

Tables 3, 4 and 5 (for rigid overlay and flexible pavements, respectively) contain the results of a linear regression analysis for each piece of equipment.

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.

* 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 from the General Motors device were not analyzed since there is no single number from this instrument representing roughness.

$$p = A_0 + A_1 F + A_2 \sqrt{C+p} + A_3 \overline{RD}^2$$

where:

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

Equipment	Factor "F"	Coefficients				Std Error	Corr. Coeff.
		A_0	A_1	A_2	A_3		
Ind. Rough.	Roughness	6.33	-0.024	-0.08		0.41	0.92
Ill. Rough.	"	6.09	-0.023	-0.08		0.38	0.93
BPR. Rough.	"	6.08	-0.021	-0.08		0.41	0.91
W.Y. Rough.	"	5.88	-0.020	-0.09		0.39	0.92
Tenn. Rough.	"	5.87	-0.021	-0.07		0.39	0.94
Mich. Rough.	"	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.	"	6.11	-0.022	-0.08		0.41	0.91
U. of Mich. Prof.	"	5.49	-0.012	-0.09		0.33	0.95
AASHO Prof.	"	4.28	-0.032	-0.10		0.48	0.88
AASHO Prof.	$\frac{SV}{\sqrt{SV}}$	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.	$\frac{SV}{\sqrt{SV}}$	4.79	-0.054	-0.11		0.64	0.78
CHLOE Prof.	$\log (1+SV)$	5.70	-0.45	-0.12		0.64	0.77
CHLOE Prof.	Texture	6.37	-2.04	-0.13		0.67	0.75
Texas Texture	"	4.54	-0.34	-0.17		0.58	0.82
S. D. Texture	"	4.51	-0.28	-0.17		0.64	0.72
Kent'ky Accel.	Accel. Index (40)	6.89	-0.0068	-0.084		0.45	0.90
Kent'ky Accel.	Accel. Index (51.5)	6.34	-0.0052	-0.105		0.61	0.80
Kent'ky Accel.	Accel. Index (60)	6.55	-0.0047	-0.131		0.67	0.75
CHLOE Prof. "	$\frac{SV}{\sqrt{SV}}$	4.45	-0.05	-0.12		0.52	0.92
CHLOE Prof. "	$\log (1+SV)$	7.28	-1.74	-0.14		0.30	0.92

Table. 4 AASHO Model Equations, Overlay Pavements

$$p = A_0 + A_1 F + A_2 \sqrt{C+P} + A_3 RD^2$$

where:

p = Present Serviceability Index

A₀ = p intercept

A₁ = Constant

F = Function of equipment measurement

A₂ = Constant

C+P = Cracking plus patching

A₃ = Constant

RD = Rut. depth

Equipment	Factor "F"	Coefficients				Std Error	Corr. Coeff.
		A ₀	A ₁	A ₂	A ₃		
Ind. Rough.	Roughness	5.35	-0.015	-0.11		0.09	0.99
Ill. Rough.	"	4.92	-0.012	-0.10	-3.78	0.08	1.00
BPR. Rough.	"	5.14	-0.014	-0.10	-4.21	0.09	0.99
N.Y. Rough.	"	5.02	-0.014	-0.07	-2.30	0.20	0.98
Tenn. Rough.	"	5.03	-0.013	-0.10	-2.60	0.11	0.99
Mich. Rough.	"	4.59	-0.004	-0.12		0.15	0.99
Mich. Rough.	Acceleration	4.87	-0.0012	-0.06	-16.34	0.19	0.98
Minn. Rough.	Roughness (E)	4.92	-0.012	-0.10		0.12	0.99
Minn. Rough.	" (M)	5.03	-0.013	-0.12	-1.65	0.11	0.99
S. D. Rough.	"	5.00	-0.012	-0.11		0.15	0.99
U. of Mich. Prof.	"	4.54	-0.0071	-0.11		0.12	0.99
AASHO Prof.	$\frac{SV}{\sqrt{SV}}$	4.24	-0.027	-0.13	-1.59	0.10	0.99
AASHO Prof.	$\log (1+SV)$	4.62	-0.28	-0.09	-4.17	0.19	0.98
AASHO Prof.	$\frac{SV}{\sqrt{SV}}$	4.92	-1.42	-0.05	-0.35	0.29	0.90
CHLOE Prof.	$\log (1+SV)$	4.29	-0.030	-0.13	-2.70	0.25	0.97
CHLOE Prof.	$\frac{SV}{\sqrt{SV}}$	4.97	-0.34	-0.09	-8.09	0.20	0.98
CHLOE Prof.	$\log (1+SV)$	5.81	-2.03	-0.04	-13.88	0.18	0.98
Texas Texture	Texture	4.28	-0.048	-0.14	-17.45	0.59	0.82
S. D. Texture	"	4.14	-0.074	-0.11	-15.59	0.54	0.83
Kent'ky Accel.	Accel. Index (40)	5.49	-0.0048	-0.03	-25.14	0.42	0.90
Kent'ky Accel.	Accel. Index (51.5)	5.36	-0.0043	-0.04	-13.87	0.44	0.89
Kent'ky Accel.	Accel. Index (60)	5.23	-0.0035	-0.10		0.51	0.85

$$p = A_0 + A_1 F + A_2 \sqrt{C+P} + A_3 R D^2$$

where:

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

$R D$ = Rut Depth

Equipment	Factor "F"	Coefficients				Std Error	Corr. Coeff.
		A_0	A_1	A_2	A_3		
Ind. Rough.	Roughness	4.78	-0.015	0.004	-0.26	0.30	0.91
Ill. Rough.	"	4.54	-0.014	-0.01		0.30	0.92
BPR. Rough.	"	4.57	-0.015	-0.0002		0.30	0.91
N.Y. Rough.	"	4.71	-0.016	-0.0003		0.30	0.92
Tenn. Rough.	"	4.64	-0.015	0.002		0.30	0.91
Mich. Rough.	"	4.09	-0.0048	-0.0003		0.30	0.91
Mich. Rough.	Acceleration	4.40	-0.0014		-2.85	0.35	0.87
Minn. Rough.	Roughness (E)	4.62	-0.014			0.31	0.90
Minn. Rough.	" (M)	4.66	-0.015			0.33	0.89
S. D. Rough.	"	4.83	-0.016	-0.004		0.32	0.89
U. of Mich. Prof.	"	4.41	-0.008	-0.006	-0.11	0.31	0.90
AASHO Prof.	$\frac{SV}{\sqrt{SV}}$	3.57	-0.04	-0.015	-1.14	0.41	0.82
AASHO Prof.	$\log (1+SV)$	4.29	-0.36	-0.01	-0.33	0.40	0.84
AASHO Prof.	$\frac{SV}{\sqrt{SV}}$	4.82	-1.70	-0.0077		0.39	0.84
CHLOE Prof.	$\log (1+SV)$	3.76	-0.03	-0.01		0.33	0.89
CHLOE Prof.	$\frac{SV}{\sqrt{SV}}$	4.52	-0.33	-0.01		0.33	0.89
CHLOE Prof.	$\log (1+SV)$	5.43	-1.47	-0.009		0.35	0.87
Texas Texture	Texture	3.18	-0.012	-0.03	-0.81	0.57	0.37
S. D. Texture	"	3.23	-0.016	-0.03		0.54	0.46
Kent'ky Accel.	Accel. Index (40)	5.08	-0.0047		-2.14	0.33	0.82
Kent'ky Accel.	Accel. Index (51.5)	4.71	-0.0027	-0.009	-0.34	0.3	0.90
Kent'ky Accel.	Accel. Index (60)	4.53	-0.0018	-0.01	-1.40	0.35	0.88

The equation for the Purdue tire pressure device is:

$$\text{P.S.I.} = 9.80 - 3.39 \log (\text{RMS Force}) - 0.06 \sqrt{C + P}$$

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

It should be noted that several blank spaces appear in the column A_2 and A_3 in Tables 4 and 5. 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 6 shows the AASHO Model Equations for the Purdue Data for the combination of flexible and overlay pavements. It will be noted that the correlation coefficients are higher than those for the flexible pavements alone.

Table 7 shows 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 $\pm$ one true standard error and 95 percent $\pm$ two true standard errors of the true values of the PSR.

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

where:

p = Present Serviceability Index

A₀ = p intercept

A₁ = Constant

F = Function of equipment measurement

A₂ = Constant

C+P = Cracking plus patching

A₃ = Constant

$\overline{RD}$ = Rut depth

Equipment	Factor "F"	Coefficients				Std Error	Corr. Coeff.
		A ₀	A ₁	A ₂	A ₃		
Ind. Rough.	Roughness						
Ill. Rough.	"						
BPR. Rough.	"						
N.Y. Rough.	"						
Tenn. Rough.	"						
Mich. Rough.	"						
Mich. Rough.	Acceleration						
Minn. Rough.	Roughness (E)						
Minn. Rough.	" (M)						
S. D. Rough.	"						
U. of Mich. Prof.	"						
AASHO Prof.	SV	3.72	-0.036	-0.027	-2.75	0.42	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
CHLOE Prof.	SV						
CHLOE Prof.	$\sqrt{SV}$						
CHLOE Prof.	log (1+SV)						
Texas Texture	Texture						
S. D. Texture	"						
Kent'ky Accel.	Accel. Index (40)						
Kent'ky Accel.	Accel. Index (51.5)						
Kent'ky Accel.	Accel. Index (60)						

Table 7 Summary of Standard Errors and Correlation
Coefficients For AASHO Model Equations

Equipment Type	Rigid Pavements		Overlay Pavements		Flexible Pavements	
	St'd Error	Corr. Coef.	St'd Error	Corr. Coef.	St'd Error	Corr. Coef.
Roughometers *	0.41	0.92	0.13	0.99	0.30	0.91
U. of Michigan 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**	0.92**				
$\sqrt{SV}$	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 Pres. ***	0.37	0.95				

* Average for all roughometers

** Sections 6, 9a and 83 deleted for analysis

*** For all pavements

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 due to de-icing operations. Scaling of these pavements was correlative with other surface defects from the stand point of pavement age.

A second observation deals with 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 derived from combining two sets of data are presented in this section. 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.
- (2) Purdue--Nakamura.

Equations derived from regression analysis of the combined Purdue-AASHO Road Test data are presented in Table 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 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.

Table 8 Combined Equations--Purdue and AASHO Road Test

Data--AASHO Profilometer

$$p = A_0 + A_1 F + A_2 \sqrt{C + P} + A_3 \frac{RD^2}{RD}$$

Where:

p = Present Serviceability Index

A_0 = p intercept

A_1 = Constant

F = Function of equipment measurement

A_2 = Constant

A_3 = Constant

Pavement Type	F	Regression Equation Coefficients				Standard Error of Estimate	Correlation Coefficient
		A_0	A_1	A_2	A_3		
R *	$\sqrt{SV}$	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**	$\sqrt{SV}$	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

* Rigid pavements

** Combination of flexible pavement and overlay pavement data

Relationships Among Instruments

Equations which relate $\log (1 + SV)$, as measured by the AASHO Profilometer, with measurements obtained by other instruments are shown in Tables 9 through 12.

Method of Using Combined Equations With Equipment Equations

It is believed that equations appearing in Table 8 are the best available at the present time since 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 12 (on line 11)

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

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 PSI to the measurement of each piece of equipment with none of the other physical measurements in the equations. The results are reported in Tables 14 through 16.

The results show that the roughometers and profilometers, with the exception of the CHLOE profilometer on rigid pavement, predicted PSI with similar standard errors of estimate.

Table. 9 Equipment Equations for Rigid Pavements

$$(\log (1+SV))$$

$$\log (1+SV) = A_0 + A_1 F$$

where:

$\log (1+SV)$ = Data from AASHO Profilometer

A_0 = Intercept

A_1 = Constant

F = Function of equipment measurement

Equipment	Factor "F"	Coefficients		Std Error	Corr. Coeff.
		A_0	A_1		
Ind. Rough.	Roughness	-0.15	0.011	0.17	0.91
Ill. Rough.	"	-0.02	0.010	0.17	0.91
BPR Rough.	"	0.01	0.009	0.20	0.88
N.Y. Rough.	"	0.08	0.009	0.17	0.91
Tenn. Rough.	"	0.08	0.009	0.17	0.91
Mich. Rough.	"	0.29	0.0034	0.25	0.85
Mich. Rough.	Acceleration	0.13	0.0008	0.18	0.90
Minn. Rough.	Roughness (E)	-0.06	0.010	0.19	0.89
Minn. Rough.	" (M)	-0.13	0.011	0.18	0.90
S. D. Rough.	"	-0.005	0.010	0.19	0.88
U. of Mich. Prof.	"	0.29	0.005	0.18	0.90
AASHO Prof.	SV				
AASHO Prof.	$\sqrt{SV}$				
AASHO Prof.	$\log (1+SV)$				
CHLOE Prof.	SV				
CHLOE Prof.	$\sqrt{SV}$				
CHLOE Prof.	$\log (1+SV)$	-0.03	0.94	0.37	0.63
Texas Texture	Texture	0.90	0.124	0.32	0.62
S. D. Texture	"	0.92	0.102	0.34	0.57
Kent'ky Accel.	Accel. Index (40)	-0.47	0.003	0.14	0.94
Kent'ky Accel.	" " (51.5)	-0.14	0.002	0.25	0.79
Kent'ky Accel.	" " (60)	-0.28	0.002	0.27	0.75
CHLOE Prof.*	$\log (1+SV)$	0.32	0.68	0.16	0.87

* Sections 6, 9a and 83 deleted from analysis

Table. 10 Equipment Equations for Overlay Pavements

$$(\log (1+SV))$$

$$\log (1+SV) = A_0 + A_1 F$$

where:

$\log (1+SV)$ = Data from AASHO Profilometer

A_0 = Intercept

A_1 = Constant

F = Function of equipment measurement

Equipment	Factor "F"	Coefficients		Std Error	Corr. Coeff.
		A_0	A_1		
Ind. Rough.	Roughness	-0.12	0.010	0.20	0.91
Ill. Rough.	"	0.18	0.008	0.21	0.90
EPR Rough.	"	0.005	0.009	0.19	0.92
N.Y. Rough.	"	0.04	0.009	0.20	0.92
Tenn. Rough.	"	0.09	0.009	0.19	0.91
Mich. Rough.	"	0.44	0.002	0.24	0.87
Mich. Rough.	Acceleration	0.25	0.008	0.24	0.87
Minn. Rough.	Roughness (E)	0.15	0.008	0.21	0.90
Minn. Rough.	" (E)	0.17	0.009	0.25	0.85
S. D. Rough.	"	0.14	0.008	0.24	0.87
U. of Mich. Prof.	"	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.	$\log (1+SV)$	-0.42	1.31	0.17	0.94
Texas Texture	Texture	0.90	0.043	0.44	0.40
S. D. Texture	"	0.84	0.063	0.38	0.62
Kent'ky Accel.	Accel. Index (40)	-0.14	0.003	0.31	0.76
Kent'ky Accel.	" " (51.5)	-0.24	0.003	0.24	0.86
Kent'ky Accel.	" " (50)	-0.20	0.002	0.28	0.81

Table 11 Equipment Equations for Flexible Pavements

$$(\log (1+SV))$$

$$\log (1+SV) = A_0 + A_1 F$$

where:

$\log (1+SV)$ = Data from AASHO Profilometer

A_0 = Intercept

A_1 = Constant

F = Function of equipment measurement

Equipment	Factor "F"	Coefficients		Std Error	Corr. Coeff.
		A_0	A_1		
Ind. Rough.	Roughness	0.23	0.007	0.14	0.90
Ill. Rough.	"	0.31	0.007	0.13	0.92
BPR Rough.	"	0.28	0.007	0.15	0.89
N.Y. Rough.	"	0.28	0.007	0.14	0.91
Tenn. Rough.	"	0.28	0.007	0.14	0.91
Mich. Rough.	"	0.56	0.002	0.15	0.89
Mich. Rough.	Acceleration	0.49	0.0006	0.19	0.82
Minn. Rough.	Roughness (E)	0.29	0.006	0.14	0.90
Minn. Rough.	" (M)	0.25	0.007	0.14	0.91
S. D. Rough.	"	0.17	0.008	0.14	0.91
U. of Mich. Prof.	"	0.39	0.004	0.14	0.91
AASHO Prof.	SV				
AASHO Prof.	$\sqrt{SV}$				
AASHO Prof.	$\log (1+SV)$				
CHLOE Prof.	SV	0.70	0.016	0.13	0.92
CHLOE Prof.	$\sqrt{SV}$	0.28	0.171	0.11	0.94
CHLOE Prof.	$\log (1+SV)$	-0.23	0.994	0.10	0.95
Texas Texture	Texture	1.00	0.009	0.31	0.36
S. D. Texture	"	1.01	0.009	0.30	0.39
Kent'ky Accel.	Accel. Index (40)	0.11	0.002	0.16	0.88
Kent'ky Accel.	" " (51.5)	0.29	0.001	0.16	0.87
Kent'ky Accel.	" " (60)	0.36	0.0009	0.17	0.86

Table.1 Equipment Equations for Flexible and Overlay Pavements

$$(\log (1+SV))$$

$$\log (1+SV) = A_0 + A_1 F$$

where:

$\log (1+SV)$ = Data from AASHO Profilometer

A_0 = Intercept

A_1 = Constant

F = Function of equipment measurement

Equipment	Factor "F"	Coefficients		Std Error	Corr. Coeff.
		A_0	A_1		
Ind. Rough.	Roughness	0.11	0.008	0.17	0.89
Ill. Rough.	"	0.25	0.008	0.16	0.91
BPR Rough.	"	0.18	0.008	0.17	0.90
N.Y. Rough.	"	0.17	0.008	0.16	0.91
Tenn. Rough.	"	0.20	0.008	0.16	0.91
Mich. Rough.	"	0.50	0.002	0.18	0.88
Mich. Rough.	Acceleration	0.38	0.0007	0.20	0.84
Minn. Rough.	Roughness (E)	0.25	0.007	0.17	0.89
Minn. Rough.	" (M)	0.24	0.008	0.18	0.88
S. D. Rough.	"	0.16	0.008	0.17	0.89
U. of Mich. Prof.	"	0.42	0.004	0.17	0.89
AASHO Prof.	SV				
AASHO Prof.	$\sqrt{SV}$				
AASHO Prof.	$\log (1+SV)$				
CHLOE Prof.	SV	0.71	0.016	0.20	0.85
CHLOE Prof.	$\sqrt{SV}$	0.19	0.229	0.22	0.88
CHLOE Prof.	$\log (1+SV)$	-0.42	1.308	0.17	0.94
Texas Texture	Texture	0.99	0.010	0.35	0.34
S. D. Texture	"	0.99	0.011	0.35	0.40
Kent'ky Accel.	Accel. Index (40)	0.09	0.002	0.23	0.80
Kent'ky Accel.	" (51.5)	0.36	0.001	0.24	0.76
Kent'ky Accel.	" (60)	0.52	0.0008	0.27	0.69

Table 13 Comparison of standard Errors and Correlation Coefficients
of Equipment Equations for CHLOE Profilometer and Roughometer

Function of 44/SHO and CHLOE Profilometers	Instrument (CHLOE or Roughometer)	Rigid		Overlay		Flexible		Flexible & Overlay	
		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*	0.87*						
	Roughometer **	0.13	0.59	0.22	0.89	0.15	0.91	0.17	0.89
SV	CHLOE	1.56	0.70	0.74	0.95	0.53	0.97	0.74	0.95
		0.53*	0.91*						
	Roughometer **	0.93	0.90	0.63	0.96	0.67	0.89	0.72	0.87

* Sections 6, 9a and 83 were deleted from analysis

** Average for all roughometers

Table. 14 Equations for Predicting Serviceability Using
Instrument Measurements Only, Rigid Pavements

$$p = A_0 + A_1 F$$

where:

p = Present Serviceability Index

A_0 = Intercept

A_1 = Constant

F = Function of equipment measurement

Equipment	Factor "F"	Coefficients		Std Error	Corr. Coeff.
		A_0	A_1		
Ind. Rough.	Roughness	6.09	-0.025	0.42	0.90
Ill. Rough.	"	5.81	-0.024	0.40	0.91
BPR Rough.	"	5.78	-0.023	0.44	0.90
N.Y. Rough.	"	5.56	-0.021	0.41	0.91
Tenn. Rough.	"	5.61	-0.027	0.36	0.93
Mich. Rough.	"	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.	" (M)	6.05	-0.025	0.44	0.89
S. D. Rough.	"	5.81	-0.023	0.44	0.89
U. of Mich. Prof.	"	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	"	3.67	-0.290	0.72	0.68
Kent'ky Accel.	Accel. Index (40)	6.65	-0.007	0.47	0.88
Kent'ky Accel.	" " (51.5)	6.01	-0.006	0.63	0.77
Kent'ky Accel.	" " (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	0.8C

* Sections 6, 9a and 83 deleted from analysis

Table. 1. Equations for Predicting Serviceability Using
Instrument Measurements Only, Overlay Pavements

$$p = A_0 + A_1 F$$

where:

p = Present Serviceability Index

A_0 = Intercept

A_1 = Constant

F = Function of equipment measurement

Equipment	Factor "F"	Coefficients		Std Error	Corr. Coeff.
		A_0	A_1		
Ind. Rough.	Roughness	5.23	-0.019	0.40	0.89
Ill. Rough.	"	4.69	-0.015	0.40	0.89
BPR Rough.	"	4.98	-0.017	0.39	0.90
N.Y. Rough.	"	4.98	-0.018	0.32	0.93
Tenn. Rough.	"	4.88	-0.017	0.37	0.90
Mich. Rough.	"	4.29	-0.005	0.42	0.88
Mich. Rough.	Acceleration	4.58	-0.002	0.42	0.88
Minn. Rough.	Roughness (E)	4.76	-0.015	0.37	0.90
Minn. Rough.	" (H)	4.73	-0.016	0.46	0.85
S. D. Rough.	"	4.87	-0.015	0.38	0.90
U. of Mich. Prof.	"	4.36	-0.009	0.40	0.89
AASHO Prof.	SV	3.64	-0.004	0.46	0.85
AASHO Prof.	$\sqrt{SV}$	4.40	-0.350	0.38	0.90
AASHO Prof.	$\log (1+SV)$	4.82	-1.621	0.37	0.91
CHLOE Prof.	SV	3.69	-0.038	0.50	0.83
CHLOE Prof.	$\sqrt{SV}$	4.76	-0.431	0.42	0.88
CHLOE Prof.	$\log (1+SV)$	5.75	-2.326	0.37	0.91
Texas Texture	Texture	3.36	-0.073	0.82	0.35
S. D. Texture	"	3.44	-0.102	0.75	0.52
Kent'ky Accel.	Accel. Index (40)	5.39	-0.006	0.52	0.80
Kent'ky Accel.	" " (51.5)	5.53	-0.006	0.46	0.85
Kent'ky Accel.	" " (60)	5.49	-0.005	0.53	0.80

Table.10 Equations for Predicting Serviceability Using
Instrument Measurements Only, Flexible Pavements

$$p = A_0 + A_1 F$$

where:

p = Present Serviceability Index

A_0 = Intercept

A_1 = Constant

F = Function of equipment measurement

Equipment	Factor "F"	Coefficients		St'd Error	Corr. Coeff.
		A_0	A_1		
Ind. Rough.	Roughness	4.76	-0.015	0.28	0.91
Ill. Rough.	"	4.55	-0.015	0.29	0.91
BPR Rough.	"	4.67	-0.015	0.29	0.91
N.Y. Rough.	"	4.71	-0.016	0.28	0.92
Term. Rough.	"	4.64	-0.015	0.28	0.91
Mich. Rough.	"	4.10	-0.005	0.28	0.91
Mich. Rough.	Acceleration	4.28	-0.001	0.35	0.80
Minn. Rough.	Roughness (E)	4.62	-0.013	0.29	0.90
Minn. Rough.	" (M)	4.06	-0.015	0.31	0.89
S. D. Rough.	"	4.84	-0.016	0.31	0.89
U. of Mich. Prof.	"	4.41	-0.008	0.30	0.90
AASHO Prof.	SV	3.59	-0.045	0.40	0.81
AASHO Prof.	$\sqrt{SV}$	4.27	-0.372	0.38	0.83
AASHO Prof.	$\log (1+SV)$	4.83	-1.735	0.37	0.84
CHLOE Prof.	SV	3.74	-0.031	0.32	0.88
CHLOE Prof.	$\sqrt{SV}$	4.52	-0.330	0.32	0.88
CHLOE Prof.	$\log (1+SV)$	5.44	-1.877	0.34	0.86
Texas Texture	Texture	3.05	-0.013	0.66	0.25
S. D. Texture	"	3.10	-0.017	0.64	0.36
Kent'ky Accel.	Accel. Index (40)	5.01	-0.005	0.32	0.88
Kent'ky Accel.	" " (51.5)	4.65	-0.003	0.32	0.88
Kent'ky Accel.	" " (60)	4.49	-0.002	0.34	0.87

Table 17 Summary of Standard Errors and Correlation

Coefficients for Equations Using Equipment Only.

Equipment Type	Rigid Pavements		Overlay Pavements		Flexible Pavements	
	St'd. Error	Corr. Coef.	St'd. Error	Corr. Coef.	St'd. Error	Corr. Coef.
Roughometers*	0.40	0.90	0.38	0.90	0.29	0.91
U. of Michigan 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

* Average for all roughometers

Slope Variance and Roughness Combined with Texture

Table 18 presents serviceability equations (based on the AASHO model) but with texture added to the equations. Addition of the texture term raised the correlation coefficients a small amount and resulted in decreased errors of estimate. The changes, however, were in general small for the pavements included in this study.

Table 19 shows equipment equations which relate $\log (1 + SV)$ with CHLOE and roughometer readings with the texture term added to each.

Table 18 Serviceability Using Slope Variance and Roughness
Combined With Texture

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

Pave. Type	Equipment	F	A ₀	A ₁	A ₂	A ₃	A ₄	St'd. Error	Corr. Coef.	St'd. Error*	Corr. Coef.*
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	-1.33	-1.82	-0.14		0.51	0.87	0.67	0.75
	Rough. **	Roughness	6.03	-0.019	-0.91	-0.09		0.33	0.95	0.41	0.91
O	AASHO	$\sqrt{SV}$	4.63	-0.28	-0.05	-0.03	-4.31	0.21	0.9	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	$\log(1 + SV)$	5.83	-2.01	-0.38	-0.03	-14.29	0.14	0.99	0.18	0.98
O	Rough. **	Roughness	4.99	-0.012	-0.02	-0.11	2.28	2.28	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. **	Roughness	4.87	-0.016	-0.11	-0.004	+0.25	0.33	0.90	0.32	0.89

* Standard error and correlation coefficient for similar AASHO Model equation but without the texture term.

** South Dakota Roughometer

Table 19 AASHO, Profilometer $\log (1 + SV)$ in Terms of Texture Readings plus CHLOE $\log (1 + SV)$, or Roughometer Readings

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

where:

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

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

Pave. Type	"F" CHLOE or Roughometer	A ₀	A ₁	A ₂	St'd. Error	Corr. Coef.	St'd Error*	Corr. Coef. *
Rigid	$\log (1 + SV)$ Roughness	0.019 0.021	0.79 0.010	0.41 0.04	0.36 0.30	0.66 0.87	0.37 0.19	0.63 0.88
Overlay	$\log (1 + SV)$ Roughness	-0.49 0.15	1.24 0.006	0.31 0.54	0.14 0.21	0.96 0.91	0.17 0.24	0.94 0.87
Flexible	$\log (1 + SV)$ Roughness	-0.22 0.11	1.06 0.007	-0.03 0.14	0.10 0.13	0.95 0.93	0.10 0.14	0.95 0.91
Flexible And Overlay	$\log (1 + SV)$	-0.20	1.11	-0.12	0.15	0.92	0.17	0.94

* Standard error and correlation coefficient for similar equation but without the texture term.

DISCUSSION

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 discussion which follows deals in part with general concepts of pavement condition rating.

Factors Influencing Serviceability Rating

A question often poses by paving engineers is "What factors should be considered when setting up serviceability equations?" Carey and Irick in their original work (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. These methods are listed below:

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. This is 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 axis solution. A summary of the significant factors is shown in Table 20.

The factors listed in Table 20 were identified by assigning to each a descriptive name. It was difficult to interpret the third factor shown in Table 20; the remaining factors, however, 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. It is interesting to note, in Table 20, that rating has the same algebraic sign as bleeding and bituminous patching and the opposite sign of the roughometer, profilometer and texture readings. It is apparent that "smoothness" (both macro and micro) are desirable properties in so far 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 21. Also given in this Table are correlation coefficients (correlative with Present Serviceability Rating) which are greater than these minimum values.

It is significant to note from Table 20, as well as from the correlation matrices, that the major factors which influence serviceability

Table 20 Summary of Factor Analysis

Factor	Latent Root	Element	Factor Loading
Longitudinal Distortion (Flexible Pavements)	13.7410	Roughometer U. of Mich. Prof. Kt'ky Accel. AASHO Prof. Texture Rating Flex. pave.	0.8935 0.8876 0.8649 0.7040 0.5970 -0.8481 0.5556
Longitudinal Distortion (Rigid Pavements)	9.3556	Roughometer U. of Mich. Prof. Kt'ky Accel. AASHO Prof. Rating Long. fault Trans. fault Rigid pave.	0.5022 0.3360 0.5622 0.4097 -0.3075 0.6570 0.8260 0.7674
Maintenance	3.5149	Roughometer Texture Ave. fault Rating Rigid pave. Overlay pave. Flex. pave.	-0.1414 0.4219 0.4319 0.1192 0.0622 -0.6587 0.5268
Transverse Distortion	2.6093	Ave. rut depth Roughometer Rating Ave. Long. fault	0.5157 0.0288 -0.2223 0.4178
Micro-Roughness	2.2198	Rating Major bleeding Bit. patching Sealed cracks Un-sealed cracks Texture reading	-0.1019 -0.5127 -0.5634 -0.2789 0.4516 0.2984

Table 21 Summary of Simple Correlation Coefficients

(a)

Pavement Type	Absolute Minimum Value of Coef.
Rigid	0.35
Overlay	0.37
Flexible	0.30

(b)

Physical Measurement	Coefficient
Average transverse fault	-0.80
Blowups	-0.74
Bituminous patching	-0.65
No. of joints	0.65
Maximum transverse fault	-0.61
Average longitudinal fault	-0.40
Cracking and patching	-0.37

(c)

Physical Measurement	Coefficient
Maximum rut depth	-0.90
Bituminous patching	-0.69
Average rut depth	-0.63
Cracking and patching	-0.63

(d)

Physical Measurementt	Coefficient
Maximum rut depth	-0.74
Bituminous patching	-0.57
Bleeding *	-0.69

(a) Minimum correlation coefficient for 90% probability that coefficient is nonzero.

(b) Coefficients for rigid pavement

(c) Coefficients for overlay pavements

(d) Coefficients for flexible pavements.

* Sum of major, intermediate, and minor bleeding.

rating are longitudinal 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 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 users 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 later 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, pavement color, etc.) in the variables under study. No significant effects of these variables were apparent.

Table 22 shows the mean rating of individuals that rode in the rear seat of the automobile compared to the mean rating of those that rode in the front seat. Since there is little difference among ratings assigned

Table 22 Mean Ratings vs Position in Automobile
(H.R.B. Committee Panel)

Position of Rater in Automobile	Mean Ratings		
	Rigid pavements	Overlay pavements	Flexible pavements
Right-front	3.02	3.11	2.71
Right-rear	3.06	3.12	2.71
Left-rear	3.00	2.90	2.70
Mean of all raters in panel	3.03	3.05	2.71

from various positions in the automobile, it appears that the raters ability to see the pavement had little, if any, influence on his rating.

The major importance of slope variance (or roughness) is demonstrated further in Table 23. Here it is seen that 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. These results are shown in column 7 of Table 23. Considering the data as a whole, there appears to be no need to change the mathematical models originally proposed by Carey and Irick (see Table 24).

Comparison of Equipment

From previous discussions it is apparent that good correlations can be obtained between rating and variety of physical measurements. Observation of Tables 7 and 17 indicates 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 roughometer yielded consistently good results on all types of pavement. The above observation, coupled 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.

Table 23 Comparison of Various Equation Models with the AASHO Model

Pave. Type	Term	Regression Coefficients						
		AASHO (1)	Model (2)	(3)	(4)	(5)	(6)	(7)
Rigid	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
	Blowups			-0.58	-0.61			-0.68
	Ave. tran. fault			-3.68	-3.33			-4.36
	Ave. 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
Over- lay	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
	$RD^2 *$	-4.17		-4.49	-2.59			-22.0
	Standard error	0.19	0.09	0.31	0.31			0.46
Flex.	Correlation Coeff.	0.98	0.99	0.95	0.95			0.86
	Intercept	4.29	4.73	4.27	4.87	4.60	4.03	3.34
	Roughness		-0.015		-0.016	-0.01		
	$\sqrt{SV}$	-0.36		-0.35			-0.28	
	$\sqrt{C + P}$	-0.01	0.004	-0.01	-0.03			
	$\sqrt{P}$					-0.04	-0.08	-0.11
	$RD^2 **$	-0.33	-0.26	-0.33	-4.31	-1.52		-2.81
	Texture log (1+T)			0.62	-0.05			
	Bleeding					-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

Note: Blowups and bleeding are in square feet of area per 1000 square feet of pavement, faults are in inches and other terms are same as for AASHTO equations.

* Average of rut depth in right and left wheel paths

** Average of rut depths in right and left wheel paths for AASHO Model

(Col. 1 and 2); for the equations in col. 3 thru 7, rut depth is right wheel path only.

*Physical
exp.*

*IF
RD
Blow*

Table 24 Examples of Possible Transformations

	Equipment Function "F"	Function of)	Pave. Type	A ₀	A ₁	A ₂	A ₃	St'd Error	Corr. Coef.
Combined Serviceability	AASHO log (1 + SV)	p log p	R	5.51 0.89	-1.88 -0.35	-0.08 -0.01		0.31 0.07	0.96 0.93
				4.95 0.79	-1.83 -0.32	-0.01 -0.002	-1.34 +0.20	0.36 0.07	0.89 0.90
p vs function of roughness (R) as measured by Ind. Roughometer	R log R	p	R	6.09 17.71	-0.025 -7.13			0.42 0.43	0.90 0.90
				5.23 14.09	-0.019 -5.41			0.40 0.40	0.89 0.91
				4.76 11.58	-0.015 -4.20			0.28 0.29	0.91 0.90
Equipment using R to predict log (1 + SV) as measured by AASHO Prof.	R log R	p	F						
				-0.15 -5.40	0.011 3.2			0.17 0.25	0.91 0.85
				-0.12 -5.59	0.010 3.28			0.20 0.14	0.91 0.96
Equipment using R to predict log (1 + SV) as measured by AASHO Prof.	R log R	y value is log (1 + SV)	O						
				0.23 -3.11	0.007 2.05			0.14 0.13	0.90 0.91

The University of Michigan Profilometer produced excellent results throughout the testing program. Records which show change in pavement profile, as a function of 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 used in this study 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. It appears worthy to note that 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, yielded 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 of this report 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 13 shows a comparison of 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. The same can be said 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.

SUMMARY

The following paragraphs will summarize the major items of this research project. 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 were developed so that each state cooperating in the study could compare their own instrument with those from other agencies.

A. Rating Panels

1. A study of variance of 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. The reasons for this are unknown.

B. Serviceability Equations From This Study.

1. Serviceability equations using the AASHO mathematical model were developed for each piece of equipment. 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. These equations showed, in general, lower correlation coefficients and higher errors of estimate than the AASHO model equations.

C. Combined AASHO Model Serviceability Equations and Equipment Equations.

1. Data from this study were combined with data obtained in connection with the AASHO Road Test (Table 13). Equations comparing measurements by each instrument with various functions of slope variance determined by the AASHO Slope Profilometer were developed.
2. The combined Purdue-AASHO serviceability equations are for two pavement types, (1) rigid and (2) 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.

D. Combined Roughometer Serviceability Equations and Equipment Equations.

1. Data obtained with the Indiana Roughometer in this study were combined with those previously reported by Nakamura and Michael. The Relationship between the Indiana Roughometer and other instruments was determined.
2. The above 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 those 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.

E. 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 of this study indicated that this transformation did not increase the precision of prediction a significant amount.
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.

F. Equipment

1. The results of the field tests made during this study indicated that, from the standpoint of precision of predicting serviceability, little difference existed among the various instruments.

2. On the basis of the above, 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 profiles and/or slope variance. The Kentucky Accelerometer device 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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Appendix
(Figures 1 through 14)

Figure 1. Portions of typical field maps.

Figure 2. Bureau of Public Roads Roughometer.

Figure 3. AASHO Slope Profilometer. Note the double set of wheels used to measure slope variation and the calibrated odometer wheel.

Figure 4 CHLOE Profilometer. A single set of wheels are used to measure slope variation.

Figure 5. Texture meter. Note the prongs, dial, and deformable ribbon.

Figure 6. Kentucky accelerometers mounted on passenger's chest.

Figure 7. University of Michigan Profilometer.

Figure 8. Purdue tire pressure device mounted on test vehicle.

SECTION NO.		HIGHWAY NO.		
PAVE. TYPE	Vehicle	Date	a.m. p.m.	Rater

5 — **Very Good**

4 — **Good**

3 — **Fair**

2 — **Poor**

1 — **Very Poor**

0 —

Acceptable	
Yes	
No	
Doubtful	

Influence of behavior elements on present serviceability rating.

Longitudinal Distortion	NO INFLUENCE	MINOR INFLUENCE	APPRECIABLE INFLUENCE	PRONOUNCED INFLUENCE
Transverse Distortion				
Cracking				
Faulting				
Surface Deterioration				

Remarks: _____

Figure 9. Rating card.

Figure 10. Variance of mean panel ratings.

Figure II. Example of Individual Ratings vs. Mean Panel Ratings.

Figure 12. Comparison of professional and lay panels.

Figure 13. Acceptability vs. mean rating.

Figure 14. AASHO Profilometer Slope Variance vs. CHLOE Slope Variance, Rigid Pavements.