PAVEMENT SERVICEABILITY EQUATIONS USING THE SURFACE DYNAMICS PROFILOMETER

by

Freddy L. Roberts
W. Ronald Hudson

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Development of a System for High-Speed Measurement of Pavement Roughness

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

PREFACE

This is the third in a series of reports covering the results of Research Project No. 3-8-63-73, "Development of a System for High-Speed Measurement of Pavement Roughness." The project was initiated in 1963 for the purpose of evaluating the existing roughness measuring devices and providing to the sponsors a recommendation as to the best existing system for accurate measurement of road profiles. In the first report, Research Report No. 73-1, "High-Speed Road Profile Equipment Evaluation," the General Motors Road Profilometer was recommended and after authorization from the Bureau of Public Roads a contract was initiated with the company licensed to manufacture it.

The profilometer, called the Surface Dynamics (SD) Profilometer, was manufactured by K. J. Law Engineers, Inc., and was delivered to the Texas Highway Department on February 6, 1967. Evaluation began immediately and Research Report No. 73-2, "A Profile Measuring, Recording, and Processing System," provides a detailed analysis of the measurement system, description and evaluation of the recording and processing systems, a calibration and operational procedure for obtaining accurate road profiles, and a method for validating the recorded profile data.

To correlate the roughness measurements made with the SD Profilometer to the subjective opinion of the highway user, a series of rating sessions were conducted. A preliminary rating session was conducted to orientate the raters to the rating procedures and to operate the profilometer under field conditions. After analysis of these data, two additional rating sessions were conducted to obtain additional data for the correlation studies. The profilometer data were summarized and the relationships between rater opinion and quantitative roughness data were derived. This report contains these evaluations and presents equations for predicting present serviceability from roadway roughness and condition survey variables.

Freddy L. Roberts

W. Ronald Hudson

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LIST OF REPORTS

Report No. 73-1, "High-Speed Road Profile Equipment Evaluation," by W. Ronald Hudson, presents a review of existing roughness measuring equipment and recommends the GM Profilometer as the most promising of all available equipment for high-speed profile measurements.

Report No. 73-2, "A Profile Measuring, Recording, and Processing System," by Roger S. Walker, Freddy L. Roberts, and W. Ronald Hudson, presents a description of the Surface Dynamics Profilometer profile measuring system, an operating procedure for use with the equipment, and a system analysis procedure for validation of the profile data.

Report No. 73-3, "Pavement Serviceability Equations Using the Surface Dynamics Profilometer," by Freddy L. Roberts and W. Ronald Hudson, presents a brief description of the measuring system, a complete description and analysis of three rating sessions, and the development of equations relating the mean panel rating to various summary statistics. Equations for predicting PSI for both flexible and rigid pavements are presented.

Report No. 73-4, "Analog-to-Digital System," by Roger S. Walker, and W. Ronald Hudson, describes the Hewlett-Packard 2115 computer analog-to-digital computing facility.

ABSTRACT

The riding quality of a highway pavement is of concern to the highway administrator, the design engineer, and the maintenance engineer as well as the traveling public. In an attempt to relate riding quality to measurable roadway characteristics at the AASHO Road Test, Carey and Irick developed the present serviceability-performance concept and established equations relating subjective riding quality to these measurable roadway characteristics. Such a technique was used in this study to relate present serviceability rating (PSR) to roughness measured with the Surface Dynamics (SD) Profilometer and condition survey information.

The SD Profilometer is a vehicle containing all the necessary sensors for producing a road profile. The measuring system consists of (1) a set of two road-following wheels, one in each wheel path; (2) two vertically mounted potentiometers, one connected between each road-following wheel and the vehicle body; (3) two accelerometers, one mounted inside the vehicle directly above each potentiometer; and (4) a special purpose analog computer with two independent circuits, one for each of the two profiles. The computer integrates the accelerometer signal twice and adds it to the potentiometer signal to produce a road profile for each wheel path.

A rating panel was selected to evaluate the riding quality of the selected pavements. In a preliminary session the panel rated 17 sections to provide data for checking out the complete measurement and analysis system. Two subsequent rating periods were conducted in two different topographical areas of Texas to allow a large inference space for the results of the study.

The rating data collected during these periods were analyzed using analysis of variance techniques. It was concluded that the average of all raters could be used to represent the riding quality of the pavement. From the SD Profilometer runs, summary statistics were computed and analyzed to help determine significant parameters. Finally, a set of regression equations were developed which related three different summary statistics and the condition survey variables to the average PSR of the test sections. Equations were developed to use profile data from both wheel paths as well as only one wheel path in the case of instrumentation problems. The equations can be used with confidence to evaluate pavement serviceability.

KEY WORDS: Surface Dynamics (SD) Profilometer, analysis of variance, present serviceability index (PSI), regression analysis, riding quality, slope variance, roughness index, pavement roughness, profile, pavement condition.

SUMMARY

This report describes in detail the procedures involved in conducting a rating session, the orientation of panel members, the selection of sections and routes, and finally the recording of profile and condition survey data necessary to relate the subjective opinion of a panel of typical road users to measurable roadway characteristics. The description of summary statistics used to represent the longitudinal and transverse profiles with two numbers is included, as well as the necessary transformations for linearizing these data for use in linear regression programs. Finally, two equations are recommended for use with the SD Profilometer, one each for flexible and rigid pavements. An idea of the accuracy of the predictive equation for flexible pavements is found by comparing PSR (Pavement Serviceability Rating) for the preliminary rating session sections with the predicted value using the developed equation. An additional check on the predictive quality of the equations for both flexible and rigid pavements is made by comparing the correlations of ratings given at two different times by the panel on 10 sections with the predicted ratings from the developed equations. This check shows that the equations are about as accurate as the panel of raters in predicting the second rating value.

The profile measurements are very accurate but are expensive to obtain and analysis is very time consuming. However, the magnitude of these problems might be decreased considerably if the present sensors were replaced with some type of noncontact probe. The predictive ability of the equations would be refined if these problem areas were minimized.

Continued use of the equipment will help eliminate problems. For example, the electrical noise problem has been greatly reduced by relocating the tape-recorder and laying it on an inflated mat. The photocell noise was eliminated by installing a switch which breaks the circuit between the photocell and the Brush strip-chart recorder after the begin-of-section mark is sensed.

IMPLEMENTATION STATEMENT

The equations developed for predicting present serviceability rating may be used with data obtained with the SD Profilometer for any road in Texas. Because the profilometer data can be used to predict PSR values as accurately as the raters, but more conveniently, the profilometer can be used instead of a large panel. The profilometer provides a more economical method of determining PSR than does the rating panel. These PSI values might be used to help establish priorities for scheduling of maintenance by estimating the riding quality of the pavements.

An important use of PSI data is the continued surveillance of pavement sections to obtain feedback information for improved pavement maintenance and management functions. The use of such data is vital to modern systems analysis of the pavement (Ref 29).

In view of the trouble and expense of using the SD Profilometer in its present configuration, consideration should be given to using it as a calibration device to check the continued accuracy and correlation of several less expensive devices, such as the Mays Road Meter. This aspect of the problem is currently being investigated in the project.

The data from the SD Profilometer can be used in other studies where road profile data are required. One such study is the prediction of dynamic loads on the pavement caused by a vehicle passing over the road. The digitized profile measurements are input for the predictive model. An inquiry from the California Highway Department indicated that the analog profiles could be used to locate and measure step-offs of construction joints. This information could be provided to contractors who were bidding on resurfacing work.

There are also any number of special studies for which profile evaluations might be helpful. These could involve either the use of the PSI values or the analog or digital profile data. One such study might involve the effect on riding quality of the long waves produced by swelling subgrade soils. Profile measurements could be made before and after these occurrences to determine their effect on riding quality.

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TABLE OF ABBREVIATIONS

AASHO	American Association of State Highway Officials
ANOVA	analysis of variance
AR	all raters
A-D	analog to digital
C	cracking
CFHR	Center for Highway Research
CPCR	concrete pavement continuously reinforced
CPJR	concrete pavement jointed reinforced
D	duplicates
DAP	Data Analysis Program (Appendix 5)
DN	day versus night
df	degrees of freedom
ELV	elevation variance
F	filter
HMAC	hot mix asphaltic concrete
IPSR	individual present serviceability rating
MS	mean square
P	patching
PCC	portland cement concrete
PSI	present serviceability index
PSR	present serviceability rating
PT	pavement type
R	rater(s)

RD	rut depth
RDV	rut depth variance
RI	roughness index
Ro	roughness variable
S	section(s)
SD	surface dynamics
Sp	vehicle speed
SS	sum of squares
ST	surface treatment
STEP01	Stepwise Regression Program (Ref 10)
STy	surface type
SV	slope variance
T	texture
TLR	true length ratio
XSV	cross slope variance

CHAPTER 1. INTRODUCTION

For a number of years engineers have been interested in evaluating the riding quality of highways in an objective manner. Before the AASHO Road Test, no method was available for accomplishing this evaluation. However, during the planning for the AASHO Road Test the serviceability-performance concept was developed and reported by Carey and Irick (Ref 5). This serviceability concept serves as a basis for most current pavement rating systems and is based on the following assumptions:

(1) The primary function of a highway is to serve the public by providing a safe, comfortable, and convenient mode of transportation.

(2) The opinion of a user as to how he is being served is subjective, and, therefore, the developed concept must not be purely objective.

(3) There are characteristics of the highway which can be measured objectively which, when expressed properly, are related to the subjective opinion of the user.

(4) The serviceability of a particular highway is adequately determined by the mean evaluation expressed by all its users.

(5) Performance is the history of the serviceability with respect to applications of wheel load or time, i.e., the performance of a pavement may be described by observing the serviceability trend from construction until the time in question.

Using these assumptions, a serviceability-performance concept was developed which describes the relationship between the subjective opinion of road users and a set of objective measures of pavement roughness and deterioration. These objective measures would be (1) outputs from the available roughness measuring devices which had been developed to respond to pavement longitudinal roughness and (2) deterioration of the pavement surface such as cracking, patching, and rutting in the wheel paths. Several terms were given specific definitions for use in the serviceability-performance concept.

(1) Present serviceability: the ability of a particular pavement to serve high-speed, high-volume, mixed traffic in its present condition.

(2) Individual present serviceability rating (IPSR): an independent opinion of the present serviceability by a rater for a particular roadway section.

(3) Present serviceability rating (PSR): the mean of the individual ratings made by a panel of raters for a particular roadway section.

(4) Present serviceability index (PSI): a mathematical function which relates measured roadway characteristics to panel ratings and which is used to predict the PSR for any pavement within the prescribed limits.

To determine the subjective opinion of the test sections built at the AASHO Road Test, a panel of 15 members was formed. The average rating value for any test section was determined by averaging the individual present serviceability rating (IPSR) value given by each of the 15 members based on a linear scale from zero to five. A road with a PSR of zero could be considered impassable while a road with a PSR of five is perfect. After establishing the rating scale, in order to develop a relationship between the subjective opinion of the panel and the objective measurements made with the various roughness measuring devices and cracking, patching, and rutting, the AASHO panel of raters was asked to rate pavements located in Illinois, Indiana, Minnesota, and at the Road Test, which had a wide range of riding quality. The objective measurements were made on these same test sections. A model for predicting the rating values of the panel, called present serviceability index (PSI), was developed at the AASHO Road Test. These equations contained terms which represented profile measurements taken with the AASHO Profilometer. Subsequently, quantitative measurements made with other equipment including the BPR Roughometer (Ref 21) and the CHLOE Profilometer (Ref 4) were correlated with those from the AASHO Profilometer. The CHLOE Profilometer was developed at the Road Test to provide the states with a relatively simple instrument which would approximate measurements made by the sophisticated AASHO Profilometer.

Both the BPR Roughometer and the CHLOE Profilometer suffer severe limitations for operating on the high-speed highways today. The CHLOE must operate at approximately 3 miles per hour which makes operation hazardous on most highways. Both the CHLOE and the BPR Roughometer, which operates at speeds up to 50 miles per hour, output a single number representing the roughness for one test run over a section. This form of output is not nearly as useful as a continuous signal representing the road profile. Other devices which have been developed since the AASHO Road Test, such as the Kentucky Accelerometer (Ref 40) and the Portland Cement Association (PCA) Road Meter (Ref 45), suffer from similar limitations, either in the accuracy of the roughness measurements or in speed of operation (Ref 19).

The equipment that seemed to offer the best combination of accuracy and high operating speed was the General Motors Road Profilometer. This device was developed at the General Motors Research Laboratory (Ref 43) to provide quantitative information for the design of the suspension systems for General Motors automobiles. This device is presently known as the Surface Dynamics (SD) Profilometer. The Texas Highway Department was the first purchaser of the device from K. J. Law Engineers, Inc., the manufacturer (Ref 19).

In order to use the SD Profilometer to evaluate Texas highways it was necessary to develop serviceability equations relating the SD profile to present serviceability rating. The purpose of this report is to describe the development of such equations.

The work plan for this study was as follows:

(1) to form a rating panel consisting of members who were representative of typical road users in Texas,

(2) to select a group of pavement sections of various quality for ratings by the panel and for obtaining SD Profilometer data,

(3) to evaluate the rating data to determine if the mean value of the raters can be used to represent the present serviceability rating of each pavement section,

(4) to develop computer programs to summarize the profile data from the SD Profilometer into a single number for use in regression analyses,

(5) to develop equations for relating the PSR values to the summary statistics from the SD Profilometer data and the deterioration measurements for these selected pavement sections, and

(6) to determine the validity of the derived equations by obtaining additional data to check the predicted present serviceability rating with the value given by a small group of the original raters.

CHAPTER 2. DESCRIPTION OF THE MEASURING AND RECORDING SYSTEM

The SD Profilometer is a device developed by the General Motors GM Research Laboratory in Warren, Michigan, and manufactured under license from GM by K. J. Law Engineers, Inc. of Detroit, Michigan.

Sensors

The profilometer itself (Fig 1) is completely contained within a panel truck and can operate on any paved surface. The measuring system consists of (1) a set of two road wheels, one in each wheel path directly in line with the vehicle wheels; (2) two potentiometers, each connected at the bottom to a yoke extended from the trailing arm directly above the center of a road wheel and at the top to the vehicle body; (3) two accelerometers, each mounted inside the vehicle directly above the top of the potentiometer; and (4) a special purpose analog computer with two independent circuits, one for each of the two profiles which integrates the accelerometer signal twice and adds it to the potentiometer signal to produce a road profile for each wheel path (Fig 2).

Each road wheel is mounted on a trailing arm beneath the vehicle and is held in contact with the road by a 300-pound force exerted through a torsion bar. These two independent torsion bars are mounted in a housing beneath the vehicle. The truck mass and the suspension system form a mechanical filter between the road and the accelerometers. The relative motion between the road surface and the vehicle body is measured with the potentiometers while the accelerometers measure the vertical acceleration of the vehicle body. The resulting road profile is expressed by the following function:

$$w_{uf} = (w - z) + \ddot{z}dtdt \qquad (1.1)$$

where

w = relative displacement between the road wheel and the vehicle body,

z = displacement of the vehicle body,

Fig 1. Surface Dynamics Profilometer.

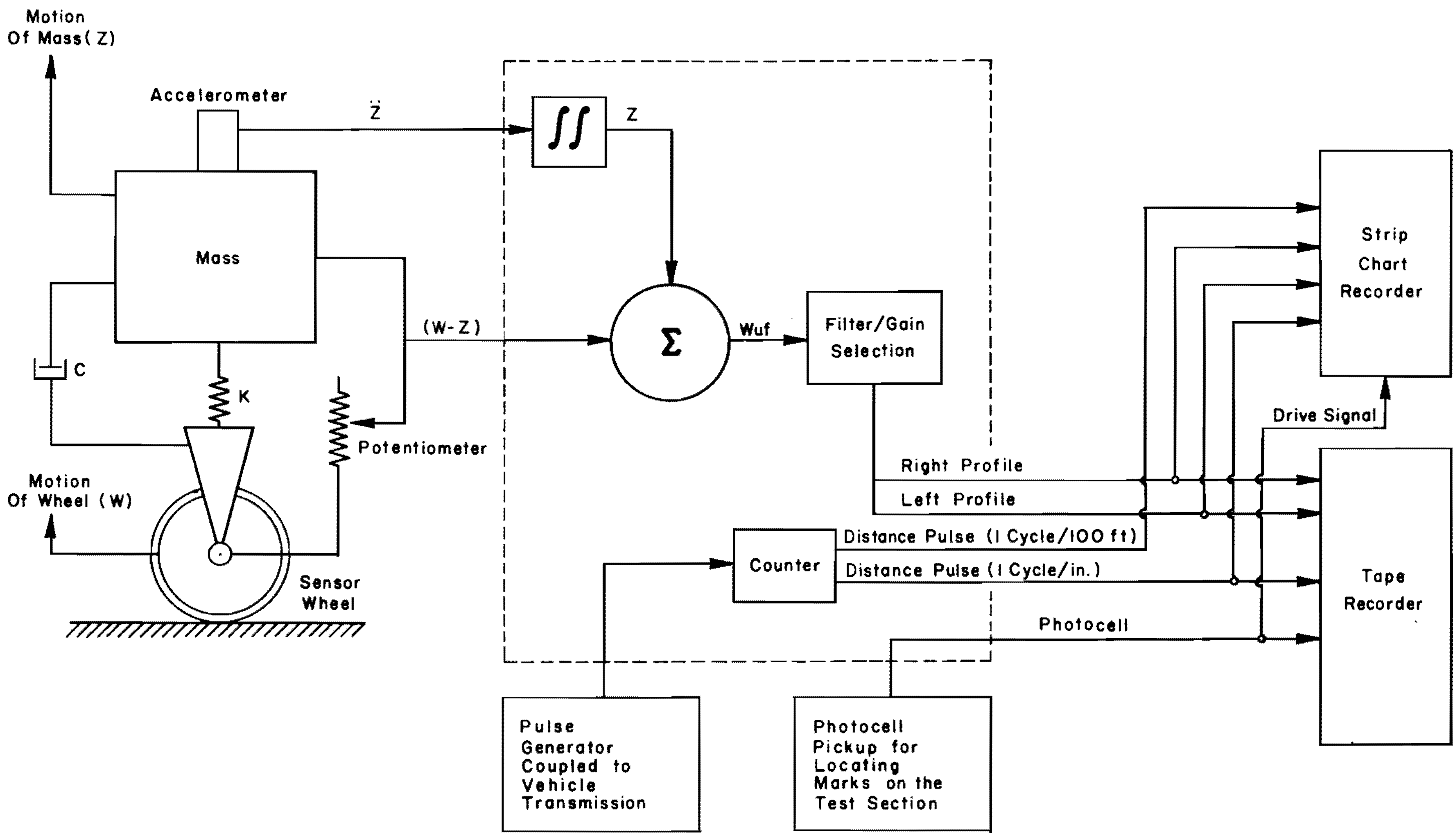


Fig 2. Detailed block diagram of measurement system.

$\ddot{z}$ = acceleration of the vehicle body,

w_{uf} = unfiltered road profile.

Profile Computer

The special purpose analog computer in the profilometer vehicle integrates Eq 1.1. However, problems are encountered when the acceleration values become very small (if they are of sufficient duration, such as a hill, and near the filter cutoff frequency) because the amplifiers in the integration circuitry become saturated (the output from integration increases without bound). The amplifiers no longer provide a meaningful signal. To overcome these problems, an active filtering system incorporated into the profile computer attenuates the long wavelengths in proportion to their amplitude for frequencies smaller than a specified value. This cutoff point is a function of the high-pass filter selection made on the analog computer before the data run (a single pass over a test section) is made. However, even with the four high-pass filter selections and an active filtering system, long wavelength or low frequency components of high amplitude and long time saturate the integrator amplifiers. To minimize these detrimental effects from this an overload circuit was incorporated to short the integrating capacitors and reinitialize the system. The profile signal during this overload period and for a short time thereafter is erroneous. The time period required to obtain stable readings is dependent upon the rate of change of the integrating capacitors, which is a function of the road profile.

System Frequency Response

The frequency response of the total system is shown in Fig 3. It should be noted that for all filter selections, the low-pass filter cutoff point is the same for all filter selections although the high-pass filtering cutoff point is different for four filters. The filter selection directly reflects the wavelength at which the amplitude of the input signal begins to attenuate, but before the attenuation point is reached on the response curve, the phase angle shift for the long wavelengths begins to increase. A phase angle shift affects the data by shifting the effect of long wavelength high-amplitude signals forward into the profile, causing distortions in the data if any of these wave forms occurs in the approach to the test section of interest. In the same manner, if these long wavelengths occurred within the test section, they

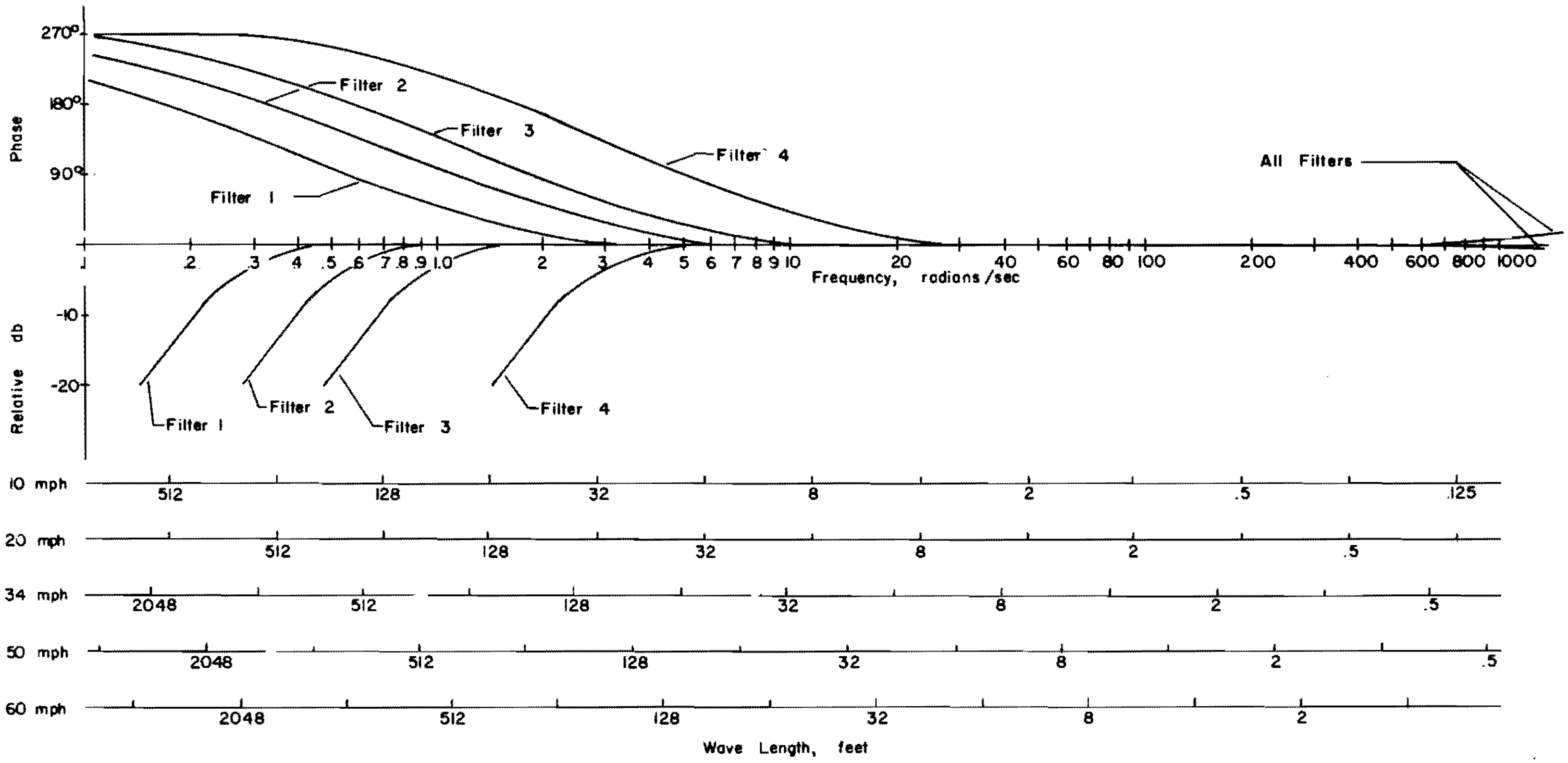


Fig 3. System frequency response.

could be shifted forward outside the limits of the recorded data. These possibilities then restrict the lower limit on the frequency range which can be considered as part of the roughness associated with the 1200-foot test sections run in this study. For example, if Filter 1 at 34 miles per hour is selected for running a 1200-foot section which has a 500-foot wave just before the section, this 500-foot wave will be shifted about 90° forward and the last 125 feet of the wave would occur within the test section. If this same 500-foot wave occurred within the test section starting at 700 feet from the beginning, it would be shifted 125 feet, or one-quarter of the wave would be shifted completely out of the test section.

System Outputs

All output signals from the profile computer are voltages in analog form. These signals are recorded on a Honeywell 8100 FM tape recorder. The right and left profiles, a photocell signal, and 100-foot markers are displayed visually on a Brush strip-chart recorder, which has an optional drive. It can be operated from a 500-cps time base or from a signal generated by the vehicle transmission as a distance base. The time base is required for recording calibration signals for the sensing units. The data runs are always recorded using the distance base, which ties the recorded data physically to distance along the pavement surface. The start of a test section is recorded by the photocell, which senses a reflective strip previously placed on the pavement signifying the beginning of the test section.

The output signals recorded on the FM tape recorder are

(1) right profile data,
(2) left profile data,
(3) photocell signal,
(4) pulses from the pulse generator,
(5) tape recorder ground, and
(6) audio instructions and information.

Calibration Signals

Two calibration signals are recorded for each test section. These signals are used to provide scaling and filter information. The scale factor is established by inducing a voltage comparable to 1 inch of displacement at the pavement surface. This value is used to transform the profile voltage data, from voltage to inches of displacement. An additional calibration signal is provided to excite the system with a voltage pulse comparable to a 1-inch impulse displacement. The free response of the computer filtering system results. The high-pass filter selection may be checked by observing (1) the time required for the voltage to decrease to zero and (2) the maximum amplitude of the response curve after it crosses the zero voltage line. Switches for performing both these calibrations are provided on the front of the profile computer (Fig 4).

The vehicle has an automatic speed control system for maintaining constant speed. The speed control, which is commercially available, operates from the throttle. The driver has a speed error indicator for monitoring speed variations. A full-scale excursion of the speed error indicator corresponds to a ±0.5 mile per hour variation. An audio speed error indicator is also available. The intensity of the audio signal increases as the speed error increases. The six speed selections (10, 20, 34, 40, 50, and 60 miles per hour) on the profile computer provide a reference for the speed error indicator so that adjustments can be made in the cruise control for desired speeds.

Because of the large quantity of data generated during only one pass of the SD Profilometer over a roadway, automatic data handling techniques were considered essential. These techniques are briefly described below and in detail by Walker et al (Ref 47).

Analog-to-Digital System

The A-D system is used to sample the analog profile signals at a specified rate to provide digital values for digital analysis techniques.

Components

The major components for the A-D operation and their tasks are

(1) Honeywell 8100 FM tape recorder for data playback,

(2) Hewlett-Packard 214A pulse generator for interface with the sampling signal from the profilometer vehicle,

(3) photocell signal booster unit for interface with the SDS 930 computer facility.

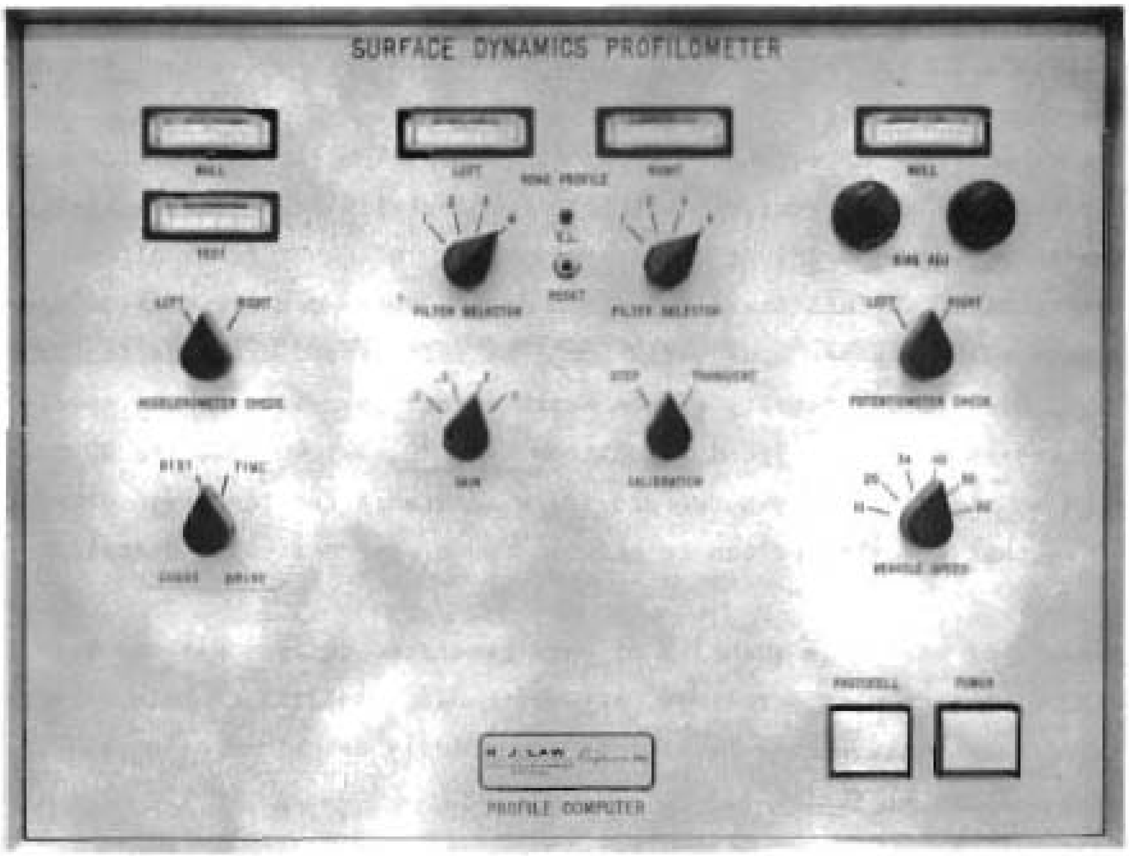


Fig 4. Profile computer.

(4) SDS 930 computer facility with an A-D peripheral unit for hardware and software for operation of the A-D program, and

(5) A-D computer program for instructions for operating the A-D system.

Figure 5 illustrates the A-D operation with all the data inputs. The begin/end convert signal, which is indicated by a verbal command from the SD Profilometer driver, starts first and initializes the system. Control is switched to the photocell channel and when this signal is received, the conversion process begins. The conversion process continues until a verbal command from the driver indicates the end of the section and the manual termination of the begin/end convert signal stops the conversion process.

As the data are digitized, the data words are read into a 1500-word buffer, with a right profile data word written first and then a left profile data word until the buffer is full. The next 1500 digitized data words are stored in a second 1500-word buffer while the first 1500 words are written in binary form on a digital magnetic tape. This process of writing data words from one buffer while the other buffer is being filled continues until the end of conversion signal is received. Upon receipt of the end of conversion signal a five-word identification record is written, which is followed by an end of file mark indicating the end of the conversion process. This five-word identification record contains (1) the file number; (2) the number of 1500-word records; (3) the number of conversions in the last record (which may not be full of data words); (4) the total number of conversions in the file; and (5) a file identification to indicate vehicle speed, filter number, gain, and date. A general flow chart of the A-D program is shown in Appendix 1. A detailed description of this program may be found in Ref 47.

Interface with CDC 6600

The data analysis techniques are being accomplished using the Control Data Corporation (CDC) 6600 computer. However, before these techniques may be performed, the 12-bit binary data words written by the SDS 930 must be converted to 60-bit binary data words used by the CDC 6600. The basic differences in the binary data words read by these two computers are as follows:

(1) The SDS 930 reads binary words in the two's complement mode while the CDC 6600 reads binary words in the one's complement mode.

(2) The read operation for the CDC 6600 is the reverse of the write operation of the SDS 930. Since five SDS 930 words are read as one

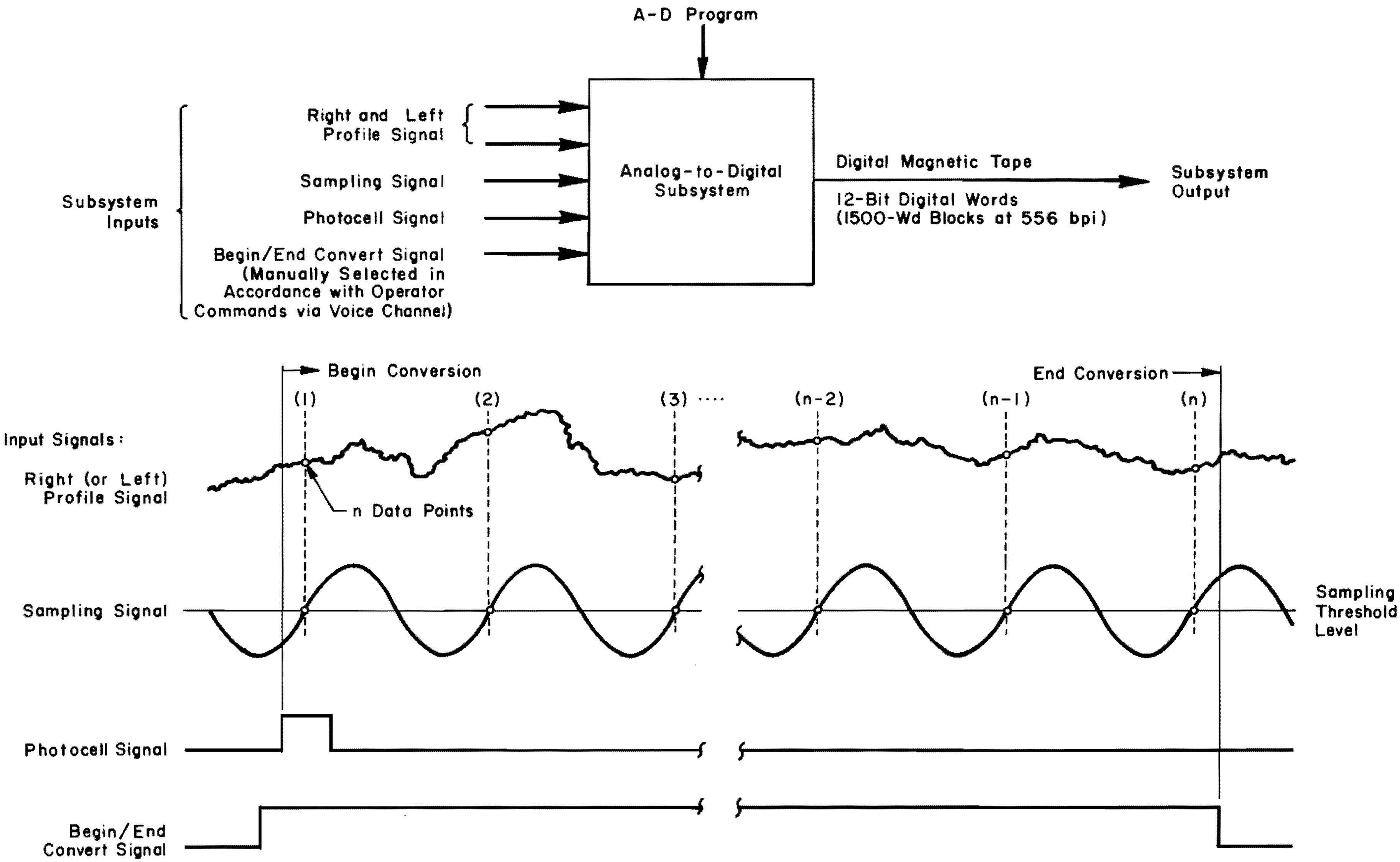


Fig 5. Analog-to-digital subsystem with inputs.

CDC 6600 word, these words must be separated and the order reversed from one to five to five to one.

A computer program was written to interface between the CDC 6600 and the SDS 930 computers. It separates the five 60-bit SDS 930 binary words and converts them to five 60-bit CDC binary words. Since the least accurate subsystem in the recording and measuring system is the Honeywell 8100 tape recorder, its accuracy of 8 bits resolution for digitized data reproduced from the analog tape was chosen as the overall system accuracy. To convert the 12-bit data to 8-bit data, assuming a value of one-half a bit or higher as the next highest bit, eight is added to the 12-bit binary word and that word is divided by 2^4, or 16, to produce the 8-bit binary word. These binary data are then in proper form to be used in the data analysis programs.

The digitized data obtained from the SD Profilometer consist of approximately one point for each inch of road over which the data are obtained. In preparing the digitized data for analyses purposes, more than 1200 feet of data are written on the CDC compatible tape or 15,760 data points which are 21 full 750-word records. Then in the analysis programs approximately 14,200 points are used per wheel path per profile data run.

CHAPTER 3. RATING AS A BASIS FOR JUDGMENT OF PAVEMENT QUALITY

Because of the public's demand for travel at faster speeds with less interference from other traffic and pedestrians, the highway engineer has had to design more sophisticated systems of highways. Since the function of a highway is to provide a convenient method for transporting people and goods, the difference in performance of any two highways is related to the difference in the degree to which the general public is satisfied. Therefore, it is logical that any method which attempts to quantify the degree of satisfaction of the public concerning a particular roadway should reflect the opinion of a representative portion of the public which uses the facility. To obtain a sample of the opinion of the traveling public a small panel of drivers was formed. The purpose of the panel was to express their opinions on the riding quality of a group of pavements in order to provide subjective values with which to correlate the objective measures of pavement roughness and deterioration as described in Chapter 1.

Panel Selection

Selecting a group of people who are representative of the traveling public is probably an impossible task. However, there is an indication that people of any background can serve adequately as panel members. Nakamura and Michael (Ref 31) showed that a panel consisting of highway engineers does not rate pavements any more consistently than a similar panel consisting of members having varied professional backgrounds. Based on this study and the results shown by Carey and Irick (Ref 5), a panel of 15 members with different professions and backgrounds and representative of the traveling public in Texas was chosen. The panel included both men and women, whose occupations were secretary (four), design engineer (one), maintenance engineer (one), accountant (two), research engineer (one), maintenance foreman (two), technical editor (one), truck driver (two), and computer programmer (one). Extreme care was exercised to insure that as many raters as possible would be present for all the rating periods, which were scheduled over a period of six to nine months.

Therefore, the raters were selected from a random group of available personnel rather than from the general public. Since the selection of the raters was not completely random, the drivers of the vehicles, who were staff members or otherwise highway orientated, were designated as a panel to check on the reasonableness of the rating values given by the panel. Each driver rated the test sections along with the panel members included in his vehicle. The vehicles selected were late model Ford and Plymouth automobiles in order to reflect the quality of vehicle which is typical of most road users. A PSR value then represented the opinion of a panel of 15 typical road users riding in a typical American automobile of the riding quality of a section of road 1200 feet long.

Preliminary Rating Session

The first of the three rating periods served for orientation and training and was designated as the preliminary rating session. It was a pilot study for the latter sessions and was set up to allow the project staff to

(1) orient and train the panel members;
(2) analyze the PSR values for any pecularities;
(3) debug the measurement system, from profile measurement to A-D operations, under field conditions;
(4) perform an analysis on the profile data, using various summary statistics; and
(5) develop a preliminary regression equation for estimating PSI.

This step-by-step procedure for analysis of the preliminary rating session data allowed consideration and investigation of procedural changes in equipment operation, collection of any additional profile and condition survey information, and any alterations in the rating procedure before the two full-scale rating periods.

Rater Training and Orientation

The preliminary session was conducted in the Austin, Texas area in February 1968. The raters were assembled at the Center for Highway Research (CFHR) at The University of Texas at Austin for instruction related to the purpose and function of the research being conducted. A brief discussion of the present serviceability performance concept developed at the AASHO Road Test and its usefulness to the highway engineer was presented. The instructions to be followed during all the rating sessions and the factors to be considered by the rater in his individual evaluation of each test section were presented. The raters were asked to observe the following general rules:

(1) Consider only the present serviceability of the pavement, i.e., "How is it serving traffic today?"

(2) Do not consider the geometrics of the roadway in your rating, i.e., try not to let the width of the pavement, the shoulder condition, or the ditch arrangement affect your rating.

(3) Consider all the pavements in exactly the same way. In order to get a variety of pavement conditions, it has been necessary to use pavements on the farm-to-market, state, and interstate highway systems. Compare their riding quality to each other and to a norm or standard which you might set for a perfect pavement.

(4) Do not be influenced by the other raters. Do not look at their rating or show them yours. We are interested in your opinion of these pavements.

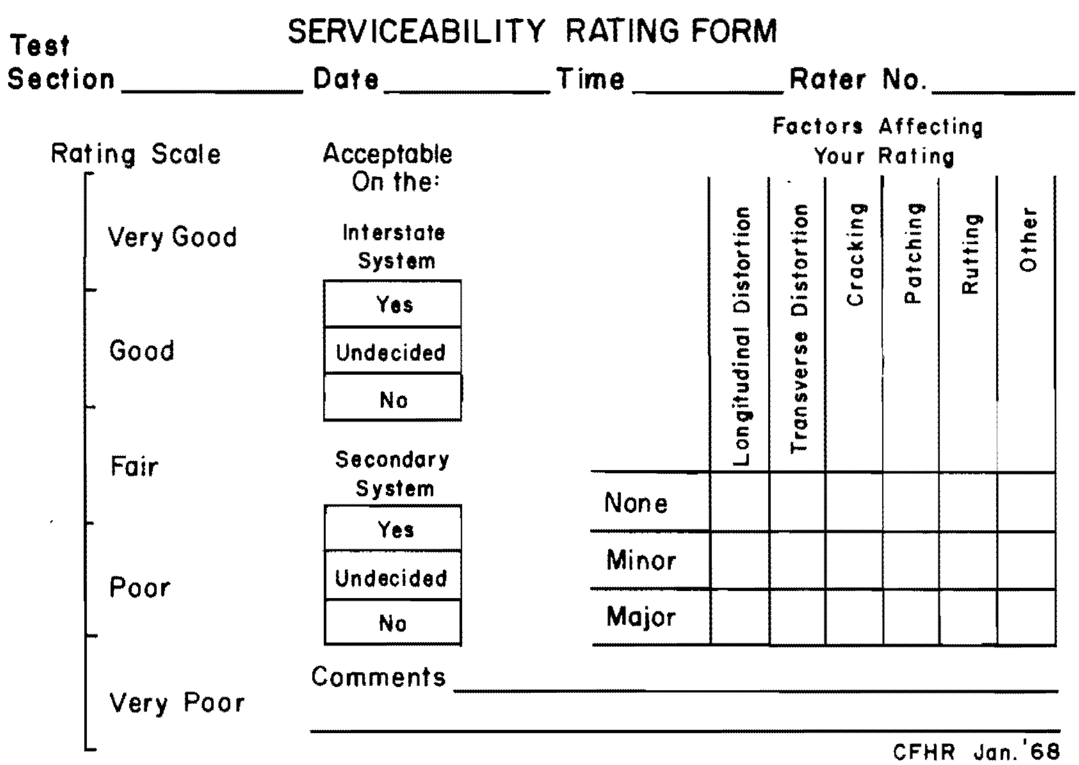
(5) Rate the pavement in any fashion you desire. Your driver will drive you over the sections at 50 miles per hour. We would like this ride to be used at least partially in making your judgment, however, you may redrive the section at any speed you desire or get out and look at or walk over the section.

(6) Sit in the car in any location except the driver's seat. It is impossible for us to let you all drive, and, therefore, we are asking that no rater drive. If you prefer to rate from the front seat, we will try to find you a car in which to do so.

(7) Remember the question you are answering is, "How well is this pavement serving me today?" - not how well it served yesterday or how well it is going to serve tomorrow.

The serviceability rating form to be used (Fig 6) was discussed in detail. Each factor affecting the rating was discussed and an example of its effect on a hypothetical rating was presented. The raters were asked to mark the forms to give maximum information relating roadway features to the individual PSR given the section.

To familiarize the raters with the rating procedure, six pavement sections known to range in quality were rated immediately after the instruction session. The raters were driven over the sections in five Texas Highway Department vehicles, all of which were full-sized low price-range automobiles of the same year and model. The vehicles were air-conditioned because two of the rating



SERVICEABILITY RATING FORM

Test Section ________ Date ________ Time ________ Rater No. ________

Rating Scale

- Very Good
- Good
- Fair
- Poor
- Very Poor

Acceptable On the:

Interstate System

Yes
Undecided
No

Secondary System

Yes
Undecided
No

Factors Affecting Your Rating

	Longitudinal Distortion	Transverse Distortion	Cracking	Patching	Rutting	Other
None						
Minor						
Major						

Comments ____________________

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Fig 6. Individual present serviceability form.

periods were scheduled for the summer months and the same type vehicles were to be used during all three rating periods.

In this familiarization period, each rater marked a rating card. Then the raters and driver in each vehicle discussed the rating given by each and the factors which affected their ratings. This allowed the raters to establish a normal pattern for rating. After rating the six sections, all personnel returned to the CFHR to discuss questions on rating procedure or the use of the serviceability rating form. The raters were asked not to discuss the ratings for any test section during the remaining three rating periods.

Pavement Selection and Routing

The 20 pavement sections selected for the preliminary rating session were within a 50-mile radius of Austin. They were hot mix asphaltic concrete (HMAC) or surface treated, the only types available in the area. These sections which were chosen had an estimated PSR range of 1.5 to 4.5, and the average panel ratings were from 1.8 to 4.1. The vehicles were routed over the sections in a way intended to remove any bias caused by the time at which a particular section was rated; however, the order of rating was not random. Because the shortest routes were around 250 miles, driving time was minimized for economic reasons. All vehicles left Austin in different directions using five different routes. It was hoped that no systematic bias was introduced by the routing procedure used.

Two sections were removed from the test during the field rating process because of uncontrollable circumstances, and a third section was removed before data runs with the SD Profilometer could be performed. As a result the rating data analysis was made using 18 sections while the correlation study of SD Profilometer data included only 17 sections.

Analysis of the Rating Information

Three raters and a driver occupied each of the five vehicles. The rating values they recorded during the preliminary rating session are shown in Table 1. To determine whether the average of the raters for a particular section could be used to represent the riding quality of the section, an analysis of variance (ANOVA) was performed on these data. A mixed model, cross-classified, nested analysis of variance design was used. Basically, the ANOVA consisted of clas-

TABLE 1. PRELIMINARY RATING SESSION PSR DATA

Position	Drivers' Group				Right Front Group					Left Rear Group					Right Rear Group				
Rater No.	16	17	18	19	3	6	8	9	12	1	4	10	13	14	2	5	7	11	15
Section Number 1	3.0	3.8	3.5	2.8	3.0	1.9	2.9	3.6	3.1	3.5	4.0	2.8	1.5	3.0	2.8	2.0	3.0	3.2	4.0
2	3.0	3.1	3.1	3.1	2.5	3.7	2.8	3.4	3.1	2.8	1.8	2.9	3.1	3.0	3.3	2.0	2.9	4.4	3.7
3	3.5	3.5	4.3	2.3	4.0	3.9	3.7	4.7	3.8	4.4	3.8	3.2	3.1	3.0	3.7	3.8	4.2	3.6	4.0
4	2.5	3.1	3.2	3.4	2.2	3.5	3.1	3.1	3.9	3.3	3.3	2.1	3.8	2.0	3.9	2.0	3.1	3.4	2.8
5	3.9	3.8	4.4	3.5	3.9	4.2	3.9	4.8	4.7	3.5	4.1	3.9	3.9	4.0	3.8	3.9	4.7	3.7	4.3
6	2.3	2.9	3.2	2.3	2.2	2.4	1.6	2.4	2.8	2.7	3.1	2.7	1.2	1.0	1.8	1.8	1.7	3.4	1.7
7	3.5	2.9	3.8	3.0	3.4	3.5	3.2	3.1	3.7	3.0	3.2	4.1	2.8	4.0	2.8	4.0	4.0	3.4	4.0
8	3.1	3.1	3.7	3.0	2.5	4.2	2.6	2.9	4.1	2.7	2.7	3.1	2.7	3.0	2.9	3.1	4.1	3.4	3.8
9	4.3	3.9	4.5	3.7	3.3	3.9	3.8	4.8	4.5	4.1	3.4	3.9	3.7	4.0	4.2	4.2	4.7	4.6	4.4
10	2.2	3.5	2.4	1.7	1.2	2.9	2.1	3.0	2.4	2.8	2.4	2.2	1.9	2.0	1.5	1.8	1.7	2.6	1.3
11	3.5	4.3	3.9	3.7	4.0	3.9	4.2	4.3	4.8	3.9	3.7	3.9	3.4	4.0	3.5	3.7	3.9	4.0	3.9
12	2.1	2.8	2.4	1.4	1.4	1.4	1.6	2.9	1.8	2.8	1.0	1.6	0.9	1.0	1.3	1.4	1.9	3.3	1.3
14	4.3	4.1	3.8	3.8	3.9	3.8	3.7	3.9	3.7	4.4	3.9	3.2	3.1	3.0	3.3	2.4	3.8	3.4	3.9
16	2.6	3.5	3.1	3.1	2.2	3.6	2.7	2.9	3.9	3.3	2.4	3.1	2.8	3.0	3.2	2.5	3.4	3.4	2.6
17	2.6	3.2	3.0	2.1	1.7	2.0	1.8	2.3	3.7	2.5	1.5	3.1	1.9	2.0	2.4	2.6	3.3	3.2	2.3
18	3.7	3.9	4.0	3.2	3.7	4.2	3.8	4.8	4.8	3.5	3.9	4.1	3.2	3.0	3.3	4.0	4.0	3.2	4.0
19	3.5	3.9	3.9	3.6	3.4	4.8	3.9	4.8	4.2	3.5	4.1	3.3	3.7	4.0	3.5	3.4	4.1	4.0	4.3
20	3.9	3.9	4.2	3.7	3.9	4.3	4.0	4.7	4.4	4.4	4.1	3.7	3.9	4.0	4.1	4.3	4.3	4.0	4.8
Total	57.5	63.2	64.4	53.4	52.4	62.1	55.4	66.4	67.4	61.1	56.4	56.9	50.6	53.0	55.3	52.9	62.8	64.2	61.1
Group Total				238.5					303.7					278.0					296.3
Block Total				238.5															878.0
Grand Total																			1116.5

sifying and cross-classifying data to allow testing of the means or variances of different classifications for significant differences. The statistical assumptions for using this method are homogeneity of variances, normal distribution of errors, fixed positions in the vehicle, random pavement sections, and random rater samples. This ANOVA is shown in Table 2. To test for any difference in rating values between the official panel and the drivers, the personnel involved were divided into two blocks or groups, raters, and drivers. The two sums of squares were computed (Ref 32) for each, using the totals for each rater over all the sections from Table 1. The mean square (MS) was computed by dividing the sum of squares (SS) for a source of variation by the degrees of freedom (df) for that source of variation. As noted in Table 2, the SS for raters is partitioned into four sources of variation. This is necessary to determine any variations between positions caused by variations within panel members for any position in the vehicle. The F-test, which is a ratio of two mean squares, was used to test for significant difference in these variations. The test indicated that the variation among raters within positions was about the same. This allowed the "pooling" of the SS from the three positions for subsequent testing.

To determine if the average ratings for all three seating positions were the same, a test for variations in rating according to position in the vehicle was necessary. Such a test, as shown in Table 3(b), indicated that an average of positions may be used.

Since the drivers were set up as a control group to indicate the normality of the rating panel, i.e., to represent the traveling public, a test for variations between the drivers and the raters was made. This test, as shown in Table 3(c), indicated that overall the drivers and raters rated the sections the same. However, it should be noted that, as shown in Table 3(d), there are highly significant variations among personnel when all (drivers and raters) are included. This was expected within a diverse group of highway users. Significant variations of opinion concerning highways should be expected.

In a special study conducted during the preliminary rating session several of the raters rerated some test sections during the night in a test initiated to determine the general effect of visibility on the rating value for a set of sections. The data recorded during this study are given in Table 4. Section 25 corresponds to section 1 and so forth. An ANOVA was performed on these data, as shown in Table 5, using day versus night as a fixed effect and

TABLE 2. ANOVA FOR DATA FROM TABLE 1

	Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square
	All Raters (AR)	18	27.20	
	Drivers Group vs Raters Group	1	0.21	0.21
(c)	Drivers in Drivers Group	3	4.38	1.46
	Raters in Raters Group	14	22.61	1.62
		18	27.20	

	Partitioning of Raters SS:	df	SS	MS	
(b)	1) Position in Vehicle	2	3.89	1.95	
(a)	2) Raters in Rt. Front	4	9.79	2.45	Pooled MS* 1.56
(a)	3) Raters in Lt. Rear	4	3.58	0.90	
(a)	4) Raters in Rt. Rear	4	5.35	1.34	

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square
Sections (S)	17	164.77	9.69
Residual (AR x S)	306	64.14	0.21
Total	341	256.11	

$$\text{* Pooled MS for positions} = \frac{9.79 + 3.58 + 5.35}{4 + 4 + 4} = 1.56$$

TABLE 3. F-TESTS ON SOURCES OF VARIATION FROM TABLE 2

(a) F-Test for Variations Among Raters within Positions:

$$F_{4,4} \text{ (Calculated)} = \frac{2.45}{0.90} = 2.72 < 4.11$$

$F_{4,4}$ (0.90) = 4.11 $\qquad$ $F_{4,4}$ (0.75) = 2.06

Since the $F_{4,4}$ (Calculated) is smaller than $F_{4,4}$ (0.90), we can accept the hypothesis that the variation among raters was about the same no matter what position they occupied in the vehicle. This allows the "pooling" of the sum of squares from the three positions for subsequent testing.

(b) F-Test for Variations in Ratings due to Position in the Vehicle:

$$F_{2,12} \text{ (Calculated)} = \frac{1.95}{1.56} = 1.25 < 1.56$$

$F_{2,12}$ (0.90) = 2.81 $\qquad$ $F_{2,12}$ (0.75) = 1.56

Therefore, we can accept the hypothesis that the average ratings for the three seating positions are the same. We can pool all three for the average PSR.

(c) F-Test for Variations Between Raters and Drivers:

$$F_{14,3} \text{ (Calculated)} = \frac{1.62}{1.46} = 1.11 < 2.53$$

$F_{14,3}$ (0.90) = 2.53 $\qquad$ $F_{14,3}$ (0.75) = 1.53

Therefore, we can say that in general the drivers and raters rate the sections, overall, the same.

(d) F-Test for Variations within All Raters (Raters and Drivers Combined)

$$F_{18,306} \text{ Calculated} = \frac{1.51}{0.21} = 7.20 >> 1.44$$

$F_{18,306}$ (0.90) = 1.44 $\qquad$ $F_{18,306}$ (0.75) = 1.20

TABLE 4. PSR DATA FOR 4 SECTIONS RATED DURING BOTH DAY AND NIGHT

Test Section Number		Rater Number 4	6	8	9	11	13	17	19
Rated at night	25	3.7	2.9	2.7	3.2	3.5	1.9	3.8	2.5
	26	2.9	3.9	2.9	3.1	3.7	3.1	3.1	3.1
	27	4.0	3.9	2.9	4.0	3.4	3.4	3.9	3.0
	28	4.1	4.2	3.7	4.3	3.9	4.0	3.9	2.8
Rated during day	1	4.0	1.9	2.9	3.6	3.2	1.5	3.8	2.8
	2	1.8	3.7	2.8	3.4	4.4	3.1	3.1	3.1
	3	3.8	3.9	3.7	4.7	3.6	3.1	3.5	2.3
	20	4.1	4.3	4.0	4.7	4.0	3.9	3.9	3.7
TOTAL		28.4	28.7	25.6	31.0	29.7	24.0	29.0	23.3
GRAND TOTAL									219.7

TABLE 5. ANOVA FOR DATA IN TABLE 4

Source	df	SS	MS
Sections (S)	3	8.8430	2.9476
Raters (R)	7	6.8848	0.9835
R × S	21	10.3183	0.4913
D vs. N (DN)	1	0.0127	0.0127
DN × S	3	0.1942	0.0647
DN × R	7	1.0411	0.1487
DN × R × S	21	2.0070	0.0956
TOTAL	63	29.30109	

TABLE 6. F-TESTS OF INTEREST FOR ANOVA IN TABLE 5

Source of Variation	F Calculated	Degrees of Freedom		F_{ν_1,ν_2}		Significance Level	
		ν_1	ν_2	90%	75%	90%	75%
DN × R	$\frac{0.1487}{0.0956} = 1.55$	7	21	2.02	1.42		X
R	$\frac{0.9835}{0.4913} = 2.00$	7	21	2.02	1.42		X
R × S	$\frac{0.4913}{0.0956} = 5.14$	21	21	1.78	1.35	X	X
DN	$\frac{0.0127}{0.1486} = 0.09$	1	3	5.54	2.02		

raters and sections as random effects, with sections nested within day versus night. A direct test for day versus night (DN) is not possible in such an analysis; however, a test may be made for DN using either the DN $\times$ R or the DN $\times$ S interactions. The subsequent test for DN with DN $\times$ R is a conservative test since the MS for DN has components of variance from DN $\times$ S, DN $\times$ R, DN $\times$ S $\times$ R, and DN. Because the result of the test for DN, as shown in Table 6, was not significant, it can be said that there is no significant difference caused by the times of the rating.

During the preliminary rating session, four of the test sections were re-rated by all the raters to check their individual and collective ability to repeat an observation of the same roadway section. These data are shown in Table 7 and are arranged so that the male raters form one group and the female raters a second group. The data are set up in this manner to allow for a test to determine if any overall differences in opinion exist between the two groups. The ANOVA for the data in Table 7 is shown in Table 8. The three tests of interest are done for effect of duplicates with a two-factor interaction term and two tests on the partitioned rater sum of squares. As indicated in Table 9, the result of the test to determine any significant difference in the variations within men and within women raters was not significant at either the 75 or 90 percent levels. The result of the test for determining if the variations between men and women were greater than the variations within these groups was also not significant. It is possible to state, then, that more variation exists within the two groups than between them. The third test, on duplicates (D), was not significant at either of the significance levels. This indicates that in rerating a particular section, the panel average as a whole was the same.

From the above analyses, it was concluded that there were variations among raters in general, among raters according to positions in the vehicle, and among raters within the male and female groups. However, these variations were such that the average of the whole panel of raters could be used to represent the PSR of each test section.

Other information was available from the rating forms and is shown in Figs 7 through 13. These data were obtained from the "Factors Affecting Your Rating" and the "Acceptability" sections of the Serviceability Rating Form (Fig 6). A graph showing the percent of the panel members who judged each pavement to be acceptable on the Interstate System is shown in Fig 7.

TABLE 7. PRELIMINARY RATING SESSION DUPLICATE SECTION PSR VALUES

	Male Raters										Female Raters				
Rater No.	2	4	5	6	7	8	9	10	14	15	1	3	11	12	13
1	2.8	4.0	2.0	1.9	3.0	2.9	3.6	2.8	3.0	4.0	3.5	3.0	3.2	3.1	1.5
2	3.3	1.8	2.0	3.7	2.9	2.8	3.4	2.9	3.0	3.7	2.8	2.5	4.4	3.1	3.1
3	3.7	3.8	3.8	3.9	4.2	3.7	4.7	3.2	3.0	4.0	4.4	4.0	3.6	3.8	3.1
20	4.1	4.1	4.3	4.3	4.3	4.0	4.7	3.7	4.0	4.8	4.4	3.9	4.0	4.4	3.0
21	2.7	3.1	2.1	3.2	3.0	2.7	3.3	2.5	3.0	3.0	2.6	2.7	3.1	3.6	2.0
22	2.8	3.0	2.4	3.9	3.7	3.2	3.1	3.1	3.0	2.9	3.5	2.7	3.5	3.4	2.7
23	3.4	4.0	3.3	3.9	4.3	3.1	4.2	3.2	4.0	4.2	3.8	2.9	3.5	4.4	4.0
24	3.5	4.0	4.0	4.1	4.3	3.6	4.7	3.7	4.0	4.4	4.1	3.7	4.2	4.8	3.9
TOTAL	26.3	27.8	23.9	28.9	29.7	26.0	31.7	25.1	27.0	31.0	29.1	25.4	29.5	30.6	24.2
BLOCK TOTAL										277.4					318.8
GRAND TOTAL															416.2

TABLE 8. ANOVA FOR THE DATA IN TABLE 7

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	
Raters (R)	14	11.2497		
Partitioning of Rater SS:				
Between Male and Female Groups	1	0.0002	0.0002	
Within the Male Raters	9	7.3580	0.8176	Pooled
Within the Female Raters	4	3.8915	0.9729	MS
	14	11.2497		0.8654
Sections (S)	3	30.2703		
Duplicates (D)	1	0.0653	0.0653	
R × S	42	8.5497		
R × D	14	2.4447		
S × D	3	0.2427	0.0809	
R × S × D	42	5.3173	0.1266	
TOTAL	119	58.1397		

TABLE 9. F-TESTS OF INTEREST FOR THE ANOVA IN TABLE 8

Source of Variation	F Calculated	Degrees of Freedom ν_1	Degrees of Freedom ν_2	F_{ν_1,ν_2} 90%	F_{ν_1,ν_2} 75%	Significance Level 90%	Significance Level 75%
Within the Female Raters	$\frac{0.9729}{0.8176} = 1.12$	9	4	3.94	2.08		
Between Male and Female Groups	$\frac{0.0002}{0.8654^*} = 0.00$	1	13	3.14	1.45		
Duplicates (D)	$\frac{0.0653}{0.0809} = 0.81$	1	3	5.54	2.02		

$$* \text{ Pooled MS} = \frac{7.3580 + 3.8915}{9 + 4} = \frac{11.2495}{13} = 0.8654$$

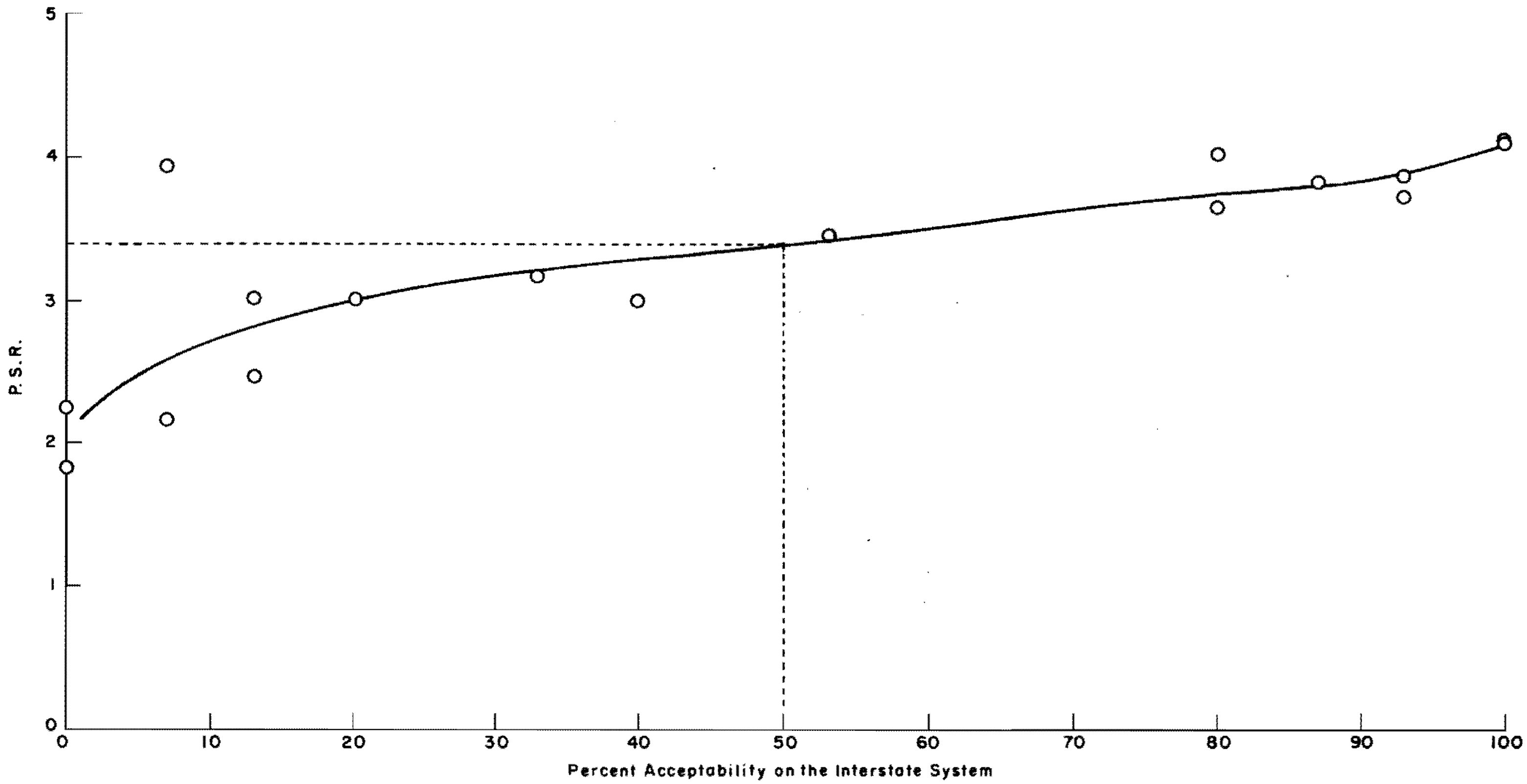


Fig 7. Percent acceptability on the Interstate System - preliminary rating session.

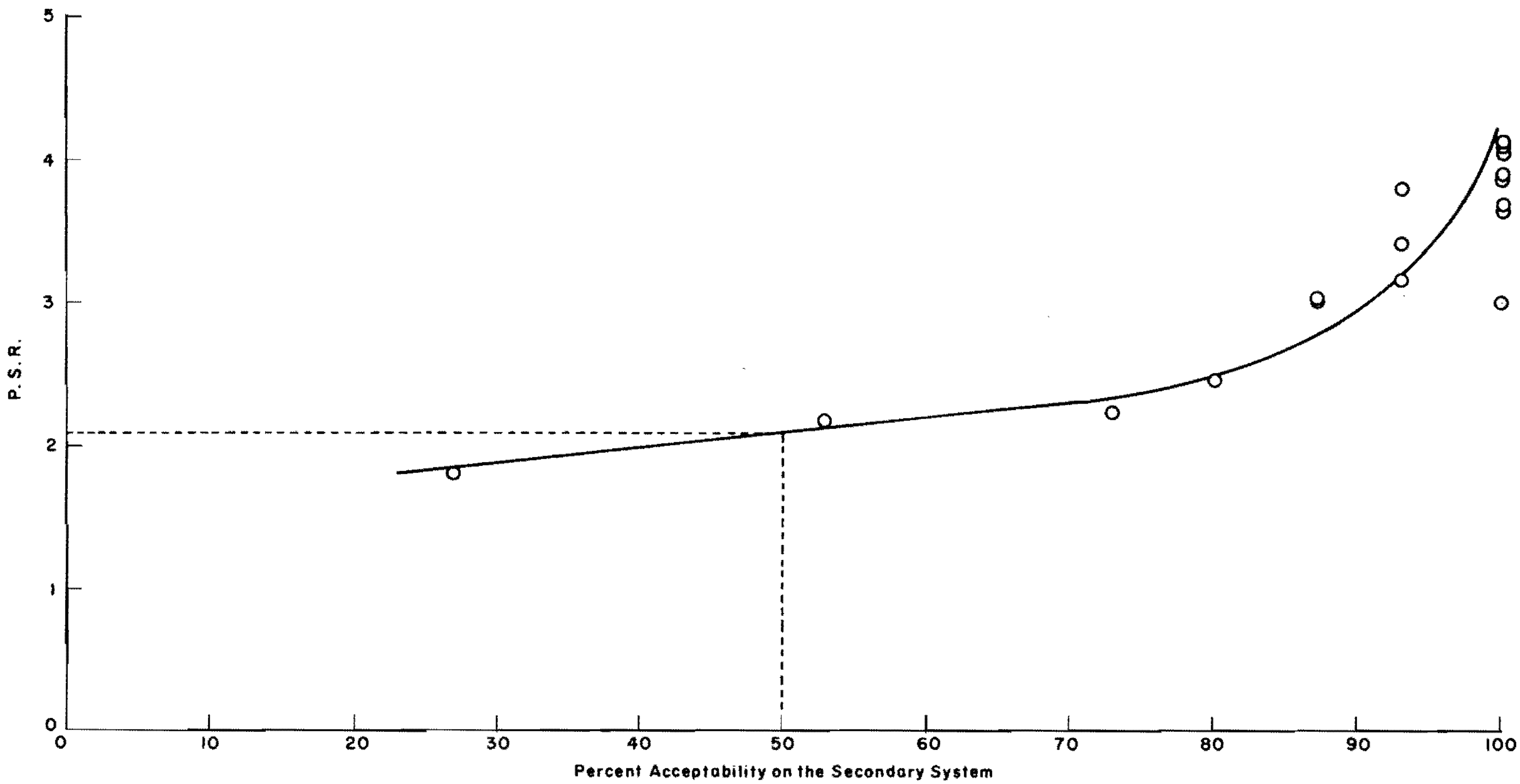


Fig 8. Percent acceptability on the Secondary System - preliminary rating session.

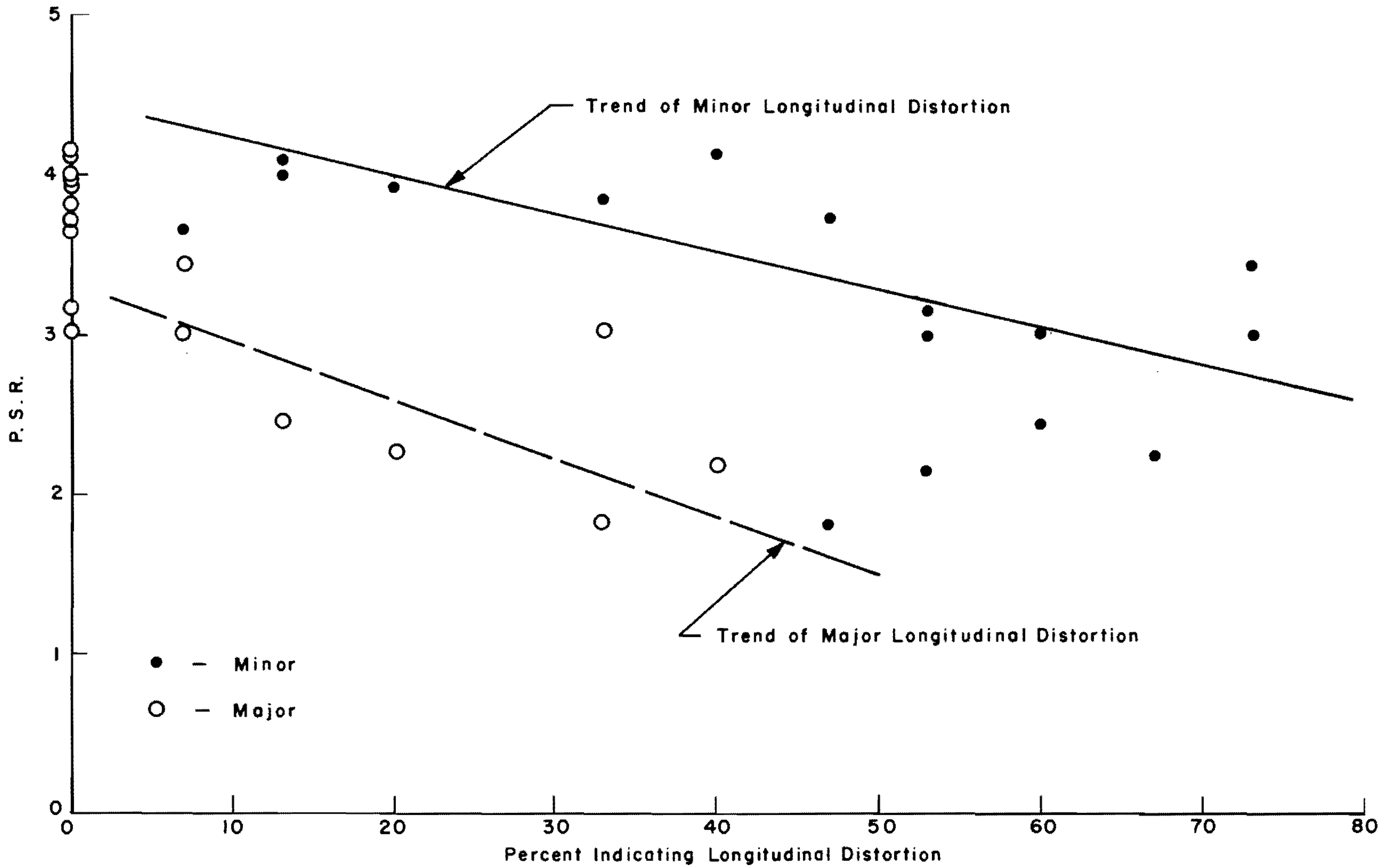


Fig 9. Percent of raters indicating longitudinal distortion as a factor - preliminary rating session.

As expected the curve is an "S" shaped curve. The PSR level at which 50 percent of the panel members felt that a particular road was acceptable on the Interstate System is 3.3. At any PSR level below this, more than half the people felt that the pavement was not of sufficient quality to serve on the Interstate System. A similar curve for the Secondary System is shown in Fig 8. However, the PSR level at which 50 percent of the panel members felt that a road was acceptable on the Secondary System was 2.1, much lower than for the Interstate System, where one-half of the test sections were below the 50 percent acceptability level. Figure 9 shows a plot of the percent of the panel members who indicated that longitudinal distortion was a factor which affected their rating versus the PSR for that section. There are two trends in the data. One indicates the effect of minor longitudinal distortion and the other indicates the effect of major longitudinal distortion. Both trends have about the same negative slope. It is interesting that even though all test sections had one or more raters indicating minor longitudinal distortion as a factor in their rating, only one test section (Figs 7 and 9) which was above the 50 percent acceptability level for the Interstate System had more than one-half the panel indicating minor longitudinal distortion as a factor in their rating. The same statement is true for minor transverse distortion, as indicated in Fig 10. Two negative trends are evident in this transverse distortion data and the slopes appear to be of about the same magnitude as those for the longitudinal distortion data. These two figures indicate that both longitudinal and transverse distortions should be correlated negatively with PSR. Obvious trends are not present in the plots for percent indicating cracking (Fig 11), patching (Fig 12), and rut depth (Fig 13) as factors affecting their ratings. This is evidence that little visible cracking, patching, or rut depth was present in the selected test sections.

As a direct result of these analyses, it was concluded that no changes in the rating procedure were required and the scheduling for the two subsequent summer sessions was initiated.

Replacement of Panel Members

Even though care was taken in the original selection of panel members, it became necessary to replace four of the original 15 members. Two of the secretaries and both of the truck drivers were unable to attend either of the summer

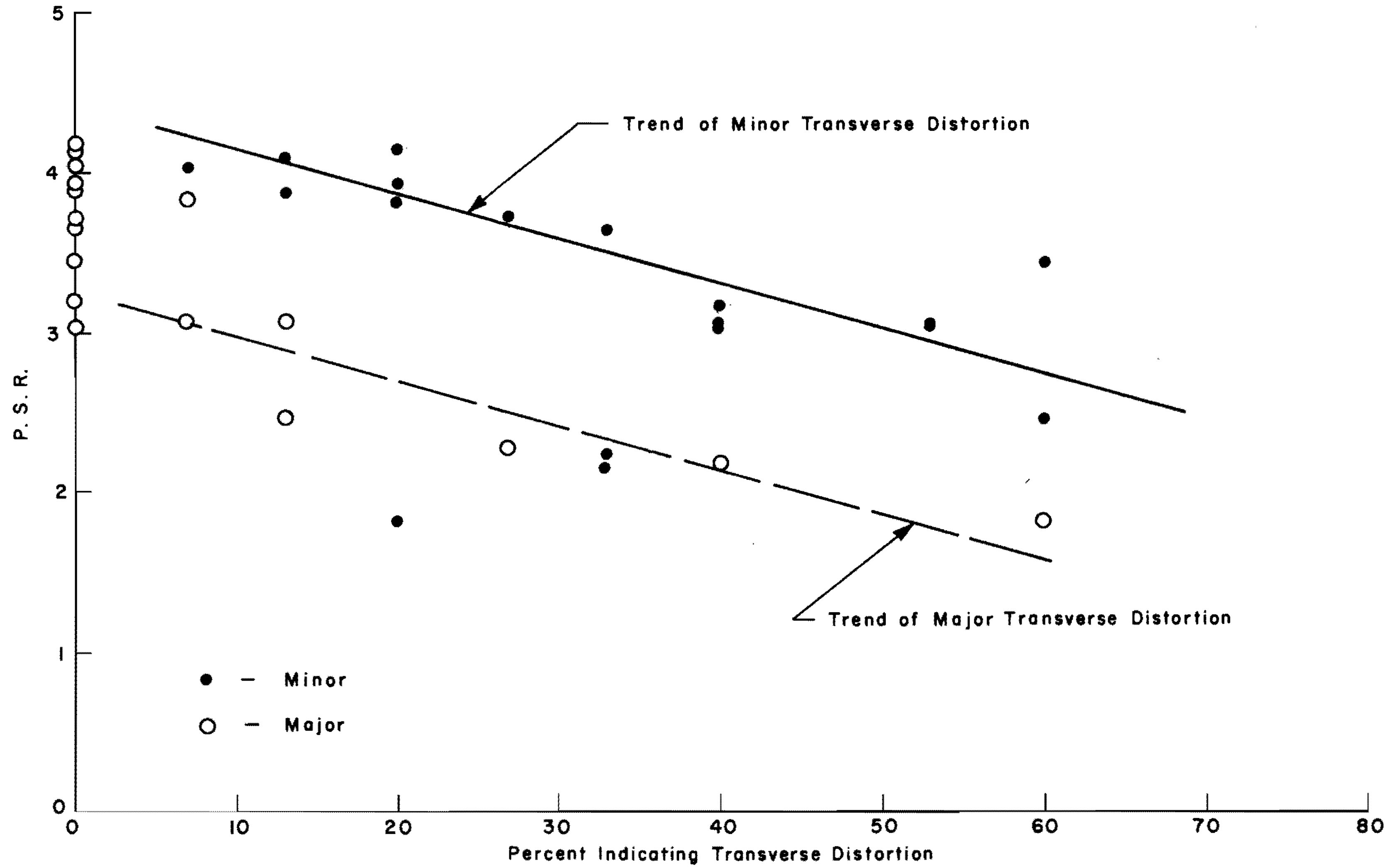


Fig 10. Percent of raters indicating transverse distortion as a factor - preliminary rating session.

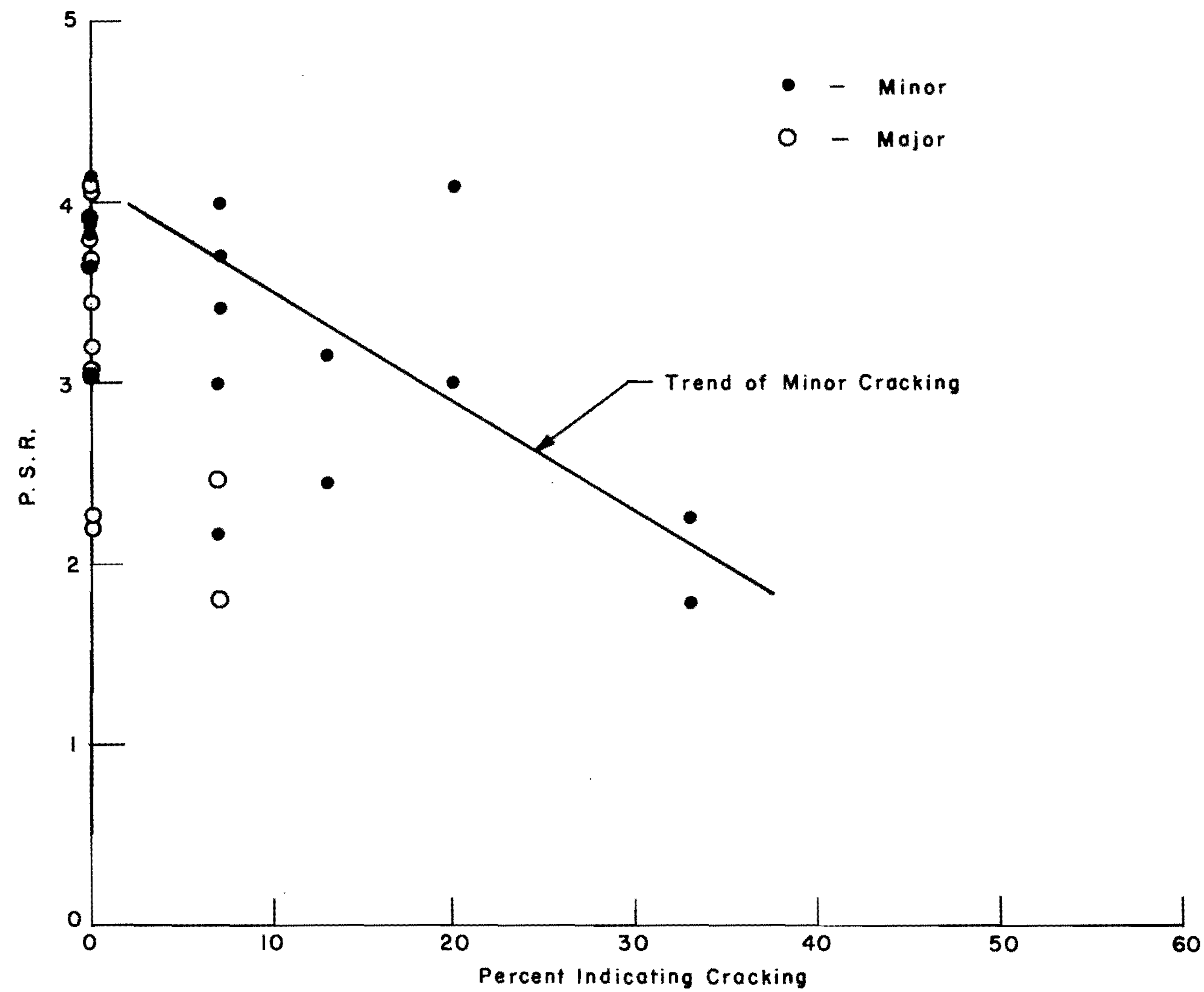


Fig 11. Percent of raters indicating cracking as a factor - preliminary rating session.

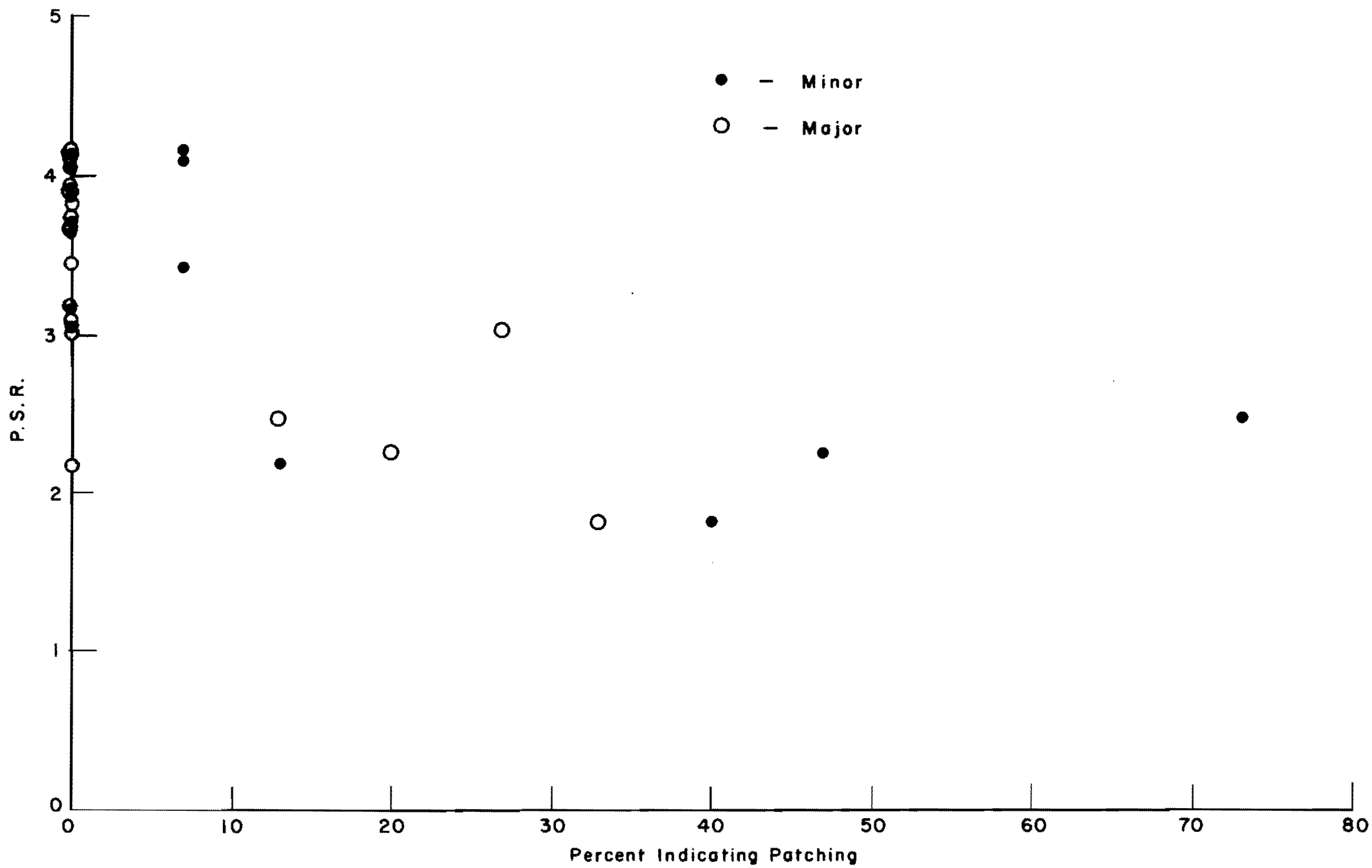


Fig 12. Percent of raters indicating patching as a factor - preliminary rating session.

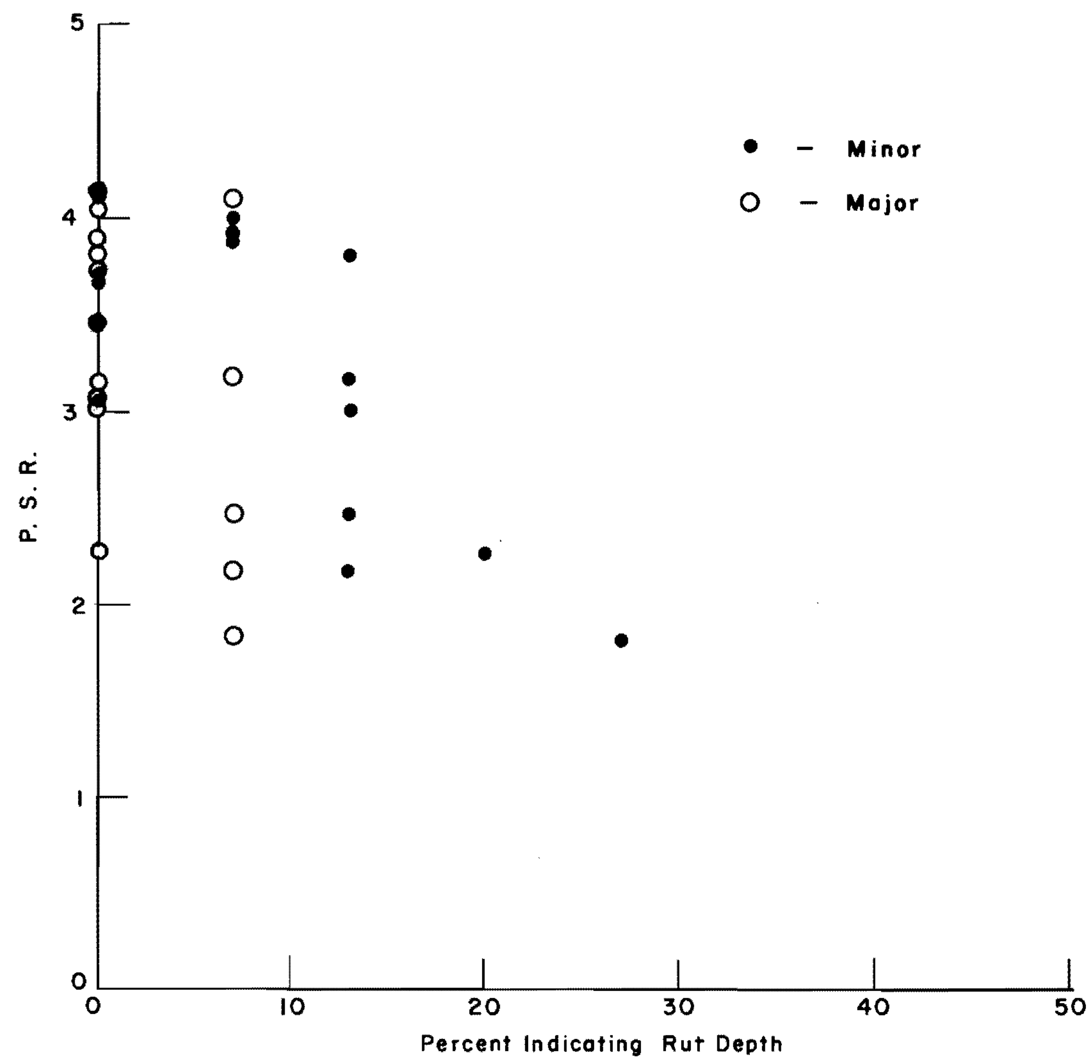


Fig 13. Percent of raters indicating rut depth as a factor - preliminary rating session.

rating periods. These members were replaced by three housewives and a retired military man. A fifth panel member was unable, at the last moment, to attend either of the sessions, and during the second summer period two rater were unable to rate because of ill health. As a result of these incidents, 14 panel members rated pavements during the first summer period, but only 12 rated during the second period. Because of the difference in the number of raters for the two periods, the results were analyzed separately.

The panel members who were selected as replacements were given the same instruction as the original 15 panel members. They rated the test sections which were used in the preliminary rating session and were considered as competent as the members of the original panel.

The sites for the two rating periods were selected to cover two different topographical areas of Texas. The first rating period was conducted in the generally flat Houston-Gulf Coast area and the second in the hilly Dallas-Fort Worth area. These diverse regions were selected to allow a large inference space for use of the results from this study.

Rating Period One

The first rating period was conducted in the Houston area from July 8 through 12, 1968. Forty-nine pavements of varying quality of HMAC, surface-treated, portland cement concrete (PCC), and PCC overlaid with HMAC pavements were included. Pavements were selected with as wide a range of PSR as possible. These test sections were selected in conjunction with Texas Highway Department District 12 personnel. The sections were generally within a 50-mile radius of Houston and represented the Interstate, U. S., State, Farm-to-Market, and County Systems. Four test sections were lost during the rating process because of maintenance and other causes. The remaining 45 sections were used for the following analyses.

For all rating sessions, the raters were asked to occupy the same positions they had in the preliminary rating session so that the conclusions drawn from the preliminary rating period data could be checked with more data. The four replacement personnel were given at random the numbers and positions of the original four panel members.

The route for each group of raters was assembled separately to insure that a time-of-day bias was not introduced as a result of having all panel members rate the sections in the same order, even if the ratings occurred on different days. To remove this possibility, five separate four-day routes were planned. (Four days of rating were required to rate all test sections once and rerate 13 selected sections.) The order of rating sections was not selected randomly, because the long distances between test sections would have made the cost of conducting the rating periods prohibitive.

The PSR data from the first rating period are shown in Table 10. These data include all the section ratings, except the second rating on the duplicated sections, which are included in another analysis. An ANOVA similar to the one performed on the preliminary rating session data is shown in Table 11. A mixed model, cross-classified, nested analysis of variance design was used, with positions in the vehicle fixed and sections and raters considered random. The F-tests of interest are shown in Table 12. In summary, these tests indicate that (1) the variations among the raters within the positions are about the same, (2) there are no significant effects caused by positions in the vehicle, (3) overall the drivers and the raters rate the pavements the same, and (4) there are as expected significant rater-to-rater variations.

The PSR data for the sections which were rerated are shown in Table 13. In this table, section 34 corresponds to 51, 35 to 52, etc. A mixed model ANOVA design was run on the data from Table 13, as shown in Table 14. Raters and sections are considered as random variables with sections nested within duplicates and duplicates considered as a fixed effect. The F-tests of interest are shown in Table 15. The test for differences between the variations within the male and female raters is not significant at the 90 percent level and the test for the difference in variations between the group of men and the group of women is also not significant. The test for duplicates is not a direct test, but a conservative test can be made by testing duplicates with the section by duplicates interaction. Since this test is not significant, it may be concluded that overall the raters rerate the sections the same. From these analyses the conclusion can be drawn that there are rater-to-rater variations and these variations are greater than (1) the variations caused by differences in sex of raters or (2) the variations caused by position that the rater occupied in the vehicle. The average of the whole panel may thus be used to represent the PSR for a particular section.

TABLE 10. PSR DATA FOR RATING PERIOD ONE

Position	Drivers' Group				Right Front Group					Left Rear Group				Right Rear Group				
Rater No.	16	17	18	19	3	6	8	9	12	1	4	13	14	2	5	7	11	15
1	3.7	4.9	3.6	3.7	4.7	3.5	4.1	4.9	4.9	3.9	3.2	4.7	3.8	4.9	4.8	4.7	3.4	4.8
2	2.4	3.8	2.1	2.1	4.1	2.7	2.9	3.8	3.8	3.1	3.2	2.8	2.8	2.9	3.0	3.4	3.4	3.1
3	3.6	3.8	3.3	3.1	3.5	3.4	2.9	4.8	4.9	3.6	3.9	3.9	3.2	3.7	3.0	4.4	3.7	3.8
4	4.1	4.8	2.4	3.6	3.6	3.6	3.8	4.9	4.9	3.4	4.1	3.7	3.6	3.7	4.0	4.4	4.0	4.1
5	1.8	2.1	1.0	1.1	0.5	1.0	1.1	2.5	3.5	1.4	1.8	1.5	2.6	1.7	1.5	4.0	3.4	2.7
6	3.3	3.8	1.3	3.0	3.1	4.0	3.7	4.0	4.9	3.1	3.1	2.6	3.7	2.5	2.8	3.6	2.7	3.1
7	1.3	1.7	0.7	0.4	0.0	1.4	0.9	1.2	3.2	0.6	1.7	0.2	2.1	0.5	1.2	2.8	2.5	2.2
8	4.8	4.9	4.8	4.5	4.7	4.9	4.9	4.8	4.9	4.7	4.2	4.3	4.4	4.9	4.9	4.9	4.4	4.9
10	1.7	1.9	1.8	1.3	1.5	2.7	2.2	2.1	2.6	1.6	2.0	0.6	1.8	2.4	1.0	2.4	2.5	3.9
11	2.3	3.3	2.4	2.0	3.5	2.7	3.9	4.2	4.2	3.1	3.1	2.4	2.6	3.2	3.2	3.3	2.5	4.1
12	2.2	2.8	2.5	2.0	1.5	1.7	2.3	1.8	2.5	2.4	3.1	0.6	2.0	1.8	1.5	2.5	2.8	2.7
13	3.5	3.8	3.3	2.7	3.3	3.1	3.9	4.7	4.8	3.8	3.9	3.6	3.6	4.3	3.6	4.7	3.3	4.6
14	2.9	4.5	2.8	4.0	4.5	3.5	4.1	5.0	4.8	3.9	3.5	2.9	4.0	4.2	4.0	4.7	3.8	4.1
15	2.5	3.8	2.6	1.0	2.5	2.4	2.8	3.2	4.6	4.6	3.2	2.7	1.8	2.9	1.4	4.0	3.3	4.2
16	1.6	3.2	1.7	0.7	1.0	1.6	1.9	2.3	3.8	2.8	2.3	2.4	2.7	2.6	2.2	2.8	2.4	3.1
17	3.2	4.7	3.2	3.7	3.4	3.5	3.9	3.5	4.8	4.0	3.8	4.1	3.9	3.3	3.3	4.1	3.7	4.4
18	3.6	4.5	2.5	4.7	4.5	4.0	4.1	4.9	4.8	4.7	4.1	3.8	4.2	4.3	4.1	4.8	4.0	4.5
20	3.9	3.9	4.3	4.1	3.6	3.9	3.6	4.0	4.6	2.5	3.2	2.3	3.8	4.5	3.8	4.8	3.4	4.8
21	1.8	1.8	1.3	2.8	2.4	2.3	2.0	2.8	3.4	2.6	2.6	0.5	2.6	2.2	2.1	3.3	2.8	3.7
22	3.2	3.6	2.7	3.3	3.0	4.2	2.9	2.5	4.1	2.4	3.0	3.8	3.1	2.9	3.1	4.3	4.0	3.8
24	2.4	2.9	3.5	2.9	4.0	3.4	2.7	4.0	3.4	4.1	3.6	2.1	2.7	2.6	2.9	3.6	3.2	3.8

(Continued)

TABLE 10. (CONTINUED)

Position	Drivers' Group				Right Front Group					Left Rear Group				Right Rear Group				
Rater No.	16	17	18	19	3	6	8	9	12	1	4	13	14	2	5	7	11	15
25	4.1	4.8	3.7	4.6	3.8	4.2	3.0	4.8	4.9	3.4	3.1	3.7	4.2	3.8	3.0	4.6	4.4	4.6
26	2.7	2.6	1.8	2.7	2.5	3.1	1.8	2.7	3.8	2.7	3.2	1.7	3.2	2.4	3.1	3.3	2.8	3.7
27	2.3	2.7	2.2	2.1	1.5	3.2	2.4	2.5	3.7	2.4	3.7	1.8	1.9	2.3	3.7	3.2	3.4	3.7
28	3.2	4.2	3.3	3.6	4.0	3.4	3.6	4.6	4.8	4.4	3.5	4.6	3.3	3.5	3.1	4.3	3.3	4.1
29	4.1	3.7	4.4	3.8	3.8	4.6	2.4	4.1	4.7	4.7	3.4	2.4	2.5	3.6	3.0	4.6	4.0	4.1
30	2.1	3.2	1.0	2.4	1.0	2.4	1.2	2.9	3.4	3.5	2.8	0.6	3.1	3.2	2.0	2.9	2.5	2.6
31	2.2	2.8	1.2	0.9	2.5	3.2	2.8	2.1	2.9	2.4	2.3	0.1	2.6	1.8	1.2	2.5	2.5	2.8
32	4.4	4.2	3.1	4.0	4.0	3.8	3.8	4.9	4.9	4.9	3.2	3.5	4.1	3.6	3.9	4.4	3.7	4.3
33	1.7	3.5	2.0	1.8	2.3	2.9	2.1	2.9	3.7	3.1	2.6	1.4	2.0	2.1	2.6	3.2	2.7	3.1
34	4.6	4.1	4.9	3.4	4.2	4.8	4.9	4.8	4.8	3.7	4.0	4.0	4.6	4.9	3.9	4.8	4.0	4.2
35	3.2	3.4	4.2	1.4	1.6	3.2	2.9	3.1	3.9	1.4	3.9	2.4	3.2	2.7	2.1	3.4	3.2	3.1
36	0.6	1.5	1.0	0.6	0.6	0.5	0.9	0.8	2.1	0.7	2.2	0.5	1.8	0.3	1.0	0.9	1.4	1.8
37	2.8	3.3	2.7	3.5	2.9	3.3	3.9	2.5	4.8	3.3	3.3	3.6	2.8	3.3	3.0	3.8	2.9	3.8
38	2.4	3.3	3.0	1.8	0.8	1.6	2.8	3.2	3.7	2.4	2.5	1.4	1.9	0.7	1.3	3.1	2.4	2.2
39	0.6	1.6	1.7	0.6	1.5	1.1	1.7	1.9	3.2	0.7	2.2	0.2	1.6	1.9	1.0	2.8	3.4	1.3
40	1.4	2.5	3.4	2.0	0.5	1.6	2.4	3.2	2.8	0.6	2.1	2.3	2.6	2.2	1.8	2.9	2.5	2.1
41	2.5	2.7	2.2	1.9	3.8	2.7	3.1	2.9	3.8	2.3	2.6	2.6	3.2	3.1	2.1	2.9	2.0	2.9
42	1.9	1.8	2.7	1.5	1.4	1.4	1.2	1.1	2.6	0.9	2.1	0.6	2.7	1.5	1.0	2.8	2.4	2.3
44	2.0	2.7	3.0	2.3	4.0	3.1	3.2	3.0	4.2	2.5	3.3	2.1	2.9	2.9	3.1	3.8	3.2	3.6
45	3.9	3.7	3.3	3.7	4.9	4.3	3.9	4.0	4.8	4.2	3.3	3.8	3.7	3.1	3.8	4.3	4.0	4.3
46	3.8	3.5	3.5	4.0	4.1	3.5	3.5	3.1	4.3	2.8	3.1	3.5	3.8	3.8	2.8	3.8	4.0	4.8
47	4.2	4.5	3.7	3.7	4.6	3.4	3.9	4.9	4.9	4.0	4.0	4.5	4.1	4.5	3.3	4.3	4.1	4.4
48	4.6	4.4	3.9	4.7	4.0	4.0	4.8	4.1	4.9	4.6	4.0	4.7	3.9	4.2	4.0	4.7	4.2	4.9

(Continued)

TABLE 10. (Continued)

Position	Drivers Group				Right Front Group					Left Rear Group				Right Rear Group				
Rater No.	16	17	18	19	3	6	8	9	12	1	4	13	14	2	5	7	11	15
49	3.7	4.2	3.5	4.0	3.9	4.0	3.9	4.9	4.9	4.2	3.5	4.7	3.8	4.6	3.4	4.6	4.0	4.9
Total	128.8	153.4	123.2	121.7	131.1	136.8	134.7	154.9	183.9	136.1	140.5	116.2	138.5	136.0	124.6	167.4	146.2	164.0
Group Totals				527.1					741.4				531.3					738.2
Grand Total																		2538.0

TABLE 11. ANOVA FOR DATA FROM TABLE 10

Source of Variation	Degrees of Freedom		Sum of Squares		Mean Square
All Raters (AR)	17		119.4089		15.23
Drivers Group vs Raters Group	1		9.7258		
(c) Drivers in Drivers Gp.	3		14.4784		4.83
Raters in Raters Gp.	13		95.2047		7.32
Partitioning of Raters SS	df	SS	MS		
(b) Position in Vehicle	2	14.5667	7.28		
Raters in Rt. Front	4	42.7548	10.68	Pooled MS* 7.33	
Raters in Lt. Rear	3	8.4051	2.80		
Raters in Rt. Rear	4	29.4780	7.37		
	13	95.2046			
Sections (S)	44		670.2000		7.0241
Residual	748		224.4911		0.3001
TOTAL	809		1014.1000		

* Pooled MS for positions $= \dfrac{42.7548 + 8.4051 + 29.4780}{4 + 3 + 4} = 7.33$

TABLE 12. F-TESTS ON SOURCES OF VARIATION FROM TABLE 11

(a) F-Test for variations among raters within positions:

$$F_{4,3} \text{ (Calculated)} = \frac{10.68}{2.80} = 3.81 < 5.34$$

$F_{4,3}$ (0.90) = 5.34 $F_{4,3}$ (0.75) = 2.39

Since the $F_{4,3}$ (Calculated) is smaller than the $F_{4,3}$ (0.90), we can accept the hypothesis that the variations among raters was about the same no matter what position they occupied in the vehicle. This allows the "pooling" of the SS from the three positions for subsequent testing.

(b) F-Test for variations in rating due to position in the vehicle:

$$F_{2,13} \text{ (Calculated)} = \frac{7.28}{7.33} = 0.99 < 1.55$$

$F_{2,13}$ (0.90) = 2.78 $F_{2,13}$ (0.75) = 1.55

Therefore, we can accept the hypothesis that the average ratings for the three positions are the same. We can pool all three for the average PSR.

(c) F-Test for variations between raters and drivers:

$$F_{13,3} \text{ (Calculated)} = \frac{7.32}{4.83} = 1.51 < 2.45$$

$F_{13,3}$ (0.90) = 5.21 $F_{13,3}$ (0.75) = 2.45

Therefore in general the drivers and raters rate the sections overall the same.

(d) F-Test for variations within all raters:

$$F_{17,748} \text{ (Calculated)} = \frac{15.23}{0.30} = 50.8 >> 1.48$$

$F_{17,00}$ (0.90) = 1.48 $F_{17,00}$ (0.75) = 1.21

TABLE 13. DUPLICATE SECTION PSR VALUES FOR RATING PERIOD ONE

	Male Raters								Female Raters					
Rater No.	2	4	5	6	7	8	9	15	1	3	11	12	13	14
Section Number 34	4.9	4.0	3.9	4.8	4.8	4.9	4.8	4.2	3.7	4.2	4.0	4.8	4.0	4.6
35	2.7	3.9	2.1	3.2	3.4	2.9	3.1	3.1	1.4	1.6	3.2	3.9	2.4	3.2
36	0.3	2.2	1.0	0.5	0.9	0.9	0.8	1.8	0.7	0.6	1.4	2.1	0.5	1.8
37	3.3	3.3	3.0	3.3	3.8	3.9	2.5	3.8	3.3	2.9	2.9	4.8	3.6	2.8
38	0.7	2.5	1.3	1.6	3.1	2.8	3.2	2.2	2.4	0.8	2.4	3.7	1.4	1.9
39	1.9	2.2	1.0	1.1	2.8	1.7	1.9	1.3	0.7	1.5	3.4	3.2	0.2	1.6
40	2.2	2.1	1.8	1.6	2.9	2.4	3.2	2.1	0.6	0.5	2.5	2.8	2.3	2.6
41	3.1	2.6	2.1	2.7	2.9	3.1	2.9	2.9	2.3	3.8	2.0	3.8	2.6	3.2
42	1.5	2.1	1.0	1.4	2.8	1.2	1.1	2.3	0.9	1.4	2.4	2.6	0.6	2.7
45	3.1	3.3	3.8	4.3	4.3	3.9	4.0	4.3	4.2	4.9	4.0	4.8	3.8	3.7
46	3.8	3.1	2.8	3.5	3.8	3.5	3.1	4.8	2.8	4.1	4.0	4.3	3.5	3.8
47	4.5	4.0	3.3	3.4	4.3	3.9	4.9	4.4	4.0	4.6	4.1	4.9	4.5	4.1
48	4.2	4.0	4.0	4.0	4.7	4.8	4.1	4.9	4.6	4.0	4.2	4.9	4.7	3.9
51	4.8	4.2	4.0	4.5	4.3	4.3	4.9	4.8	4.9	4.6	3.7	4.9	4.9	4.2
52	3.6	3.8	3.4	3.1	3.1	2.2	4.1	4.1	3.6	2.5	3.0	4.5	2.3	3.4
62	0.4	2.5	1.4	1.3	1.2	0.8	0.9	2.8	2.1	0.5	2.4	2.8	0.1	1.5
53	3.6	3.3	2.9	3.3	3.0	2.0	3.8	3.0	4.9	3.6	3.2	3.6	2.6	2.9
54	1.5	3.1	1.3	2.7	2.7	1.2	2.5	2.9	2.5	0.1	3.0	3.5	0.2	2.1
55	0.9	2.1	2.1	1.8	3.1	0.3	0.3	1.9	0.7	1.6	2.7	2.6	0.0	1.9
56	0.9	2.2	2.0	2.1	2.4	1.2	2.5	3.1	1.4	1.2	2.8	2.6	2.1	3.7
63	2.5	2.8	2.9	2.7	3.5	1.9	1.7	3.1	2.8	2.7	2.0	3.7	2.4	3.1
57	1.6	3.1	2.0	2.1	2.8	1.9	0.4	2.7	1.8	0.3	2.4	2.3	1.5	2.8
59	3.5	3.2	4.0	3.6	4.4	3.2	4.7	4.8	3.4	3.0	3.2	4.9	2.9	4.1
60	3.4	3.6	3.2	3.2	2.8	2.0	3.1	4.7	2.6	3.3	3.4	4.9	0.6	4.0
50	4.3	4.1	4.0	3.5	4.5	3.8	4.9	4.5	4.3	4.0	4.0	5.0	4.3	4.1
61	4.6	3.9	3.8	4.1	4.6	3.5	3.8	4.9	4.1	4.4	4.2	4.9	3.9	4.3
Totals	71.8	81.2	68.1	73.4	86.9	68.2	77.2	89.4	70.7	66.7	80.5	100.8	62.2	82.0
Block Totals						616.2								462.9
Grand Total														1079.1

TABLE 14. ANOVA FOR RATING PERIOD ONE DUPLICATE SECTIONS

Source of Variation	Degrees of Freedom		Sum of Squares	Mean Squares
Sections (S)	12		390.7460	
Raters (R)	13		55.1739	
Partitioning Rater SS	df	SS	MS	
Between Men & Women Groups	1	0.0020	0.0020	
Within the Men Raters	7	17.9267	2.5710	
Within the Women Raters	5	37.2452	7.4490	
	13	55.1739		
Duplicates (D)	1		0.0022	0.0022
S × R	156		73.1378	
S × D	12		5.6339	0.4695
R × D	13		12.8197	
Residual	156		30.4392	
TOTAL	363		567.9527	

TABLE 15. F-TESTS OF INTEREST FOR THE ANOVA IN TABLE 14

Source of Variation	F-Calculated	Degrees of Freedom		F_{ν_1,ν_2}		Significance Level	
		ν_1	ν_2	90%	75%	90%	75%
Within the Women Raters	$\frac{7.4490}{2.5710} = 2.82$	5	7	2.88	1.71		X**
Between Men and Women Groups	$\frac{0.0020}{4.58^*} = 0.00$	1	13	60.9	9.44		
Duplicates (D)	$\frac{0.0022}{0.4695} = 0.00$	1	12	60.7	9.41		

$$* \text{ Pooled MS } = \frac{17.9267 + 37.2452}{7 + 5} = 4.58$$

**Significant at 75 percent level.

Rating Period Two

The second rating period was conducted in the general Dallas-Fort Worth area from August 19 through 22, 1968. Fifty pavements of varying quality were selected. These pavements provided the widest possible range of PSR within each of the four types within a radius of about 60 miles of either city. The sections were selected in conjunction with the personnel of Districts 2 and 18 of the Texas Highway Department, from the Interstate, U. S., State, Farm-to-Market, and Ranch-to-Market Highway Systems. The routes for these sections were developed in the same manner as the first rating period's.

Three of the panel members were unable to attend the second rating period, and because of the short notice of the impending absences no effort was made to replace these members with additional substitutions. The following analyses include only 12 rating panel members.

The PSR data collected during the second rating period are shown in Table 16. They include ratings for all sections except the second ratings for those which were used as duplicates. A mixed model, cross-classified, nested analysis of variance design was used on these data, with positions again fixed and sections and raters considered random. The results of this analysis are shown in Table 17. The F-tests of interest are shown in Table 18. The results of these tests indicate (1) that the variations among raters within positions were not significant; (2) that there are no significant effects because of positions in the vehicle; (3) that the raters and drivers, generally, rate the pavements alike; and (4) that there are highly significant rater-to-rater variations.

The PSR data for the sections which were rerated are shown in Table 19. In this table, section 64 corresponds to section 114, 65 to 115, and so forth, with the smaller number referring to the first rating value. A mixed model ANOVA was run on these data and the results are shown in Table 20. As before, the sections and raters are considered as random while the duplicates are fixed effects. The F-tests of interest are shown in Table 21. These involved (1) testing for a difference in variations within the female raters by using the variations within the male raters to test, (2) testing for a significant difference between the male and female groups, and (3) testing for a significant effect because of rerating the sections (duplicates). From the test results shown in Table 21, it can be stated (1) that the variations within the male

TABLE 16. PSR DATA FOR RATING SESSION TWO

Position / Rater No.		Driver's Group				Right Front Group					Lt. Rear Gp.		Right Rear Group				
		16	17	18	19	3	6	8	9	12	1	4	2	5	7	11	15
Section Number	64	2.8	3.1	3.1	4.3	3.1	2.6	3.0	4.0	4.8	4.3	3.7	3.7	4.1	3.6	3.4	4.1
	65	4.4	4.2	4.3	4.4	4.2	4.2	4.7	4.8	5.0	4.4	4.1	3.8	4.3	4.8	4.0	4.8
	66	3.7	2.3	3.0	3.8	2.0	2.6	3.4	3.1	4.7	3.1	3.2	3.2	3.1	4.4	3.3	4.2
	67	3.2	3.3	2.5	3.0	3.9	3.3	3.9	3.1	4.1	2.8	2.3	2.4	2.4	4.3	3.0	3.9
	68	3.2	1.5	2.2	2.7	3.0	2.9	3.8	3.9	4.4	2.5	2.9	2.5	2.3	4.1	2.7	3.8
	69	4.2	2.2	4.0	2.7	1.1	4.2	4.7	2.8	4.2	3.5	3.3	3.8	2.1	3.3	3.4	4.1
	70	2.3	3.1	2.3	2.9	1.6	2.6	3.1	2.5	3.7	2.5	2.5	2.0	2.5	4.1	3.9	4.2
	71	3.4	4.1	2.0	4.0	4.0	3.3	4.1	4.3	4.7	4.2	4.1	3.3	3.7	3.6	3.1	4.2
	72	3.1	2.2	2.4	3.4	2.6	2.9	3.3	3.8	3.8	3.9	2.5	2.7	3.4	3.4	3.0	3.3
	73	3.3	3.9	3.7	3.9	4.0	3.2	4.1	3.9	4.6	3.8	3.2	3.6	4.1	4.2	3.4	4.2
	74	3.2	3.9	3.1	4.0	3.6	3.2	3.6	3.8	4.2	4.2	3.5	3.7	3.5	4.1	2.8	4.3
	75	2.5	1.9	2.5	2.8	1.9	3.1	3.0	3.1	3.8	2.8	2.5	2.4	2.3	3.4	3.2	4.3
	76	4.3	3.8	4.7	3.8	3.8	3.9	4.7	4.5	4.8	4.8	3.8	4.9	4.1	4.3	4.0	4.8
	77	4.4	4.5	4.7	4.3	4.1	4.7	4.9	4.3	4.9	4.2	4.3	4.8	4.0	4.7	3.5	4.8
	78	3.4	3.4	3.0	3.6	3.7	3.6	3.3	3.5	4.8	3.7	3.2	3.1	3.0	4.5	3.2	4.4
	79	4.7	4.9	4.7	4.5	4.8	4.7	4.8	4.9	4.9	4.1	3.8	3.3	4.5	4.8	4.0	4.9
	80	4.9	4.6	5.0	4.5	4.9	4.6	5.0	4.9	4.9	4.7	3.7	4.9	4.3	4.8	4.0	4.9
	81	3.9	3.9	3.3	3.8	2.5	3.4	3.2	4.2	4.7	4.4	3.7	3.0	4.3	4.3	3.5	4.5

(continued)

TABLE 16. (CONTINUED)

Position Rater No.	Drivers' Group				Right Front Group					Lt. Rear Gp.		Right Rear Group				
	16	17	18	19	3	6	8	9	12	1	4	2	5	7	11	15
Section Number																
82	3.3	4.3	3.2	4.1	4.0	3.2	3.9	4.4	4.3	4.7	3.3	4.1	4.2	4.0	4.0	4.9
83	1.5	2.9	2.0	2.6	2.0	1.9	2.3	2.4	2.9	2.3	2.9	1.3	1.1	3.0	2.6	3.2
84	2.2	2.0	2.2	2.9	1.0	2.5	1.9	1.5	3.6	1.5	3.1	2.8	1.5	4.2	3.6	2.8
85	2.2	2.4	3.9	3.6	1.8	2.1	2.2	2.8	3.4	2.1	2.9	2.6	2.8	3.2	2.6	3.1
86	1.9	1.7	2.4	3.1	1.7	2.3	2.5	2.0	3.5	0.8	1.7	1.5	2.9	4.0	3.1	3.8
87	2.2	1.3	2.0	4.2	3.0	1.8	3.1	2.6	3.9	3.5	2.2	1.9	3.1	3.6	2.5	3.1
88	2.8	3.9	3.0	3.8	3.7	2.9	3.6	4.1	4.4	2.1	3.1	3.1	2.8	4.2	3.1	4.3
89	2.0	2.6	2.0	3.2	1.9	1.7	3.3	2.5	3.2	1.4	2.1	2.5	3.4	4.1	3.0	2.8
90	3.5	3.8	2.7	3.9	3.3	3.1	3.9	3.9	3.8	3.2	3.5	3.4	3.7	3.9	3.4	3.9
91	2.7	3.7	2.8	3.6	3.7	2.5	3.4	3.1	4.2	2.7	3.0	3.2	3.0	4.4	3.1	4.6
92	2.6	4.0	3.0	3.5	3.0	3.3	3.3	3.4	3.9	2.6	3.7	3.3	3.3	4.0	3.4	4.6
93	3.2	4.6	4.0	4.0	3.9	4.4	4.9	4.9	4.7	3.3	3.8	4.4	4.2	3.9	3.0	4.5
94	3.1	3.7	3.4	3.4	3.2	3.2	3.8	4.1	3.6	3.8	3.7	4.1	2.8	4.2	3.3	4.3
95	2.9	4.3	2.8	3.8	4.1	3.4	3.5	3.8	4.7	4.0	2.8	3.3	3.8	4.2	3.6	4.5
96	3.4	4.3	3.8	4.0	4.8	4.1	3.8	4.5	4.6	3.7	3.4	4.4	4.3	4.4	4.0	4.9
97	3.1	3.4	2.9	3.4	2.0	3.0	3.1	3.9	4.7	4.7	3.2	2.5	3.0	3.8	3.7	4.5
98	3.8	5.0	3.7	4.0	4.7	4.7	3.6	4.8	4.9	4.4	4.4	3.4	4.2	4.5	4.0	4.9
99	3.8	4.0	3.1	4.6	4.3	4.1	3.2	3.2	4.3	3.6	3.5	3.6	3.9	4.2	3.0	4.8

(continued)

TABLE 16. (CONTINUED)

Position Rater No.	Drivers' Group				Right Front Group					Lt. Rear Gp.		Right Rear Group				
Section Number	16	17	18	19	3	6	8	9	12	1	4	2	5	7	11	15
100	3.7	4.1	3.4	4.5	4.0	3.7	3.7	4.1	4.7	4.2	3.9	3.7	4.4	3.6	3.7	4.6
101	2.6	3.4	3.6	3.7	3.0	2.7	3.1	3.4	4.3	4.5	3.4	2.9	3.4	4.0	3.3	4.6
102	3.3	3.3	3.1	3.4	3.0	3.9	3.5	3.5	4.6	3.7	3.1	3.2	3.4	4.4	3.7	4.7
103	3.8	4.8	2.7	4.5	5.0	3.4	3.2	3.9	4.8	3.5	3.7	3.3	4.5	4.1	3.3	4.5
104	0.6	2.5	2.3	2.3	0.7	2.2	2.2	2.1	4.8	2.4	2.7	2.2	1.8	2.7	2.2	3.7
105	0.4	0.5	0.9	1.7	0.1	0.6	0.2	0.7	0.8	1.8	1.6	1.2	0.7	1.7	1.4	2.8
106	0.4	0.5	0.9	1.3	0.0	0.2	0.9	0.9	1.6	1.3	1.8	1.3	0.4	1.3	0.4	2.9
107	3.9	4.5	3.5	3.8	3.5	3.4	3.6	4.9	4.3	3.6	3.1	3.8	3.7	4.3	3.2	4.8
108	1.7	3.7	2.6	3.0	1.5	2.2	2.8	2.8	2.2	3.4	2.8	3.4	2.3	3.0	2.5	3.9
109	2.5	1.8	1.8	3.3	0.5	1.1	2.2	2.0	4.2	2.8	2.3	3.1	2.0	4.0	3.4	4.2
110	3.8	4.4	4.4	4.2	4.0	3.5	4.1	4.7	4.9	4.7	3.7	4.8	4.2	4.5	4.0	4.9
111	2.7	3.9	4.0	3.9	4.5	4.0	4.1	2.9	3.9	3.7	4.3	4.9	3.3	4.2	3.5	4.7
112	3.8	3.9	4.0	3.5	4.0	4.1	3.5	4.1	4.9	4.8	3.7	4.0	4.1	4.3	4.0	4.8
113	4.6	4.9	5.0	4.8	4.8	4.8	5.0	4.8	5.0	4.3	4.1	5.0	4.8	4.8	4.0	4.8
Total	152.9	168.9	155.6	180.0	153.5	157.0	172.0	176.1	208.6	171.0	160.8	163.3	163.0	197.4	163.0	211.1
Group Totals				657.4					867.2		331.8					897.8
Grand Total																2754.2

TABLE 17. ANOVA FOR DATA FROM TABLE 16

Source of Variation		Degrees of Freedom	Sum of Squares	Mean Squares
All Raters (AR)		15	103.3759	10.42
Drivers Group vs Raters Group		1	1.4688	
(c) Drivers in Drivers Group		3	9.4658	3.16
Raters in Raters Group		11	87.4413	7.94
		15	103.3759	

Partitioning of Raters SS	df	SS	MS	
(b) Position in vehicle	2	5.6181	2.81	
Raters in Rt. Front	4	38.2650	9.56	
(a) Raters in Lf. Rear	1	1.0404	1.04	Pooled MS*
Raters in Rt. Rear	4	42.5178	10.63	
	11	87.4413		

	Degrees of Freedom	Sum of Squares	Mean Squares
Sections (S)	49	510.3392	6.89
Residual	735	191.9428	0.26
TOTAL	799	805.6579	

* Pooled MS for positions $= \dfrac{38.2650 + 1.0404 + 42.5178}{4 + 1 + 4} = 9.09$

TABLE 18. F-TESTS ON SOURCES OF VARIATION FROM TABLE 17

(a) F-Test for variations among raters within positions:

$$F_{4,1} \text{ (Calculated)} = \frac{10.63}{1.04} = 10.22 < 55.8$$

$F_{4,1}$ (0.90) = 55.8 $\quad\quad$ $F_{4,1}$ (0.75) = 8.58

Since the $F_{4,1}$ (Calculated) is smaller than the $F_{4,1}$ (0.90) , we can accept the hypothesis that the variation among raters was about the same no matter what position they occupied in the vehicle. This allows the "pooling" of the SS from the three positions for subsequent testing.

(b) F-Test for variations in rating due to position in the vehicle:

$$F_{2,9} \text{ (Calculated)} = \frac{2.81}{9.09} = 0.31 < 1.62$$

$F_{2,9}$ (0.90) = 3.01 $\quad\quad$ $F_{2,9}$ (0.75) = 1.62

Therefore, we can accept the hypothesis that the average ratings for the positions are the same. We can pool all three positions for the average PSR.

(c) F-Test for variations between raters and drivers:

$$F_{11,3} \text{ (Calculated)} = \frac{7.94}{3.16} = 2.51 < 5.22$$

$F_{11,3}$ (0.90) = 5.22 $\quad\quad$ $F_{11,3}$ (0.75) = 2.45

Therefore, in general, the drivers and raters rate the sections, overall, the same.

(d) F-Test for variations within all raters:

$$F_{15,\ 735} \text{ (Calculated)} = \frac{10.42}{0.26} = 40.01 >> 1.49$$

$F_{15,00}$ (0.90) = 1.49 $\quad\quad$ $F_{15,00}$ (0.75) = 1.22

TABLE 19. PSR VALUES FOR DUPLICATE SECTIONS FOR RATING PERIOD TWO

	Male Raters								Female Raters			
Rater No.	2	4	5	6	7	8	9	15	1	3	11	12
Section Number 64	3.7	3.7	4.1	2.6	3.6	3.0	4.0	4.1	4.3	3.1	3.4	4.8
65	3.8	4.1	4.3	4.2	4.8	4.7	4.8	4.8	4.4	4.2	4.0	5.0
66	3.2	3.2	3.1	2.6	4.4	3.4	3.1	4.2	3.1	2.0	3.3	4.7
67	2.4	2.3	2.4	3.3	4.3	3.9	3.1	3.9	2.8	3.9	3.0	4.1
68	2.5	2.9	2.3	2.9	4.1	3.8	2.9	3.8	2.5	3.0	2.7	4.4
69	3.8	3.3	2.1	4.2	3.3	4.7	2.8	4.1	3.5	1.1	3.4	4.2
71	3.3	4.1	3.7	3.3	3.6	4.1	4.3	4.2	4.2	4.0	3.1	4.7
72	2.7	2.5	3.4	2.9	3.4	3.3	3.8	3.3	3.9	2.6	3.0	3.8
73	3.6	3.2	4.1	3.2	4.2	4.1	3.9	4.2	3.8	4.0	3.4	4.6
74	3.7	3.5	3.5	3.2	4.1	3.6	3.8	4.3	4.2	3.6	2.8	4.2
75	2.4	2.5	2.3	3.1	3.4	3.0	3.1	4.3	2.8	1.9	3.2	3.8
76	4.9	3.8	4.1	3.9	4.3	4.7	4.5	4.8	4.8	3.8	4.0	4.8
78	3.1	3.2	3.0	3.6	4.5	3.3	3.5	4.4	3.7	3.7	3.2	4.8
79	3.3	3.8	4.5	4.7	4.8	4.8	4.9	4.9	4.1	4.8	4.0	4.9
80	4.9	3.7	4.3	4.6	4.8	5.0	4.9	4.9	4.7	4.9	4.0	4.9
114	3.2	3.4	3.8	3.4	4.2	3.3	2.9	4.5	3.2	3.7	2.5	4.6
115	3.6	4.5	4.5	4.5	4.3	4.3	4.9	4.8	4.8	4.7	4.3	4.8
116	3.4	3.2	3.0	3.3	4.3	3.5	3.1	4.9	2.7	2.1	3.7	4.7
117	3.2	3.1	3.5	3.9	4.3	3.6	3.2	4.7	3.7	3.4	3.0	4.6
118	3.5	3.0	3.1	3.0	4.0	3.4	3.9	4.3	2.4	3.2	2.8	4.3
119	3.5	2.3	1.6	3.6	4.3	2.8	4.6	4.8	3.9	1.9	3.5	4.3
120	4.2	3.3	3.7	3.7	3.8	4.0	4.8	4.6	4.6	4.0	3.3	4.9
121	3.5	2.6	3.3	3.2	3.7	2.8	3.1	4.4	2.7	2.9	3.0	3.5
122	3.0	3.8	3.7	3.1	4.3	3.4	3.8	4.1	4.1	2.3	3.0	4.6
123	3.4	2.7	3.9	3.0	4.0	3.1	3.4	4.6	3.4	2.3	2.4	3.8
124	2.6	2.9	3.0	2.9	3.5	2.8	3.2	4.2	3.8	2.7	2.8	3.7
125	4.6	4.2	4.2	4.2	4.5	4.1	4.8	4.6	3.7	3.3	3.7	4.7
126	4.3	3.2	2.4	3.8	4.5	3.4	4.0	4.8	3.5	3.1	3.5	4.5
127	4.2	4.2	4.3	4.3	4.7	4.4	4.8	4.9	4.2	4.0	4.4	4.9
128	4.6	4.7	4.5	4.6	4.7	4.8	4.8	4.9	4.8	4.7	4.2	5.0
Totals	106.1	100.9	103.7	106.8	124.7	113.1	116.7	133.3	112.3	98.4	100.6	134.6
Block Totals								905.3				445.9
Grand Total												1351.2

TABLE 20. ANOVA FOR DATA FROM TABLE 19

Source of Variation				Degrees of Freedom	Sum of Squares	Mean Squares
Sections (S)				14	83.0093	
Raters (R)				11	57.1227	
Partitioning Rater SS	df	SS	MS			
Between Men and Womens Groups	1	0.2530	0.2530			
Within Men Raters	7	29.3807	4.1972			
Within Women Raters	3	27.4890	9.1630			
	11	57.1227				
Duplicates (D)				1	0.0871	0.0871
S × R				154	40.0240	
S × D				14	3.4146	0.2439
R × D				11	3.0182	
Residual				154	20.5001	0.1331
TOTAL				359	207.1760	

TABLE 21. F-TESTS OF INTEREST FOR THE ANOVA IN TABLE 20

Source of Variation	F-Calculated	Degrees of Freedom ν_1	ν_2	F_{ν_1,ν_2} 90%	75%	Significance Level 90%	75%
Within the Women Raters	$\frac{9.1630}{4.1972} = 2.19$	3	7	3.07	1.72		X
Between Men and Women Groups	$\frac{0.2530}{5.6870^*} = 0.04$	1	10	3.28	1.49		
Duplicates (D)	$\frac{0.0871}{0.2439} = 0.36$	1	14	3.11	1.44		

$$* \text{ Pooled MS} = \frac{29.3807 + 27.4890}{7 + 3} = 5.6870$$

and female groups are about the same, (2) that there is essentially no difference in rating values between the groups, and (3) that the second rating value is essentially the same as the first one.

The other information which was available from the rating forms for both rating periods has been combined for analysis purposes. Since a percent basis is used to display these data, it was appropriate to display all the combined data in one set of plots. Figure 14 shows the plot of percent acceptability on the Interstate System versus PSR. At a PSR level of about 3.4, 50 percent of the rating panel said that roadway was acceptable on the Interstate System. Figure 15 shows that 50 percent of the rating panel said that if a roadway had a PSR of about 1.9 or higher it was acceptable on the Secondary Highway System. These two figures imply that if a highway is designated as Interstate and more than half the people are to be satisfied, the PSR level should not be allowed to drop below about 3.4 and on the Secondary System the level should not drop below about 1.9.

For the figures representing the minor effect of the factors affecting the rating, it is interesting to point out that none of the data showed a definable trend and these plots are omitted. However, each set of data in Figs 16, 17, 18, 19, and 20 shows a definite trend relating PSR to the major effect of each factor affecting the rating. It is interesting to note that only Fig 17 shows that more than 20 percent of the people indicated a major effect of any factor for a pavement above about the 3.4 PSR level. Judging from these plots one would expect that a function relating PSR to measurable roadway characteristics should include terms for longitudinal and transverse distortions, cracking, patching, and rutting. Such a function will be derived in the subsequent chapters.

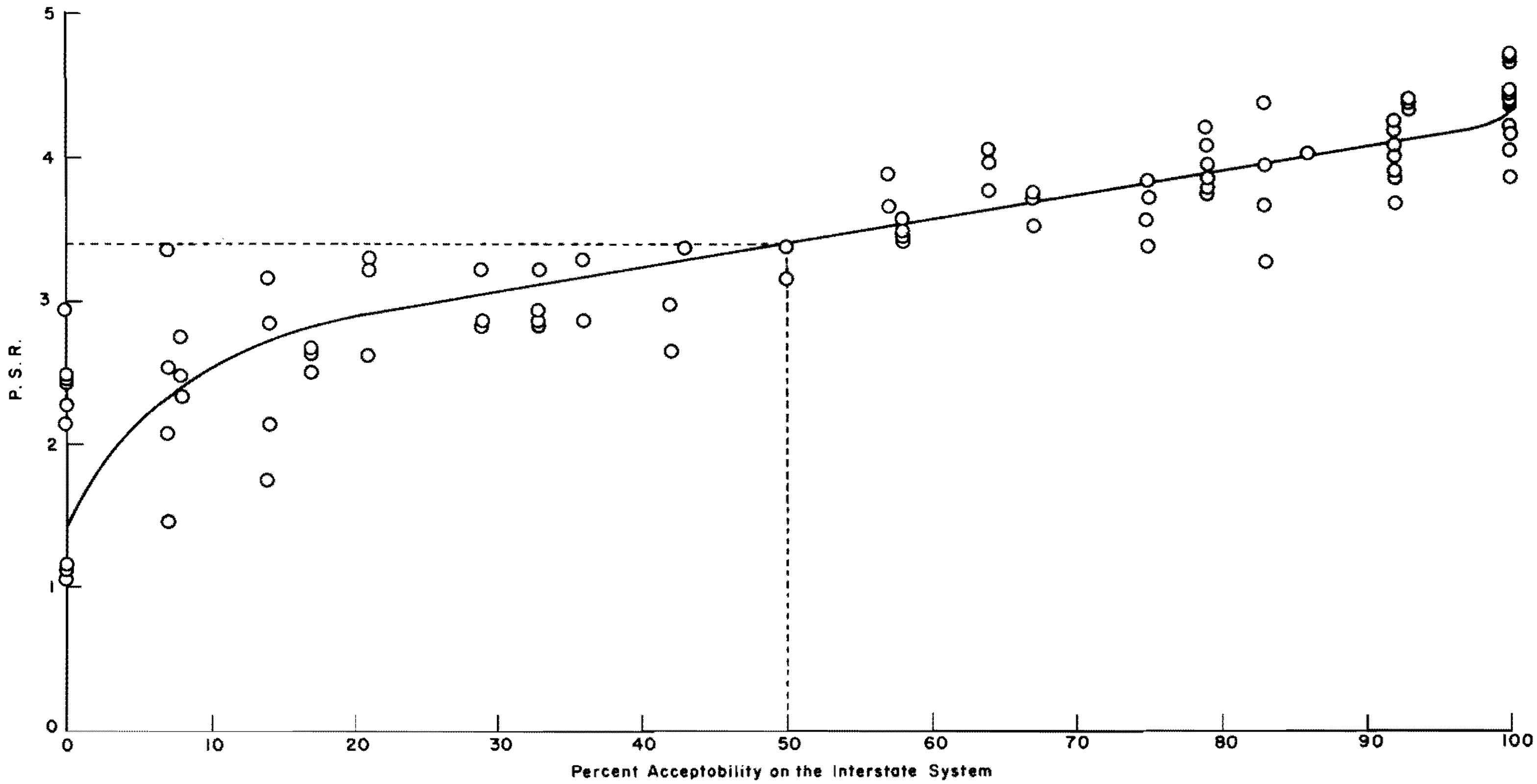


Fig 14. Percent acceptability on the Interstate System - rating periods one and two.

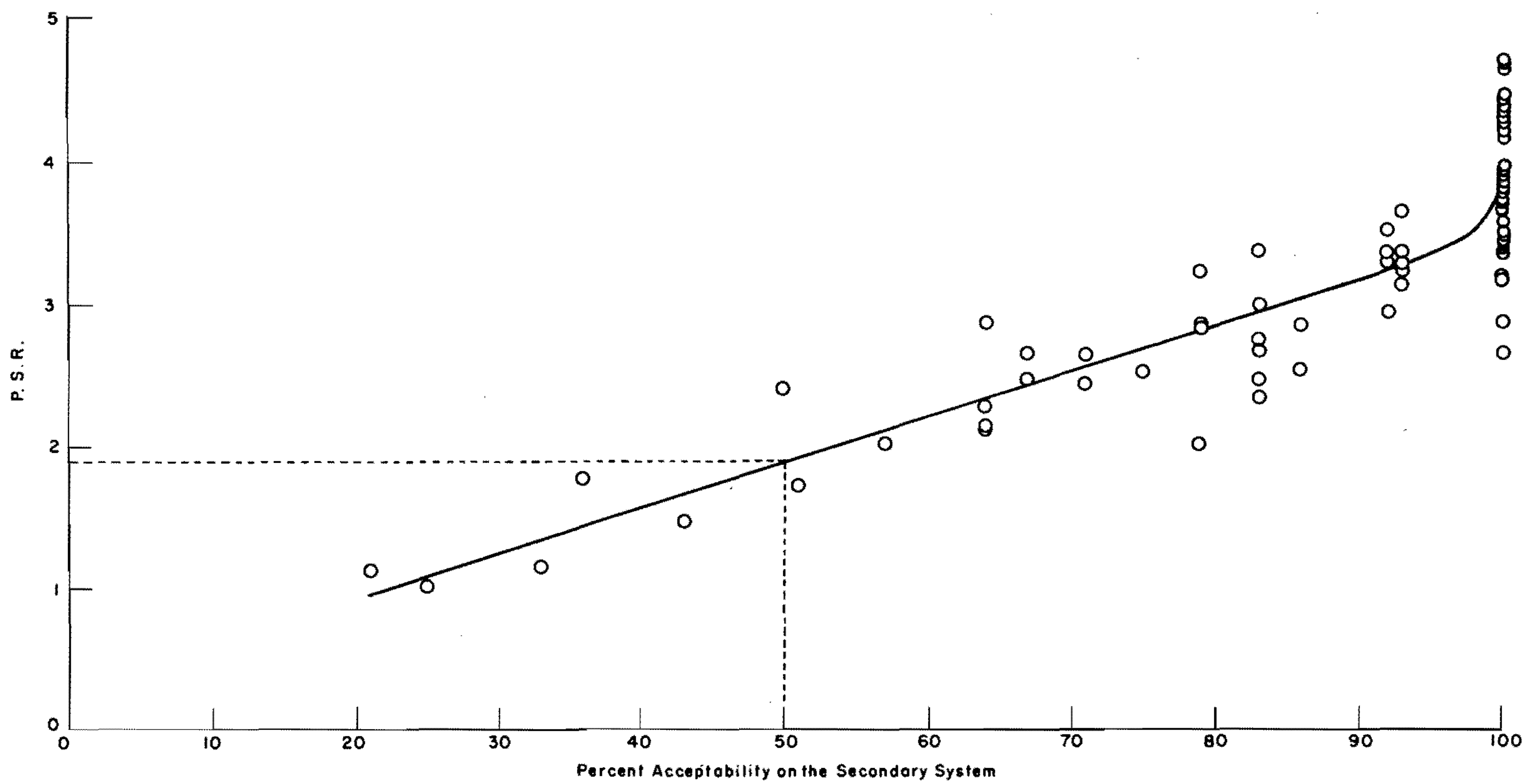


Fig 15. Percent acceptability on the Secondary System - rating periods one and two.

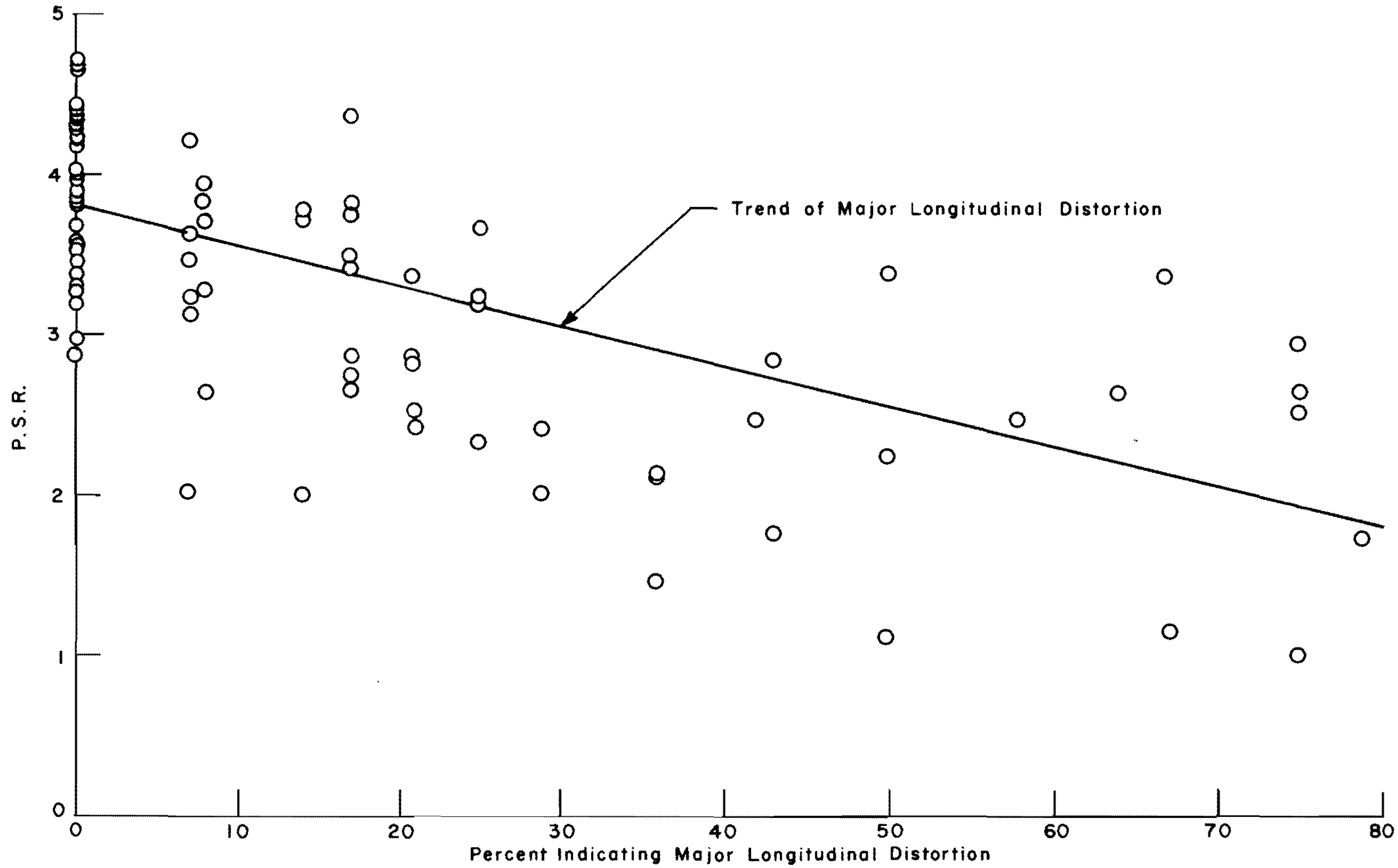


Fig 16. Percent of raters indicating major longitudinal distortion as a factor - rating periods one and two.

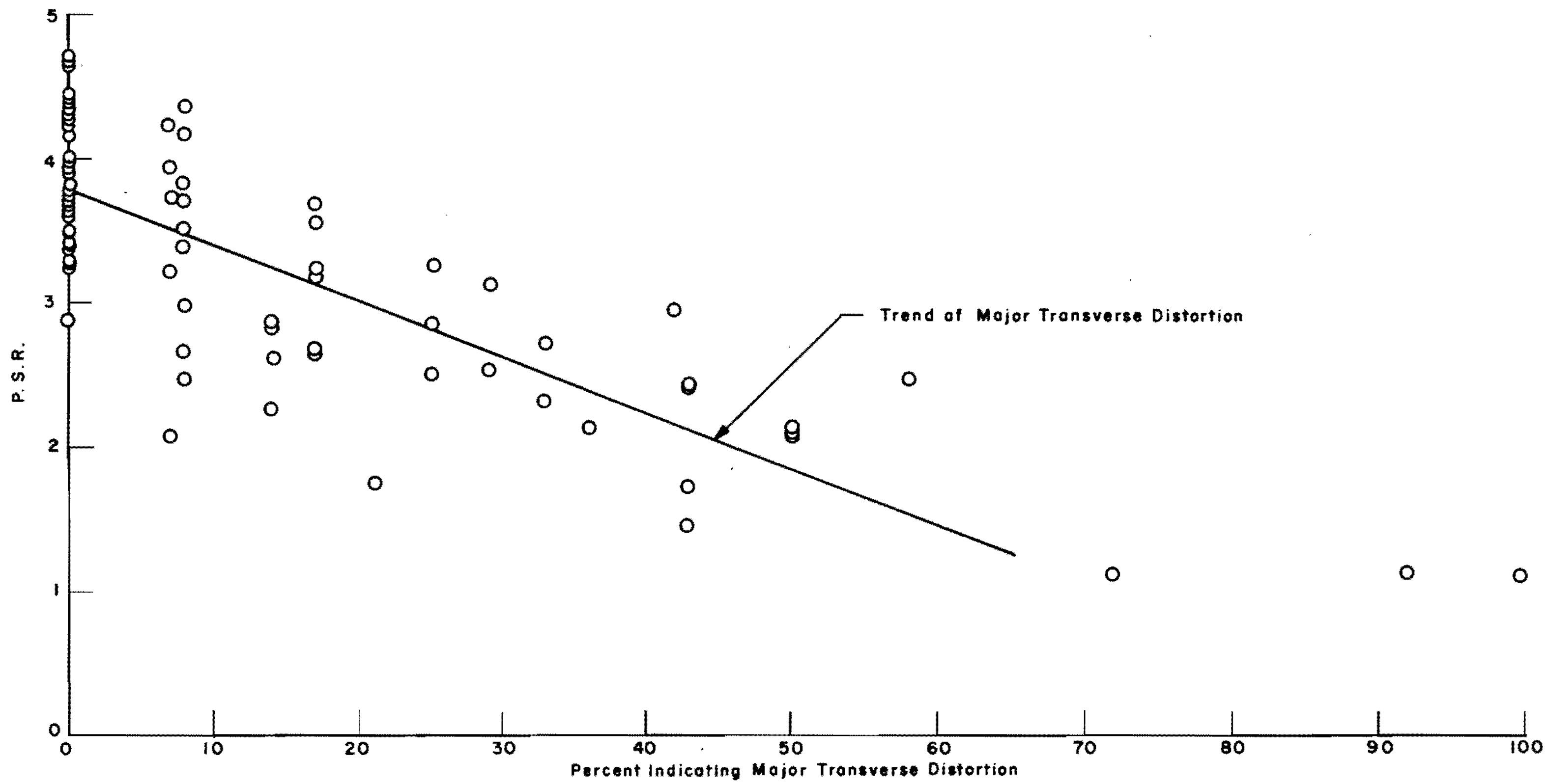


Fig 17. Percent of raters indicating major transverse distortion as a factor - rating periods one and two.

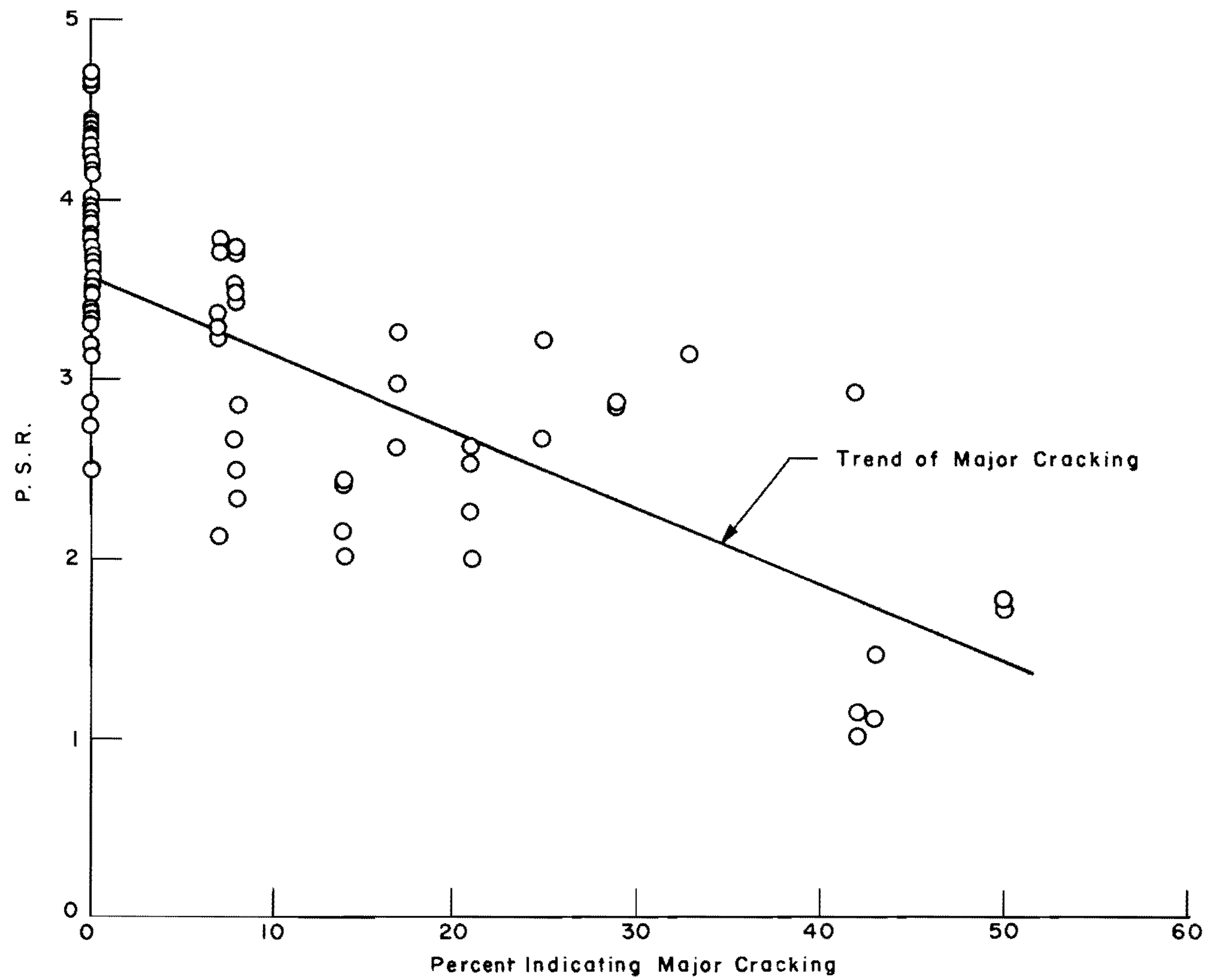


Fig 18. Percent of raters indicating major cracking as a factor - rating periods one and two.

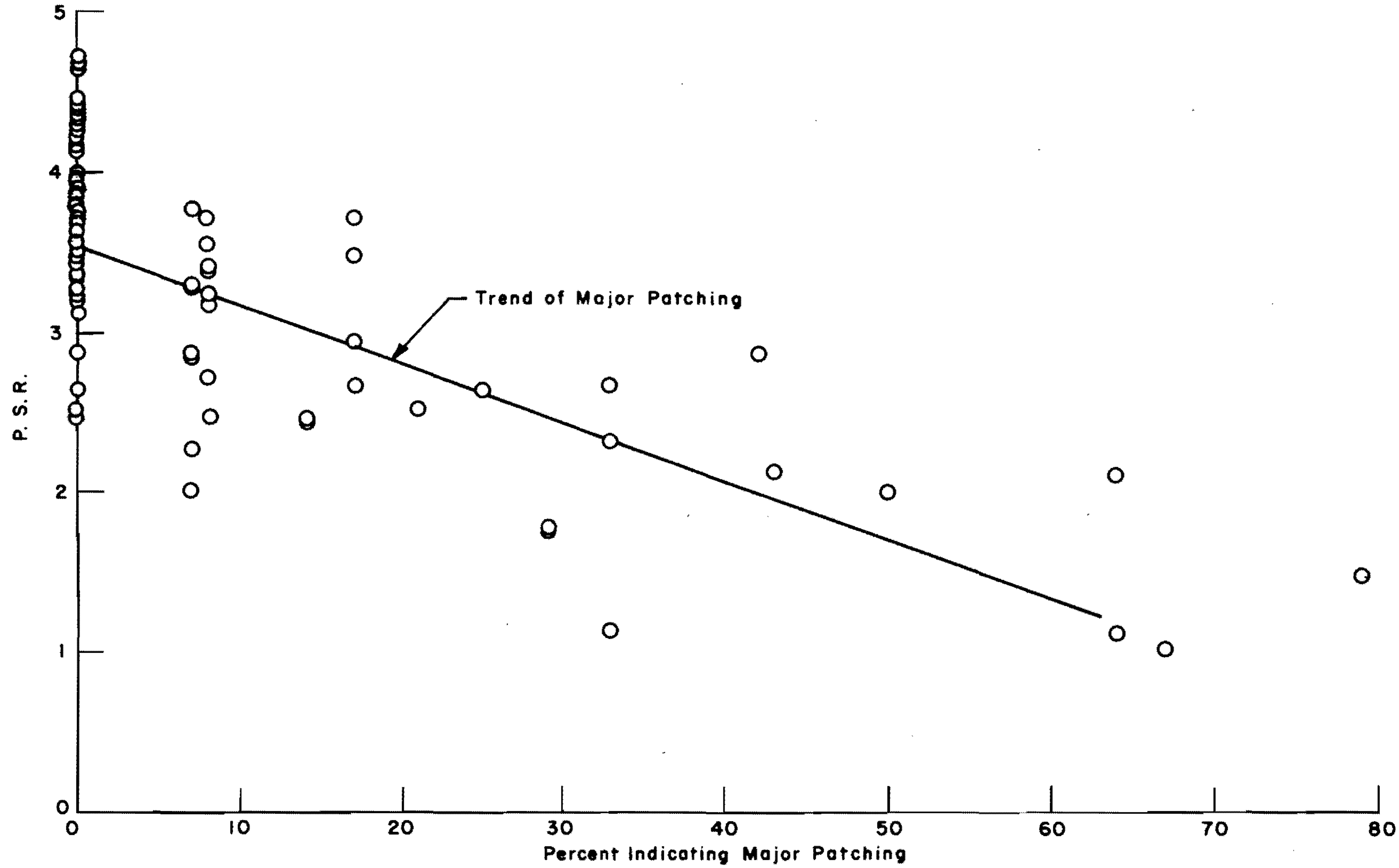


Fig 19. Percent of raters indicating major patching as a factor - rating periods one and two.

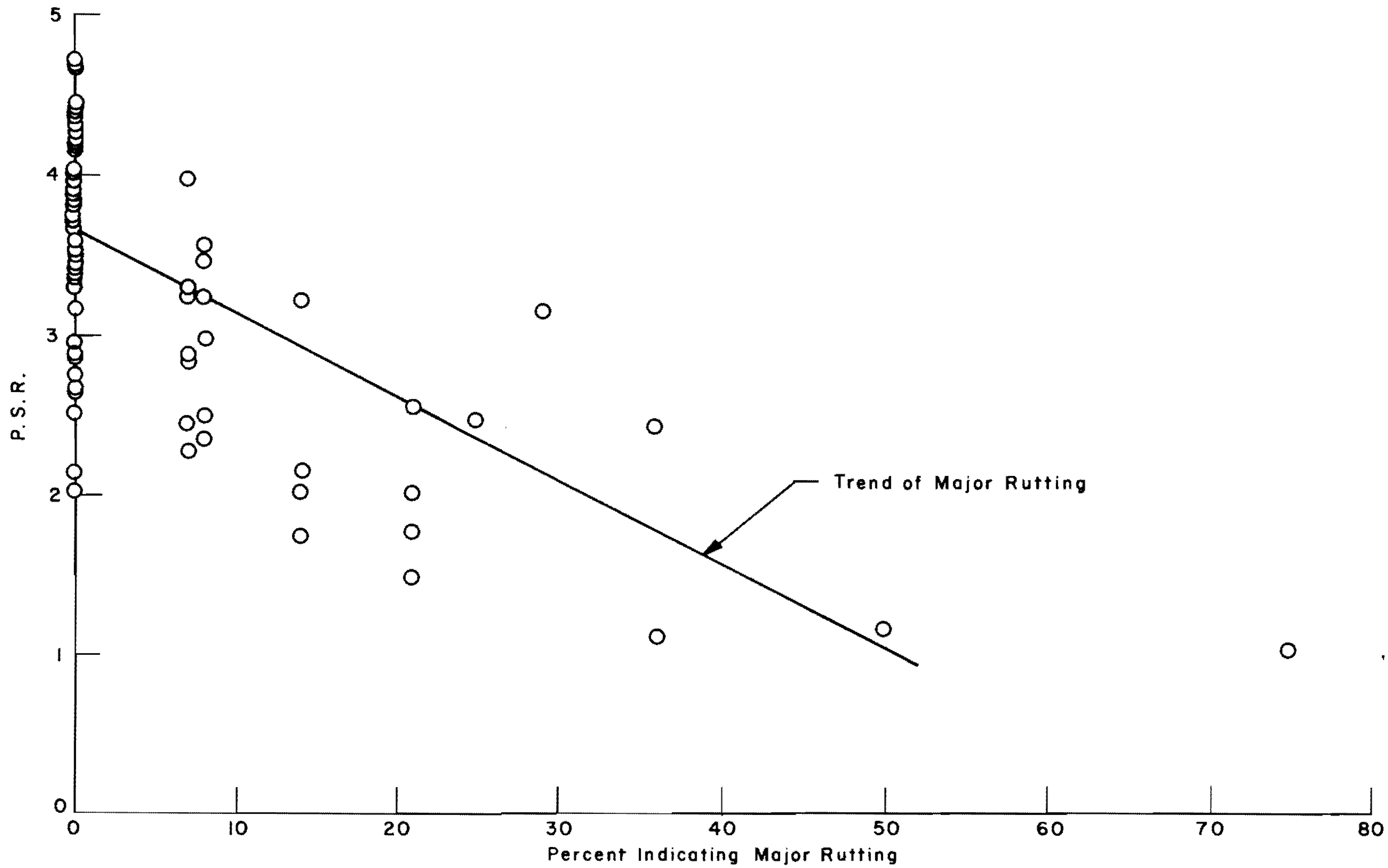


Fig 20. Percent of raters indicating major rutting as a factor - rating periods one and two.

CHAPTER 4. DATA PROCESSING AND ANALYSIS

The roughness data collection phase of this study involved obtaining measurements with the SD Profilometer and conducting condition surveys on the selected test sections. However, before these items could be accomplished, the important parameters affecting the PSR of a road were considered. Previous studies (Refs 5, 22, and 31) indicated that both the variables measurable with a roughness device (the deformations) and those reflecting the deterioration of the pavement were important in predicting the PSI. The deformations measurable with the SD Profilometer are the horizontal and transverse profiles which should reflect both permanent deformations and cyclic deformations such as warping and swelling of subgrade material. The deterioration variables were measured during the condition survey.

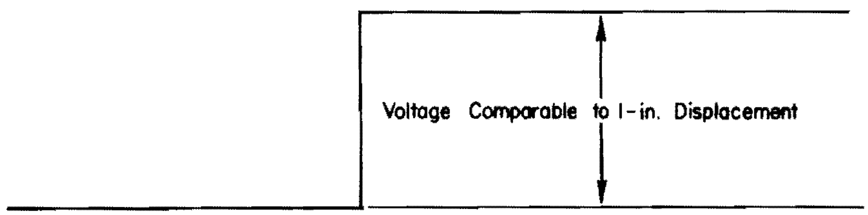
Preliminary Rating Session Data Collection

The pavement deterioration information for flexible pavements collected during the condition survey included the measurement of cracked and patched areas for the entire test section and rut depths for each wheel path. The cracking for flexible pavements, which included overlays, was divided into two general classes: (1) longitudinal and transverse cracks which were not interconnected at short distances and (2) alligator and map type cracking. The alligator cracks are interconnected cracks forming small polygons while the map cracks are interconnected cracks forming larger blocks at angles nearer 90°. The measured patching included all areas where either a seal coat, cold mix, or other repair work had been performed on part of the test section. Individually sealed cracks were not included in the patched area. The rut depths were measured in each wheel path at 100-foot intervals along the 1200-foot pavement sections. These measurements were performed with the Rut Depth Gage described in Ref 41. This rut depth is a measure of the deformation in the wheel paths caused by traffic action on the test section. The rut depth is the maximum displacement of a point on the surface measured from the center of a 4-foot transverse straightedge. The pavement deterioration information for rigid pavements included the length of cracks and the area of patching. All cracks which were visible to the condition surveyer from an upright position are included in the cracking data. No differentiation between transverse and longitudinal cracks was made for the cracking of portland cement concrete (PCC) pavements. Because of the large number of possible filter-speed combinations at which profile measurements could be obtained, the selections for data runs with the SD Profilometer presented the largest obstacle in obtaining roughness data. Four filters and six speeds are available providing 24 possible combinations for obtaining profile data. However, it should be pointed out that several of these combinations provide the same information. As indicated in Table 22, Filter 1 at 20 miles per hour, Filter 2 at 40 miles per hour, and Filter 3 at 60 miles per hour should all provide about the same profile information. Any difference in profile data occur in wavelengths which exceed the point of zero phase shift. Since the phase slopes for the four filters on the frequency response curves (Fig 3) are not the same, the long wavelength components are shifted forward into the profile by different amounts even though the attenuation, i.e., the ratio of the output signal to the input signal, slopes are identical for all four filters. Considering the above factors, the four filter-speed combinations of Filters 2 and 3 run at both 34 and 50 miles per hour were selected for running the preliminary rating session sections. These combinations provide measurement of wavelengths up to 250 feet with no attenuation. Two runs were made at each filter-speed combination resulting in eight runs per section. Two calibration signals were included with the recorded data runs (Fig 21). These are an induced voltage proportional to a 1-inch displacement on the road surface and a transient which corresponds to the free response of the system to a 1-inch impulse displacement. The first calibration signal is the scaling factor for the profile data runs and the second provides a check on the active filtering system of the profile computer.

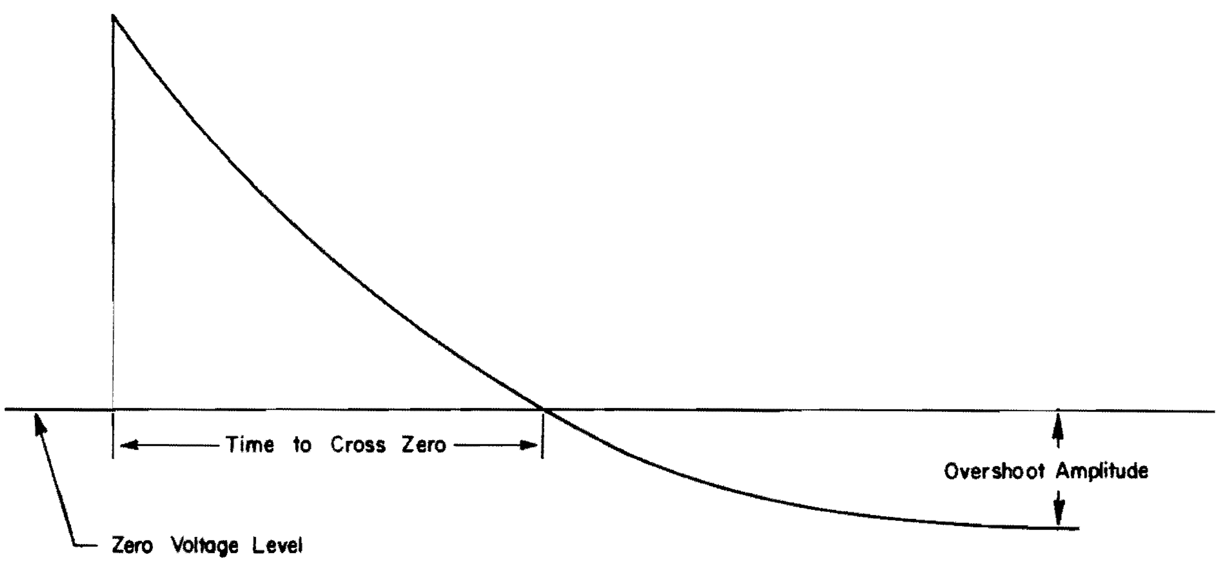
The scaling calibration information is evaluated by determining a value for the the 1-inch step calibration by use of a computer program called STEP. The general flow chart of this program is shown in Appendix 2. From a scale-factor experiment included in Ref 47,it was concluded that the difference between the averages of 100 points both before and after the voltage comparable to a 1-inch displacement (Fig 21) could be used as the scaling factor for the data for that particular filter-speed combination. The transient data were

TABLE 22. MAXIMUM WAVELENGTH CAPABILITIES WITH NO ATTENUATION AND 45° PHASE SHIFT

Filter Selection	Filter Natural Frequency (Radians/sec)	Wave Length Capability in feet at 20 mph	30 mph	34 mph	40 mph	50 mph	60 mph	Maximum Profile Amplitude (inches)
1	0.3	200	300	340	400	500	600	±20
2	0.6	100	150	170	200	250	300	±10
3	1.0	67	100	113	133	166	200	± 5
4	3.0	20	30	34	40	50	60	± 2



(a) One-inch displacement for scaling data.



(b) Transient for filter validation.

Fig 21. Typical calibration signals.

evaluated by (1) checking the time required for the signal to go from maximum positive voltage to zero voltage and (2) checking the maximum negative voltage level for the first overshoot past the zero voltage level (Fig 21). Both of the checks on the transient are made by running the analog signal through an oscillograph at a prescribed chart speed and voltage setting and checking the two sets of measurements with a scale. After validating the high-pass filtering network and determining the scaling factor for each set of data run at a particular filter-speed combination for a test section, a summary of the profile data is required.

According to engineers the major contributors toward an uncomfortable ride, and therefore a low pavement quality, are the physical features in the roadway which cause forces to be exerted on the human body. These forces are a direct result of accelerations of the vehicle body caused by longitudinal and/or transverse distortions of the roadway. It seems necessary then that the summary statistic describing a roadway be related to these features which induce forces on the rider. Two such statistics which have found wide acceptance in the highway field are roughness index (RI) and slope variance (SV) (Refs 5, 22, and 31). Roughness index is the sum of the vertical deviations of the profile throughout the section, while slope variance is the variance of slopes calculated for the length of the section. The slopes themselves are calculated as the vertical deviation between two points on the profile divided by the distance between the 2 points. These two summary statistics were among those investigated for use with the data from the preliminary rating session.

Preliminary Rating Session Data Analyses

Four summary statistics were selected for use in analyzing the preliminary rating session profile data. These were slope variance, roughness index, elevation variance, and true length ratio. Slope variance and RI are defined above while elevation variance (ELV) is the variance of the scaled profile points about the mean and the true length ratio (TLR) is the ratio of the length of the profile computed by the Pythagorean Theorem to the theoretical length of 1200 feet. Elevation variance was chosen as a variable worth investigating because the variance reflects the variation of the data points about the mean. A rough pavement would have a large variance while a perfectly smooth pavement would have zero variance. True length ratio was chosen by considering that as a pavement gets rougher the length of the line which traverses its surface with respect to a fixed base gets longer. A perfectly smooth pavement would have a TLR equal to one.

After choosing four methods for summarizing the roughness data, the sampling interval and any smoothing parameters which were appropriate remained to be selected. Upon closely investigating the available analog records the right profile data were found to contain a great deal of high frequency noise. This noise was probably due to the improper cleaning of the FM tape recorder heads. However, all efforts to salvage the right profile data were unsuccessful and the analysis was continued using only the left profile.

Because of the possibility of noise entering the data at any point during the recording stage, a running average of data points seemed advisable in order to minimize the effect of any such extraneous signals. Among the smoothing lengths used on the data were 2, 3, 4, 6, 12, and 25-point running averages with base lengths of either 6 or 9 points (inches). Several of these combinations were excluded by comparing the graphs of PSR versus one or all of the four summary statistics to other combinations and discarding the poorest. It was noted from these plots that the HMAC and surface-treated (ST) pavements seemed to follow different trends (Fig 22) which indicated that a qualitative factor should be used to differentiate between the HMAC and ST pavements.

In order to make a decision as to which combination or combinations of variables of summary statistic, length of running average, length of base, filter-speed combination, and pavement type were important, an analysis of variances was performed using the four summary statistics for the following combinations of variables: (1) Filters 2 and 3 run at speeds of 34 and 50 miles per hour, (2) base lengths of 6 and 9 points, and (3) running averages of 6 and 25 points. However, since only seven HMAC pavements were available, only seven of each pavement type were used in the ANOVA shown in Table 23. A fixed model ANOVA was run on these data. The surface type (ST_y) main effect is tested with pooled MS of sections (S), runs (Ru), Ru × S, Ru × ST, S × ST_y, and Ru × S × ST_y. This test is set up using a block effect to provide the best test for ST. The other tests are made with error (b) MS (Table 24) which is composed of all the nonzero interactions of ST, S, and Ru with the five other main effects. As noted in Table 23, filter (F), vehicle speed (SP), F × SP, roughness variable (Ro), Ro × F, Ro × SP, and Ro × F × SP are all significant at both the 75 and 95 percent levels while ST is significant at only the 75 percent

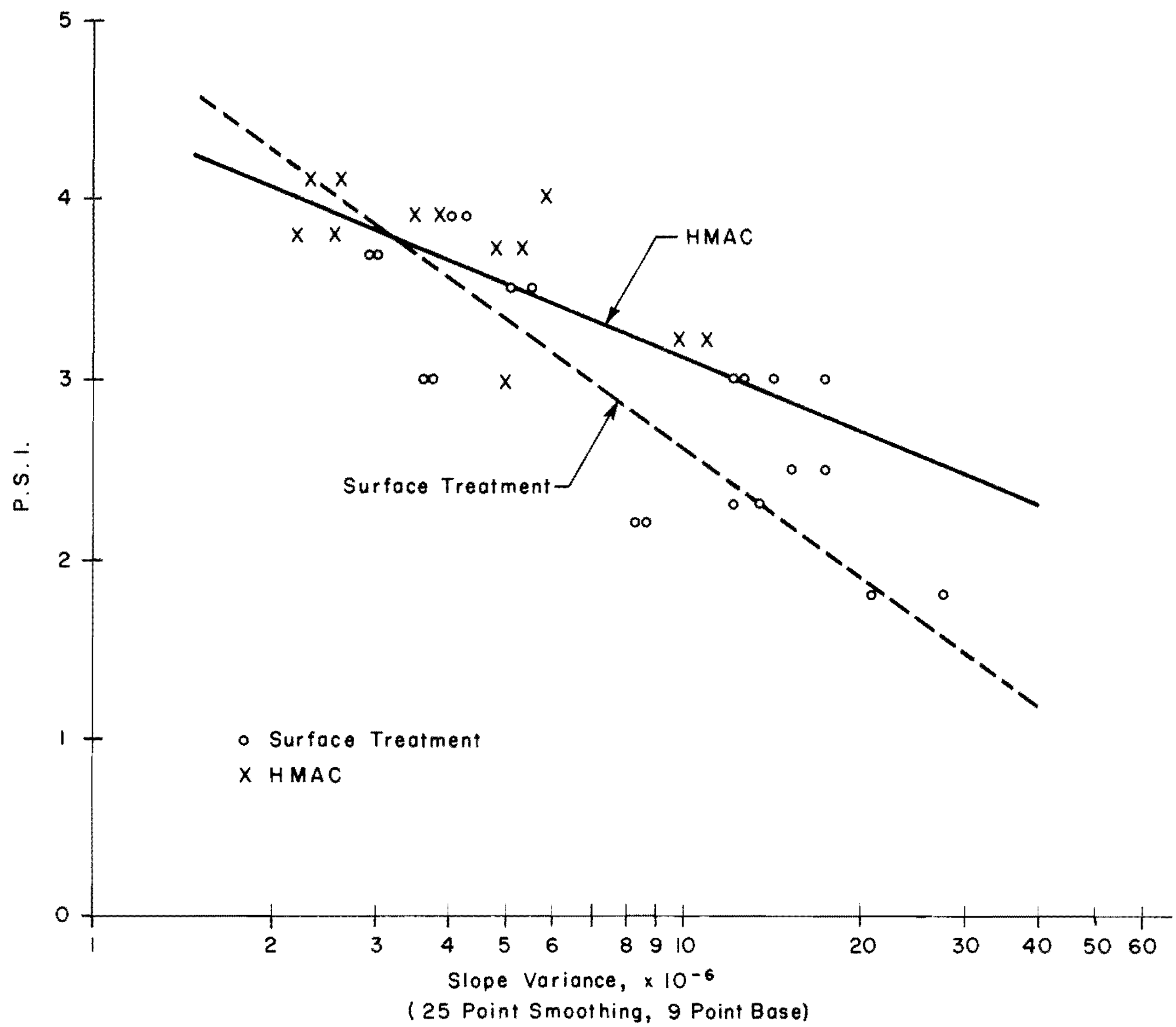


Fig 22. Preliminary rating session data vehicle speed 50 miles per hour - Filter 3.

TABLE 23. ANOVA TABLE FOR ROUGHNESS SUMMARY STATISTICS

Sources of Variation		df	SS	MS	Significance Levels 95%	Significance Levels 75%
Surface Type (ST_y)		1	.22612	.22612		X
Sections (S)	error (a)	6	2.25230	0.12330		
S × ST_y		6	.53784			
Runs (Ru)		1	.03851			
Ru × ST_y		1	.00263			
Ru × S		6	.17597			
Ru × S × ST_y		6	.20038			
		26	3.20763			
Smoothing (Sm)		1	.00964	.00964		
BASE (B)		1	.00064	.00064		
SM × B		1	.00001	.00001		
Filter (F)		1	1.77799	1.77799	X	X
F × SM		1	.00000	.00000		
F × B		1	.00000	.00000		
F × SM × B		1	.00000	.00000		
Speed (SP)		1	1.08598	1.08598	X	X
SP × SM		1	.00042	.00042		
SP × B		1	.00026	.00026		
SP × SM × B		1	.00001	.00001		
SP × F		1	.31518	.31518	X	X
SP × F × SM		1	.00009	.00009		
SP × F × B		1	.00008	.00008		
SP × F × SM × B		1	.00010	.00010		
Roughness Ro		3	291.96814	97.32271	X	X
Ro × SM		3	.02876	.00959		
Ro × B		3	.00195	.00065		
Ro × SM × B		3	.00004	.00001		
Ro × F		3	5.27392	1.75797	X	X
Ro × F × SM		3	.00000	.00000		
Ro × F × B		3	.00001	.00000		
Ro × F × SM × B		3	.00000	.00000		
Ro × SP		3	3.10484	1.03495	X	X
Ro × SP × SM		3	.00042	.00014		
Ro × SP × B		3	.00028	.00090		
Ro × SP × SM × B		3	.00056	.00019		
Ro × SP × F		3	.93823	.31274	X	X
Ro × SP × F × SM		3	.00029	.00010		
Ro × SP × F × B		3	.00030	.00010		
Ro × SP × F × SM × B		3	.00028	.00009		
Error (b)		1701	22.75489			
TOTAL		1791	330.73461			

TABLE 24. F-TESTS ON DATA FROM TABLE 23

Computed F-Test Values	Significance Level	
	95%	75%
F 1,6	3.00	1.62
F 1,∞	3.84	1.32
F 3,∞	2.60	1.37

Test for Surface Type using Error (a):

$$F_{1,26} = \frac{0.22612}{0.12337} = 1.83 < 4.23 \therefore \text{ Not Significant}$$

$F_{1,26}\,(0.95) = 4.23 \qquad F_{1,26}\,(0.75) = 1.39$

Tests using Error (b) SS - Computed by adding the nonzero SS terms and their df for computing the MS

$$\text{Error (b) MS} = \frac{22.75489}{1666} = 0.01365$$

$$\left\{ \text{For } F\ 1,\infty: \quad \frac{X}{0.01365} \geq \overset{95\%}{3.84} \text{ or } \overset{75\%}{1.32} \text{ i.e. } \begin{array}{l} X_{95\%} = 0.0524 \\ X_{75\%} = 0.0180 \end{array} \right\}$$

$$\left\{ \text{For } F\ 3,\infty: \quad \frac{Y}{0.01365} \geq \overset{95\%}{2.60} \text{ or } \overset{75\%}{1.37} \text{ i.e. } \begin{array}{l} Y_{95\%} = 0.0355 \\ Y_{75\%} = 0.0187 \end{array} \right\}$$

level. These significant effects are expected when the effect of speed and filter on the frequencies present in the profile data are considered. Since the TLR is slightly greater than one while slope variance has an exponent of 10^{-6}, significance in the roughness variable is expected. It is interesting that neither the smoothing length nor the base length nor any of the interactions of these two lengths with any other main effect showed any significance. This indicates that within the limits of the data used in this ANOVA there are no significant differences between any of the combinations of smoothing and base length. From the scatter diagrams, the combination of 25-point smoothing and 9-point base was selected as showing the best correlation between roughness variables and PSR. This choice of 25-point smoothing was verified when two subsequent data runs using smoothing lengths of 50 and 75 points with a 9-point base revealed much poorer correlation of the roughness variables with PSR than did the 25-point smooth and 9-point base. It was concluded then that the 25-point average provided an adequate length for arithmetic smoothing.

When comparisons between plots of the four roughness variables versus PSR were made, it became evident that the true length ratio and elevation variance variables were very poorly correlated with PSR while the slope variance and roughness index variables were highly correlated with PSR. These plots led us to discontinue further use of TLR and ELV and to use only SV and RI in the subsequent analyses of the data from rating periods one and two.

Rating Periods One and Two Data Collection

Because the complete analysis of the preliminary rating session data were not accomplished before the data runs for the two summer periods were to be collected, the project personnel decided to make SD Profilometer runs using Filter 1 at speeds of 20 and 34 miles per hour and Filter 2 at 50 miles per hour. Two runs were made at each of these filter-speed combinations. The condition survey information for the test sections was expanded to include the measurement of a value for surface texture. The only device readily available for such measurements was developed for use with the CHLOE Profilometer by Hudson and Scrivner (Ref 22). A tabulation of the data collected during the condition survey phase for rating periods one and two for 61 flexible pavements is shown in Appendix 3. These data are shown graphically in Figures 23, 24, 25, 26, and 27. These plots indicate the relation between condition survey variables and the average PSR for the sections. Figure 23 shows the combined linear and area type (map and alligator) cracking per 1,000 square feet of pavement area versus PSR. Although much scatter in the data is present there is indicated a general decrease in PSR with increasing amounts of cracking. Figure 24 shows the patching per 1,000 square feet of pavement area versus PSR. The data indicate poor correlation between the plotted variables since most sections had less than 50 square feet per 1,000 square feet of patching while the sections with more than 50 had PSR's ranging from 1.1 to 2.9. Figure 25 shows the mean rut depth versus PSR. The mean rut depth is the average of 26 rut-depth measurements, 13 for each of the two wheel paths. As in the case of Fig 23, there is a general decrease in PSR with increasing mean rut depth. Figure 26 shows the variance of the 26 individual rut-depth measurements about the mean versus PSR. However, almost no ruts were observed in the test sections or in the roads reviewed in the test section selection process. Figure 27 shows the average of approximately 40 measurements of texture of each wheel path versus PSR and represents the effect of the coarseness of the surface of the test section on PSR. As expected, most of the HMAC pavements have an average texture of less than five while most of the surface treatments exhibited large textures. The plot indicates a general decrease in PSR with increasing average texture.

A tabulation of the data collected during the condition survey phase for rating periods one and two for 29 rigid pavements is shown in Appendix 3. These data include the measurements for line and area cracking, patched area, and surface texture. The line cracking included all cracks, including sealed cracks, in the pavement surface while the area cracking included closely spaced (closer than about 2 feet) line cracks. The patching included all areas which were sealed with asphaltic materials including all spalled joints (very few were unpatched and these were included with the patching). Figure 28 shows the plot of combined linear and area cracking versus PSR for the 28 rigid pavements. Two trends are evident in the data: a linear trend for the CPJR pavements and a curvilinear trend for the CPCR pavements. Two trends are also evident in Fig 29 which shows the plot of patching versus PSR. The CPCR pavements show a slight decrease in PSR with increasing patching while the CPJR continuously reinforced pavements with patching show a slightly steeper negative slope. Figure 30 shows the average texture versus PSR with PSR decreasing as texture increases.

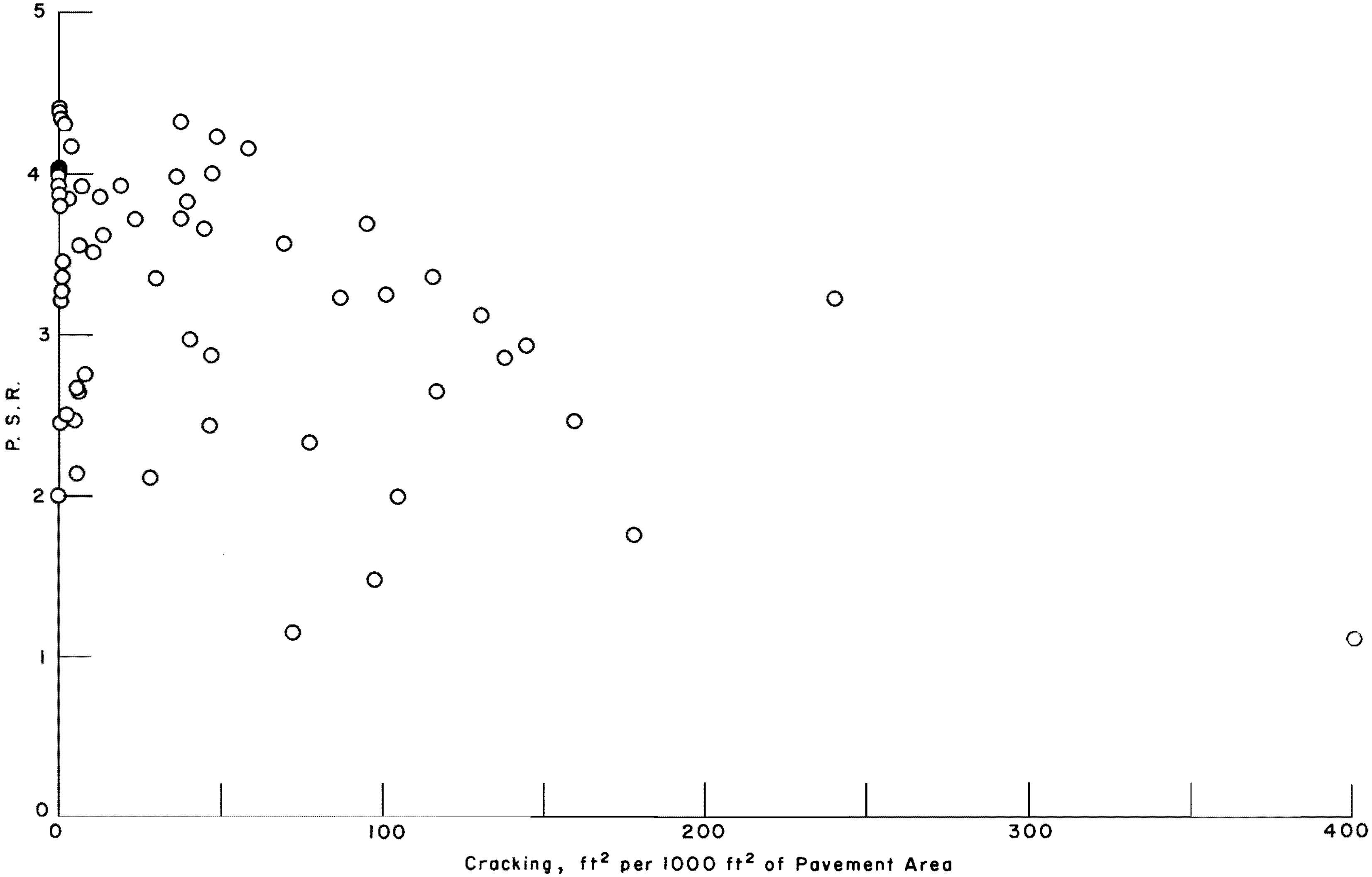


Fig 23. PSR versus cracking for 61 flexible pavements.

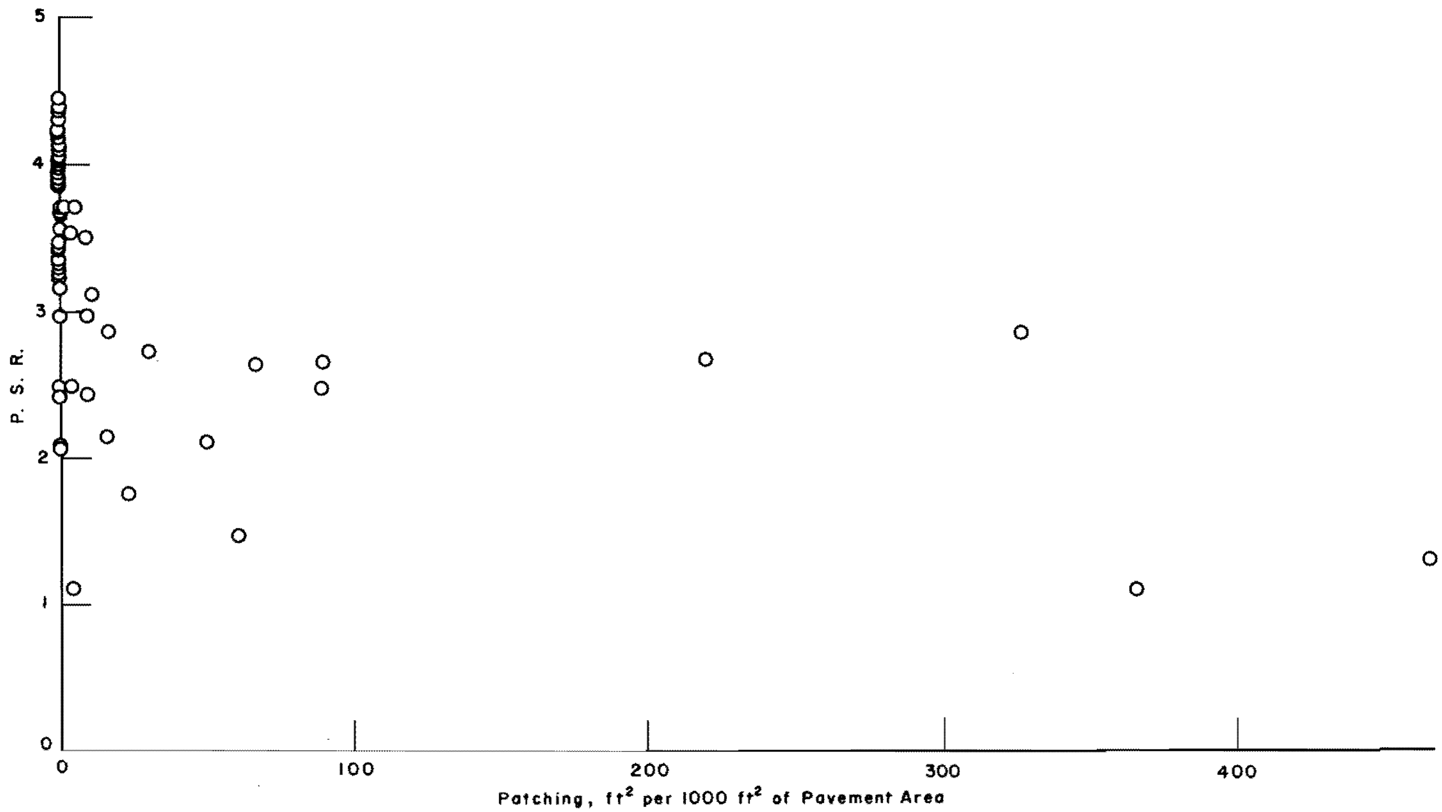


Fig 24. PSR versus patching for 61 flexible pavements.

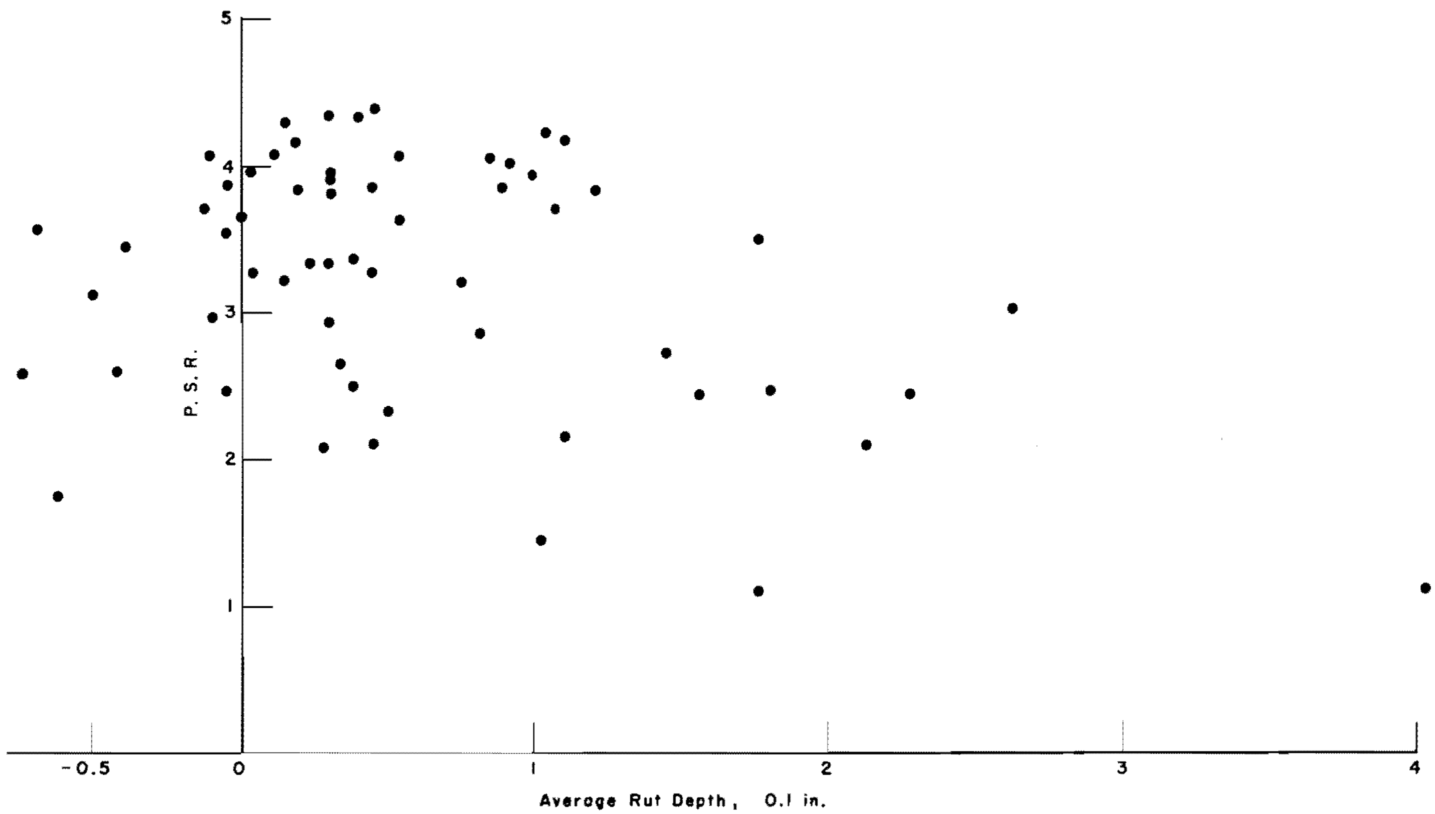


Fig 25. PSR versus average rut depth for 61 flexible pavements.

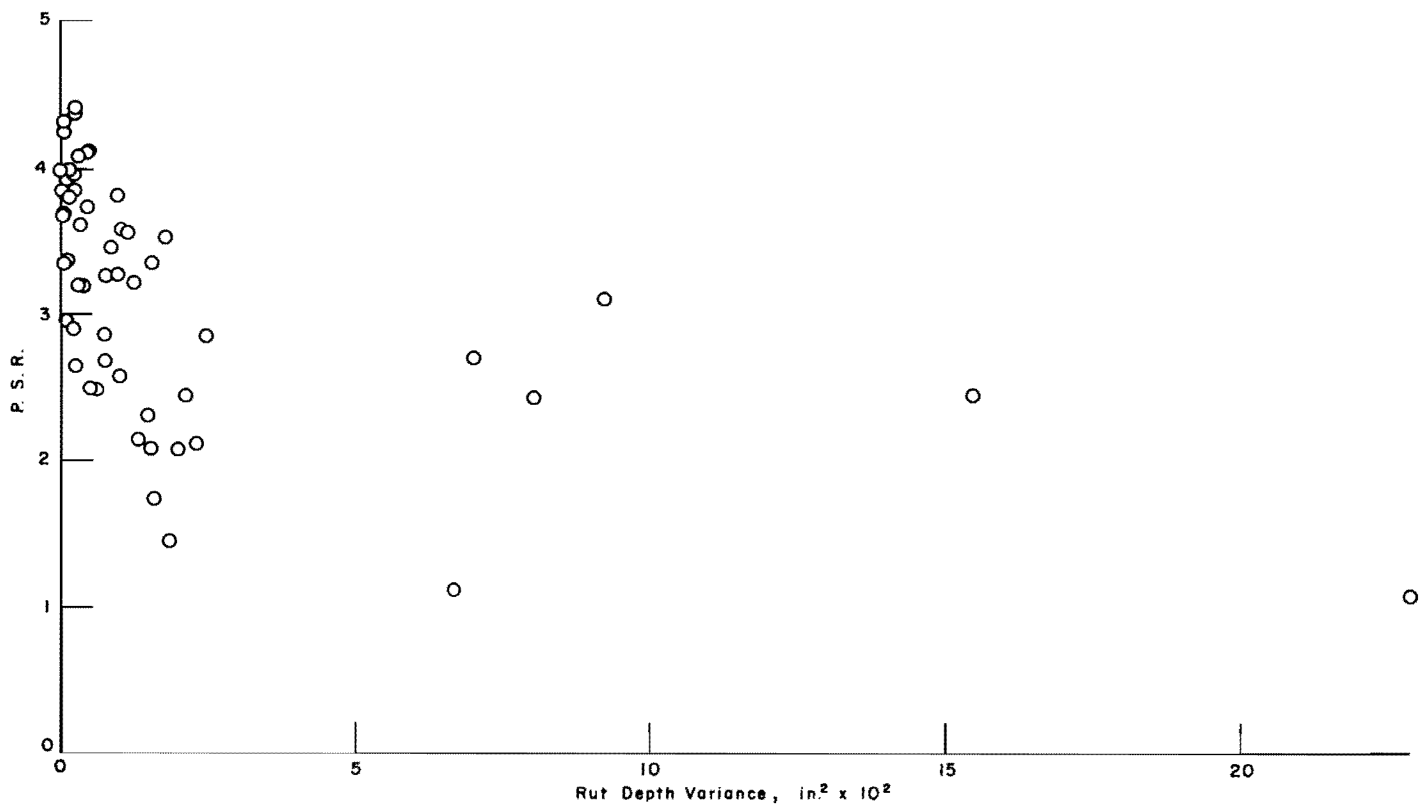


Fig 26. PSR versus rut depth variance for 61 flexible pavements.

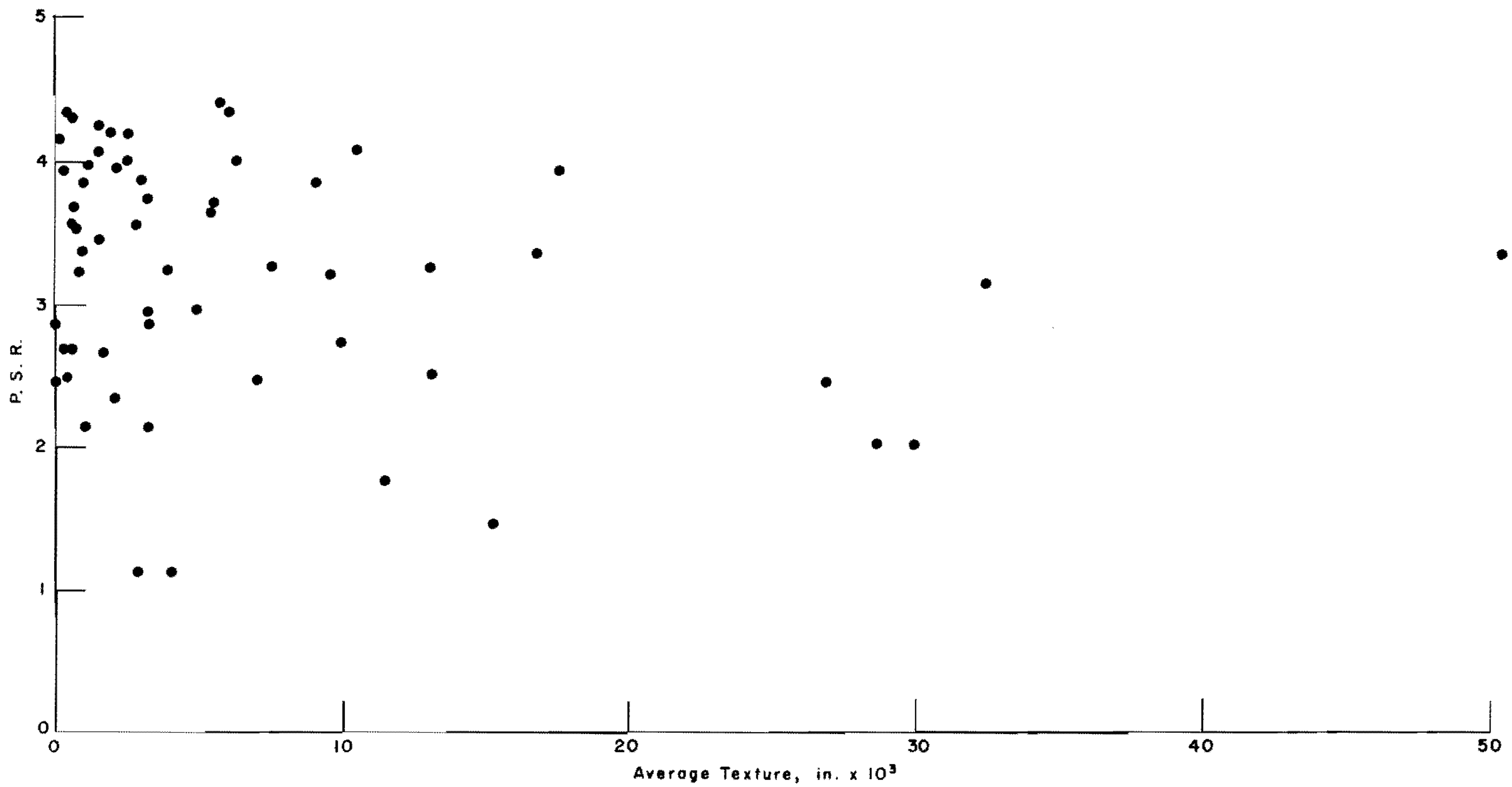


Fig 27. PSR versus average texture for 61 flexible pavements.

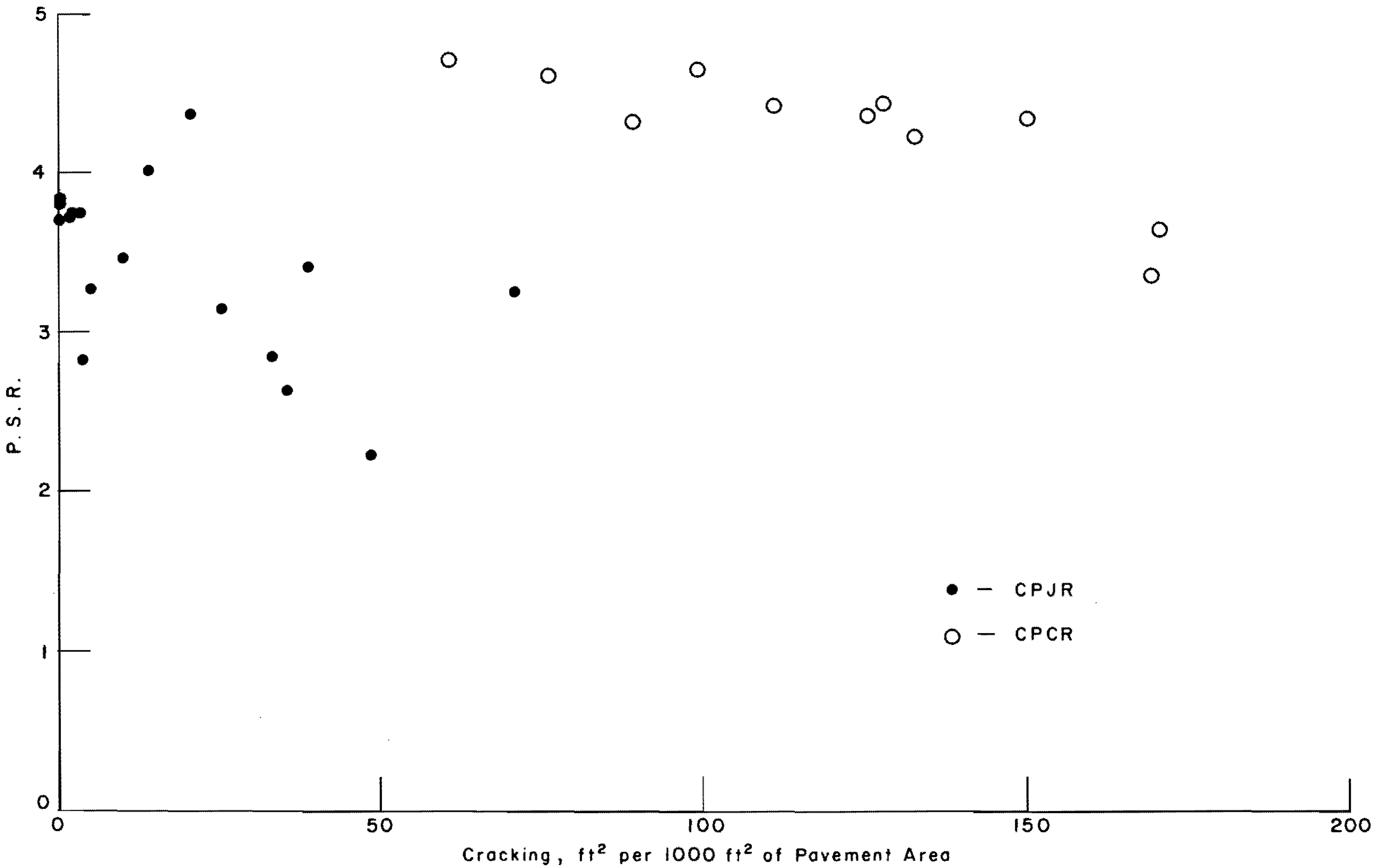


Fig 28. PSR versus cracking for 28 rigid pavements.

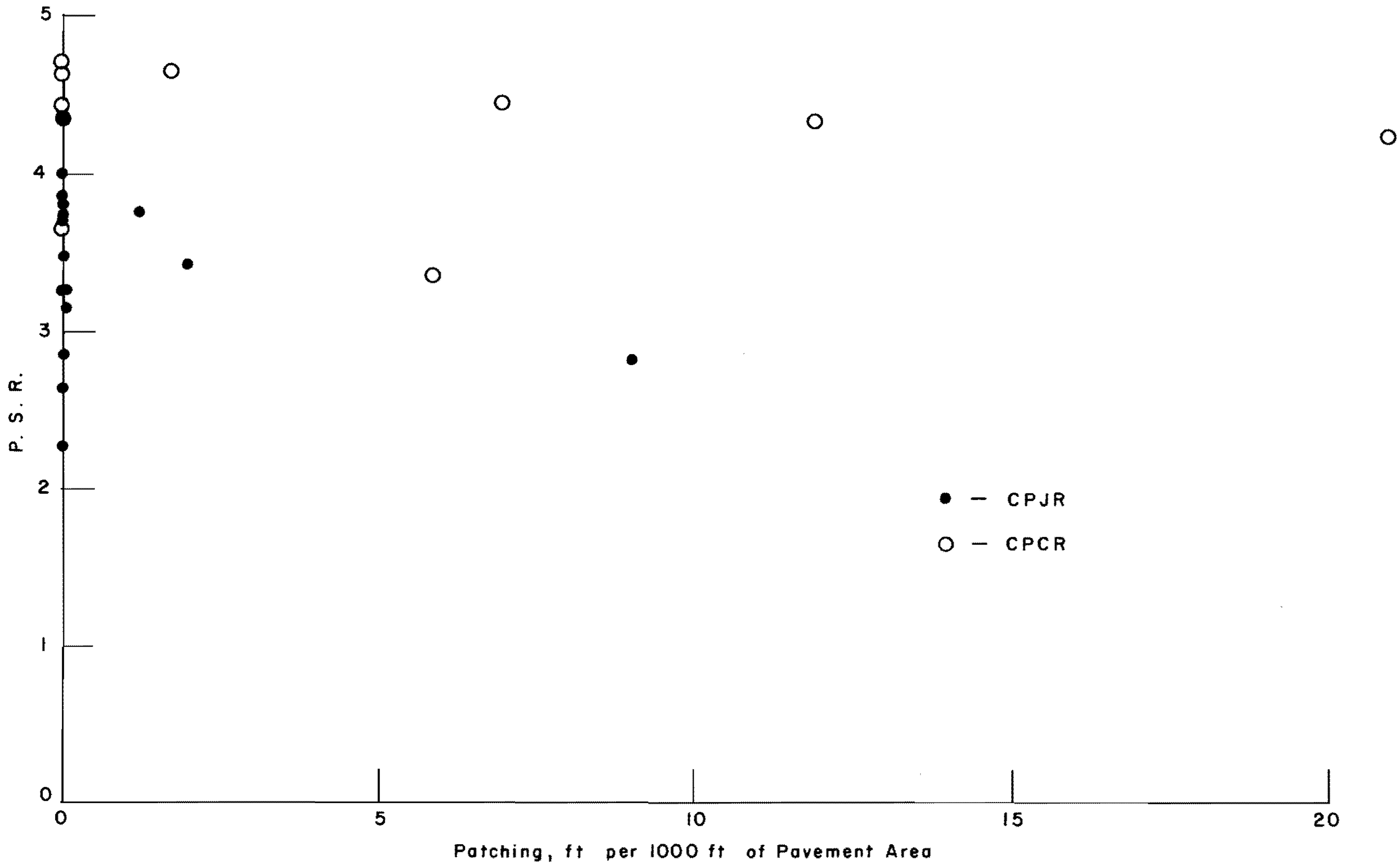


Fig 29. PSR versus patching for 28 rigid pavements.

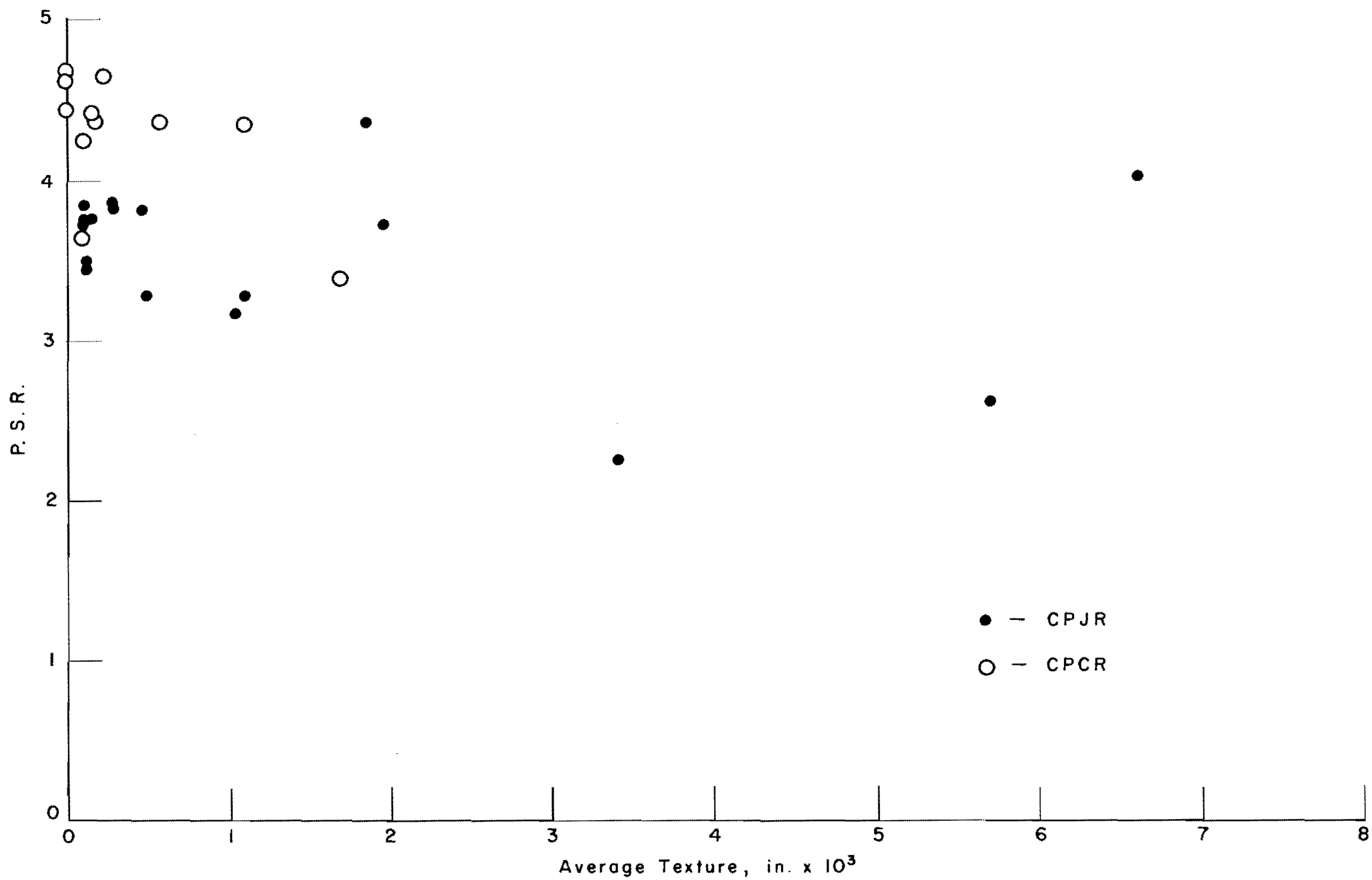


Fig 30. PSR versus average texture for 28 rigid pavements.

SD Profilometer Data Processing

Since the data from the right profile for the preliminary rating session were not usable because of noise, all of the profile data taken during rating periods one and two were monitored on an oscilloscope for the detection of any extraneous signals. This monitoring was performed at the end of each day of profile operations. By carefully cleaning all equipment and monitoring all data, most of the profile data were recorded properly. With profiles for both the right and left wheel paths, it was possible to evaluate the effect of vehicle roll on the ratings for each section.

The evaluation of the roll component was accomplished by computing the slope between adjacent points on each profile and then determining the variance of these slopes. This cross slope variance (XSV) is computed for each set of data using the same smoothing length and sampling interval as the calculations for SV and RI. This program is included in Appendix 4.

Based on the results from the preliminary rating session in which the combination of 25-point smoothing and 9-point base showed the highest correlation with PSR, the profile data from the SD Profilometer runs were summarized using the 25 to 9 combination for smoothing and base. As a check on this smoothing base combination, SV and RI were calculated using a smoothing length of 50 points with a base of 9 points. The roughness data were shifted toward the zero ordinate and this combination showed a poorer correlation of roughness variable versus PSR than did the 25 to 9 combination.

The results of the computer runs using Program DAP (Appendix 5) for computing slope variance and roughness index are shown in Tables A6.1 and A6.2 in Appendix 6 for the flexible and rigid pavements, respectively. The values of the summary statistics in these tables are the averages of the right and left profiles for the two data runs. Program DAP uses as input previously scaled digital profile data and computes the variance of slopes over a base length specified as an input variable and the sum of the vertical excursions (RI) over the same specified base length. These data were plotted versus PSR based on the speed at which the data were run and whether the pavement was flexible or rigid. Figures 31, 32, and 33 show slope variance versus PSR for speeds of 20, 34, and 50 miles per hour, respectively, for the flexible pavements. As may be noted these figures do not contain the same number of sections. Several of the test sections were lost because (1) of an oversight in

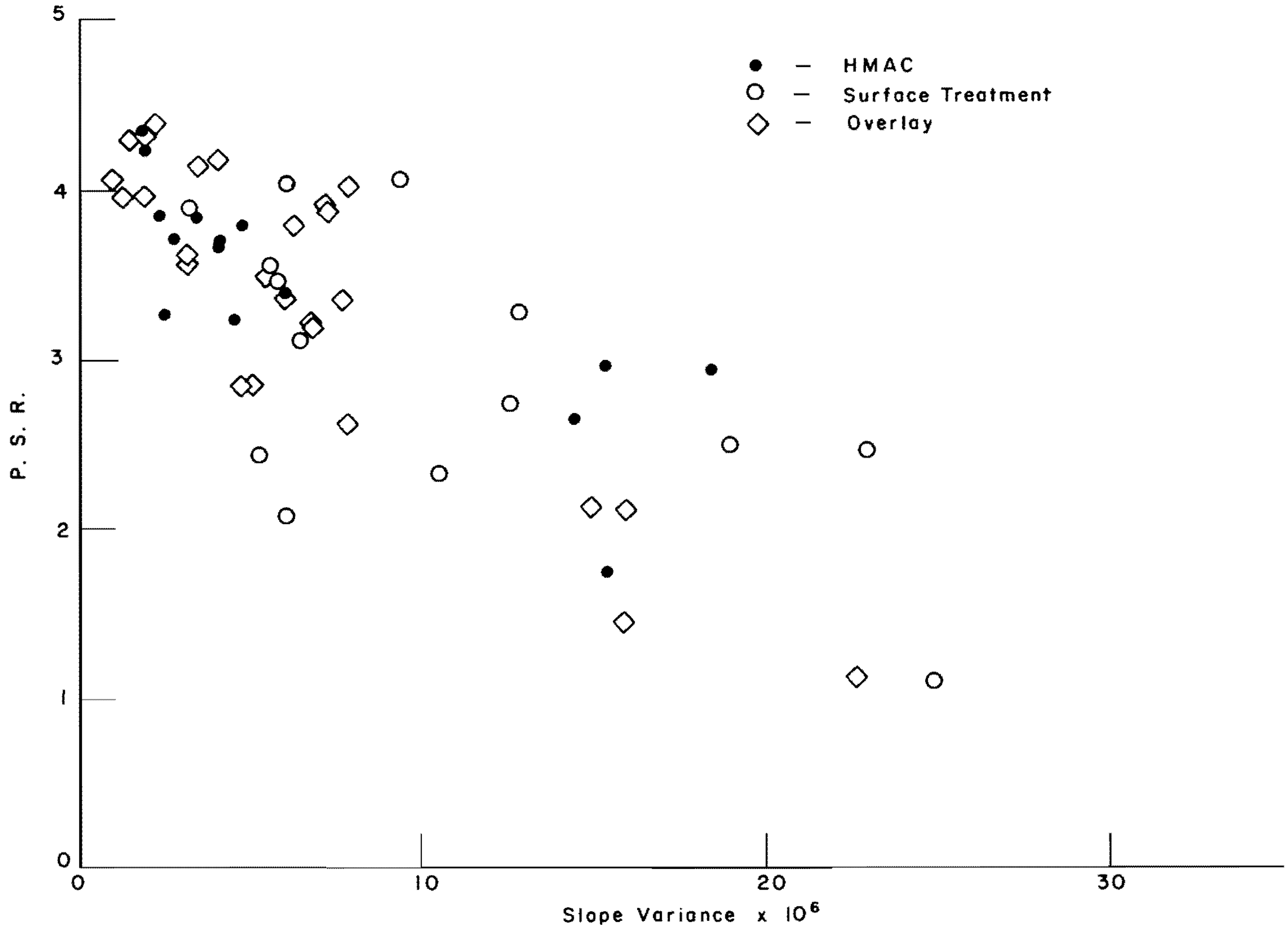


Fig 31. PSR versus slope variance for 56 flexible pavements measured at 20 miles per hour.

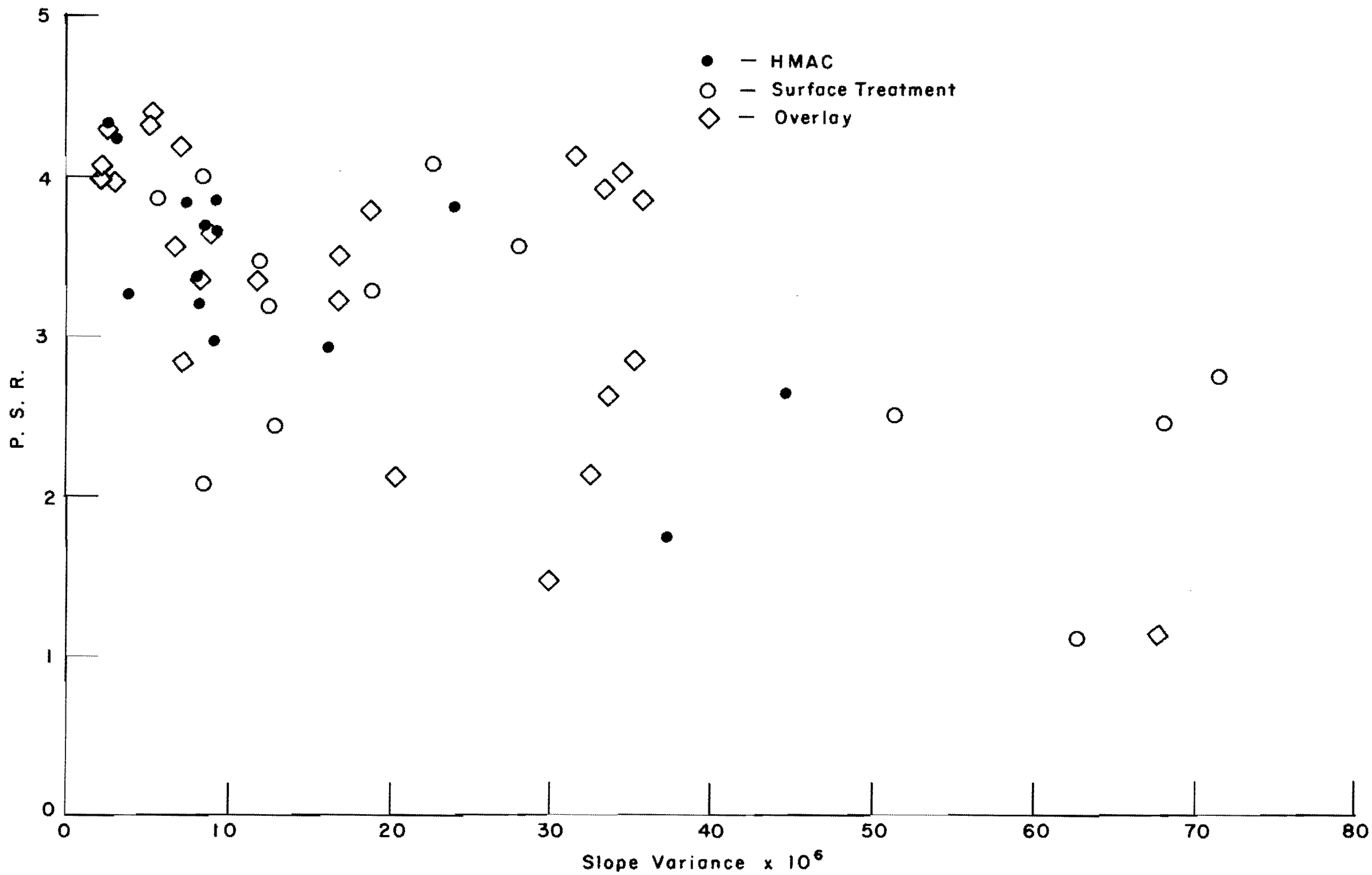


Fig 32. PSR versus slope variance for 53 flexible pavements measured at 34 miles per hour.

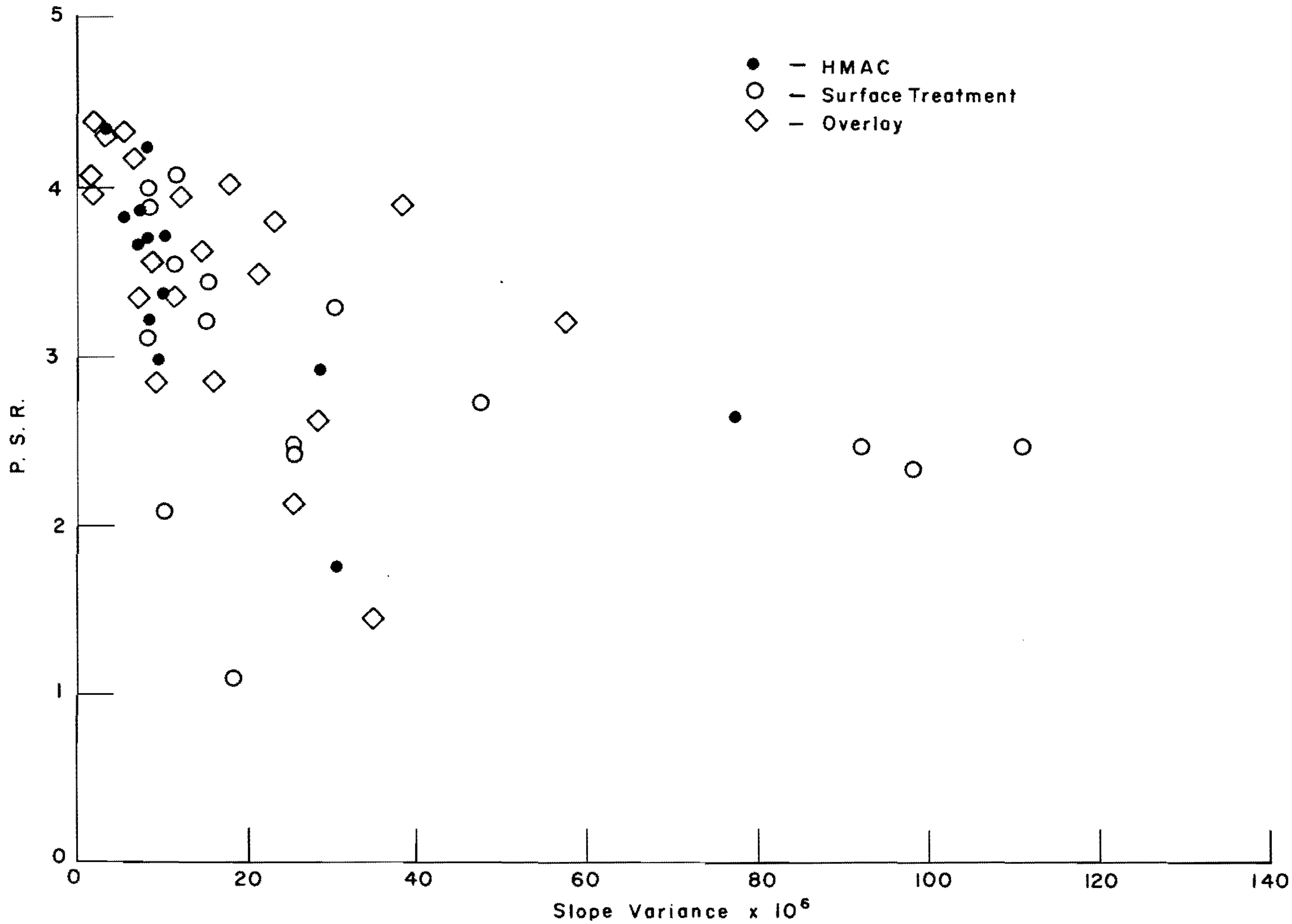


Fig 33. PSR versus slope variance for 51 flexible pavements measured at 50 miles per hour.

the selection process, (2) the approach to the test section was not long enough to permit the SD Profilometer vehicle sufficient time for acceleration to the desired speed and allow the accelerometer to stabilize before entering the section, and (3) other test sections are eliminated because of a noise problem associated with the photocell sensor which is used to determine the start of the test section. Since the photocell senses changes in reflectivity of the pavement surface, the photocell relay may be initiated many times in a test section. When the photocell relay closes, it initiates a heavy duty relay in the Brush strip-chart recorder to provide a signal on one of the event pens. When this heavy duty relay closes, electrical noise is sometimes transmitted through the profile computer into the recorded profile data. In these data the right profile data are always affected and the left profile data usually are to a much lesser degree. Another noise source is the tape recorder itself. It has been found that tape flutter can occur under a variety of conditions. This noise is produced when the magnetic tape loses contact with the recording heads of the tape recorder. Much of the noise present in the sections is from this source. This flutter is accentuated by the shock mounts which support the tape recorder. Other methods for mounting the tape recorder are presently being investigated. Those sections which were eliminated from further analyses are shown in Appendix 7. As may be noted in Appendix 7, three sections are classed as outliers. These sections had summary statistics which were 5 to 10 times greater than the other sections having the same PSR value. The data for three sections were discarded as being abnormal.

As may be noted in Figs 31, 32, and 33, there is a great deal of variation among the data for the three speeds. In general, the value of slope variance increases as speed increases. These figures were included to show the variation of a roughness statistic with speed. Because this same type of variation occurs in the roughness index and cross slope variance data, the repeated plots will be shown in Appendix 6.

Figures 34, A6.1, and A6.2 show slope variance versus PSR for the rigid pavements. In each of the plots for both flexible and rigid pavements there is a curvilinear relation between SV and PSR, i.e., with each increment decrease in PSR there is a larger corresponding increase in the SV increment. These plots indicate that a transformation will be useful in linearizing the data in subsequent regression analyses.

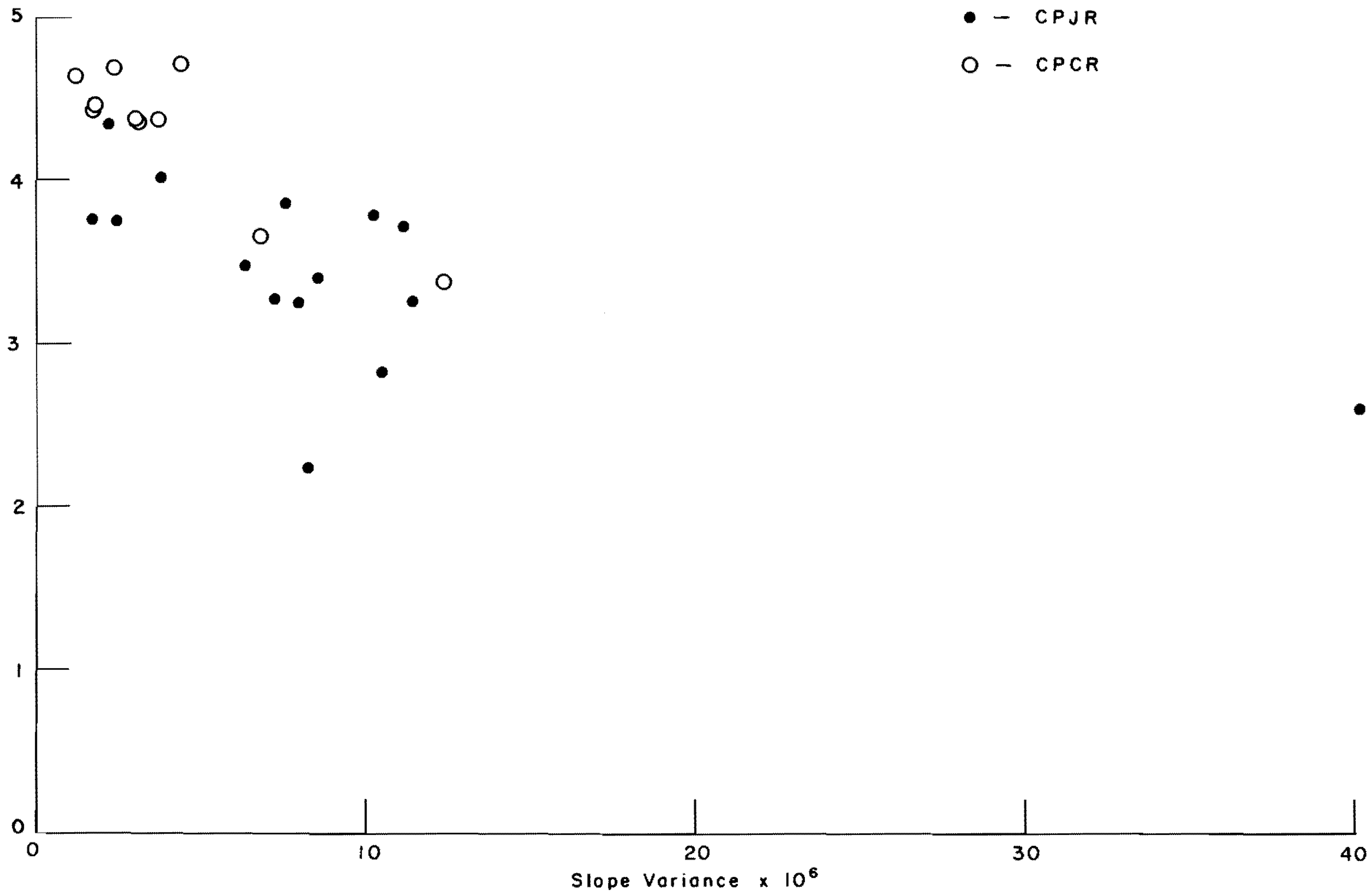


Fig 34. PSR versus slope variance for 25 rigid pavements measured at 20 miles per hour.

The roughness index versus PSR plots are shown in Figs 34 and A6.3 through A6.7. In Figs 35, A6.3, and A6.4 a general curvilinear relation between PSR and RI is seen while Figs A6.5, A6.6, and A6.7 exhibit linear trends. There appears to be about the same amount of scatter in the RI versus PSR plots as was seen in the SV versus PSR plots.

The cross slope variance versus PSR plots are shown in Figs 36 and A6.8 through A6.12. General curvilinear trends are evident in the flexible pavement plots of Figs 36, A6.8, and A6.9.and in the rigid pavement plot for 20 miles per hour. Figures A6.10, A6.11, and A6.12 show very little relation between cross slope variance and PSR.

It is evident from close examination of these plots that the 20 and 50 mile per hour data exhibit better correlation between the roughness variables and PSR than do the 34-mile per hour data. Determination of the extent of these correlations is the purpose of the next chapter.

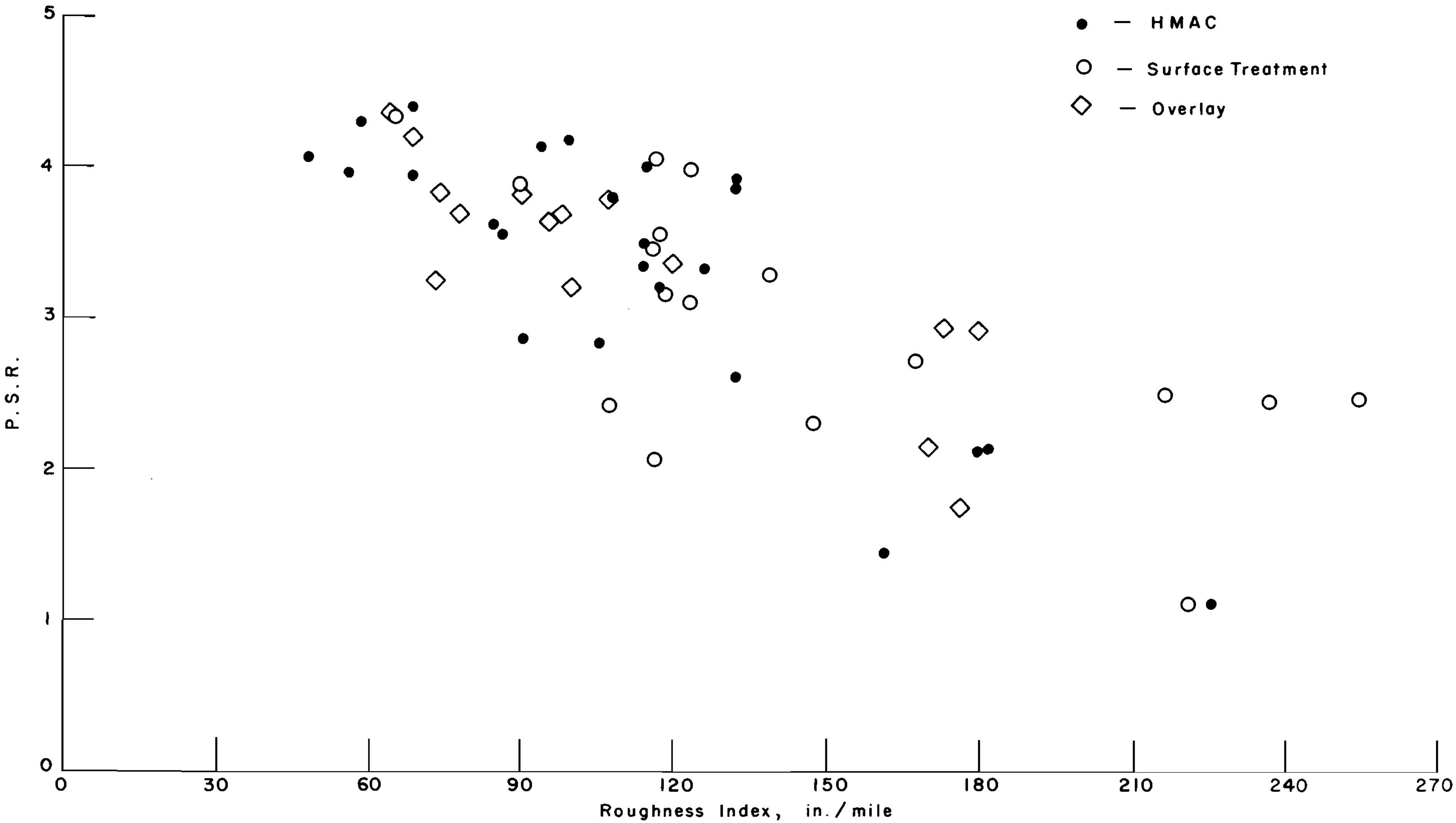


Fig 35. PSR versus roughness index for 56 flexible pavements measured at 20 miles per hour.

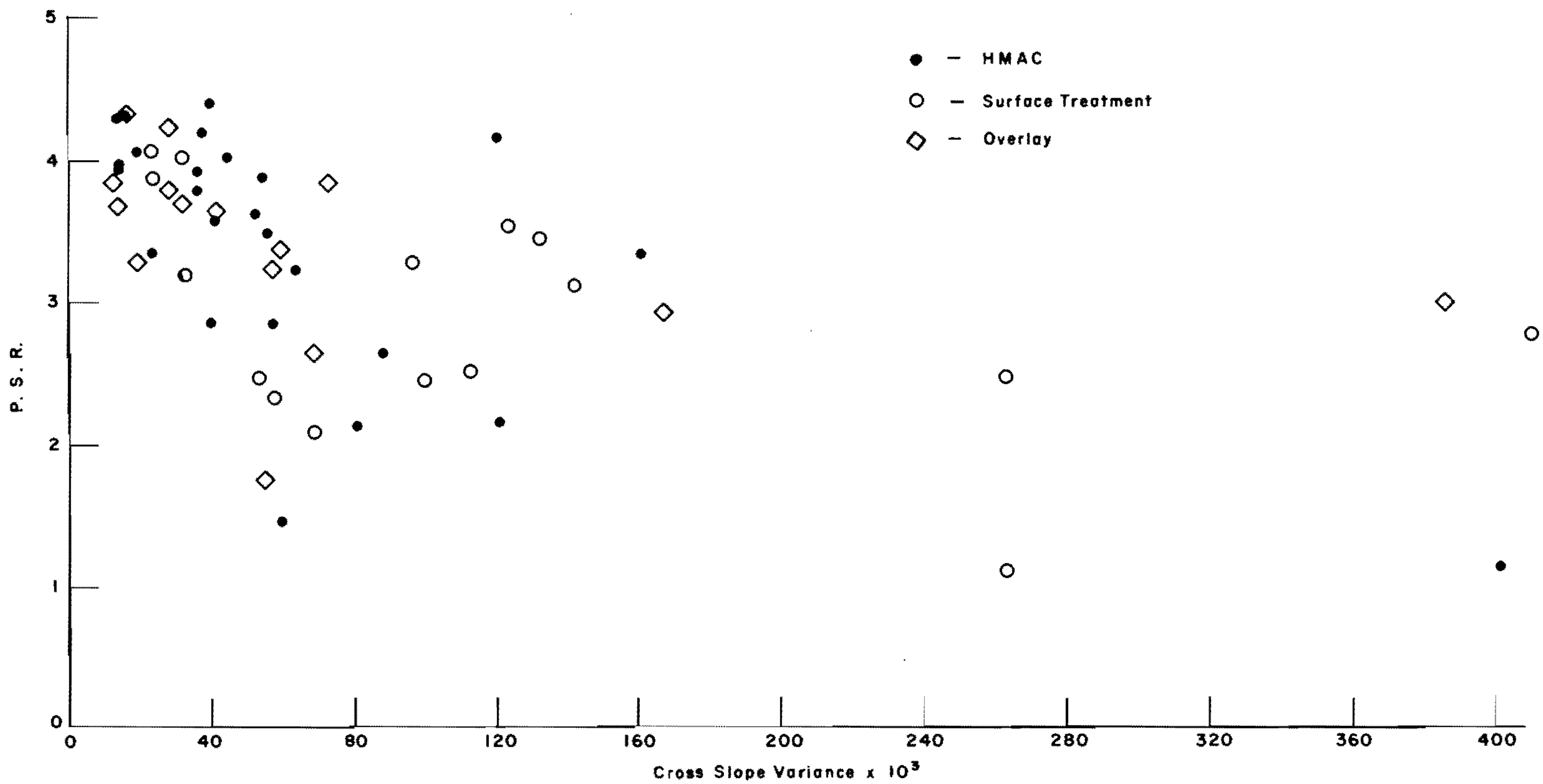


Fig 36. PSR versus cross slope variance for flexible pavements measured at 20 miles per hour.

CHAPTER 5. MODELING THE PREDICTIVE EQUATIONS

In order to relate quantitatively the condition survey and roughness summary statistic variables to PSR, linear regression analysis techniques were extensively used. These techniques are described by Draper and Smith (Ref 11) and Ostle (Ref 32). The computer program used for these regression analyses is a stepwise regression program, STEP01, which is available at the Center for Highway Research. This program is a modified version of the stepwise regression program, BMDO2R, included in Ref 10. The stepwise regression procedure was selected because of the updating method used in building the model. At each step in the procedure (a step is reached any time the program adds or deletes a variable from the model) each variable in the model is checked using a partial F-test criterion to determine if it made a contribution to the model. This provides a judgment of the contribution of each variable as if it were the last one to enter the model, irrespective of its actual point of entrance into the model. Any variable which is not significant via the partial F-test is removed from the model. The next variable which is entered is the one with the highest F-value at the step. This procedure of adding variables, checking for the contribution of each variable, and deleting any insignificant terms is continued until none of the computed partial F-values are larger than a preselected input value. At this point of termination, the program has constructed from the various independent variables (X's) the group which best predicts the dependent variable (Y).

Transformations

In performing linear regression analyses it has been found that careful study of the scatter diagrams of each independent variable versus the dependent variable (PSR) will enable the researcher to determine the most probable transformation required to linearize the data. Such study of the scatter diagrams in Chapter 4, relating the condition survey and roughness summary statistics to PSR, lead to the following transformations on these data:

(1) Cracking and patching for the rigid pavements were added together as shown in Fig 37. Two trends are obvious in the combined data. A linear trend with a negative slope for the CPJR jointed pavements and a curvilinear trend for the concrete pavements continuously reinforced (CPCR). To include such data in the regression analysis a BLOCK term was introduced to distinguish between the two types of PCC pavements. The CPCR pavements were given a value of one while the concrete pavements jointed reinforced (CPJR) pavements were given a value of zero. Then by proper manipulation the linear effect for the CPJR pavements was entered as well as both a linear and a quadratic effect for the CPCR pavements.

(2) A $\log_{10}$ (hereafter designated as log) transformation was performed on slope variance data for flexible pavements run at 20, 34, and 50 miles per hour. These transformed data are shown in Figs 38, 39, and 40. Though a great deal of scatter is still present in the data, the transformation does linearize the data.

(3) A log transformation was performed on the roughness index data for flexible pavements measured at 20, 34, and 50 miles per hour. This transformation did not improve the trends for the 34 and 50-mile per hour data; therefore, no regression analyses were performed using these sets of data. A regression analysis was performed using the 20-mile per hour transformed data and the plot for these data is shown in Fig 41.

(4) A log transformation was performed on the slope variance data for rigid pavements measured at 20, 34, and 50 miles per hour. These transformed data are shown in Figs 42, 43, and 44 and do exhibit better linear trends than do the untransformed data of Figs 34, A6.1, and A6.2. Regression analyses were performed on all of these transformed data.

(5) A log transformation was performed on the cross slope variance data for the flexible and rigid pavement data measured at 20, 34, and 50 miles per hour. An example of these plots is shown in Fig 45. As is evidenced in Fig 45 and each of the other plots, a great deal of scatter is present in the data, but this transformation does provide a better linear trend than do the arithmetic plots for the flexible pavements of Figs 36, A6.8, and A6.9. Cross slope variance measured at 20 miles per hour for rigid pavements shows some correlation with PSR, but the data measured at 34 and 50 miles per hour show very little correlation with PSR. However, these transformations were used in the regression analyses.

These attempts to linearize the data are important in linear regression analyses because the analysis uses only a constant coefficient and not a variable in estimating the effect of a term. For example, in considering a model such as

$$Y = \beta_0 + \beta_1 X + \beta_2 X^2 + e$$

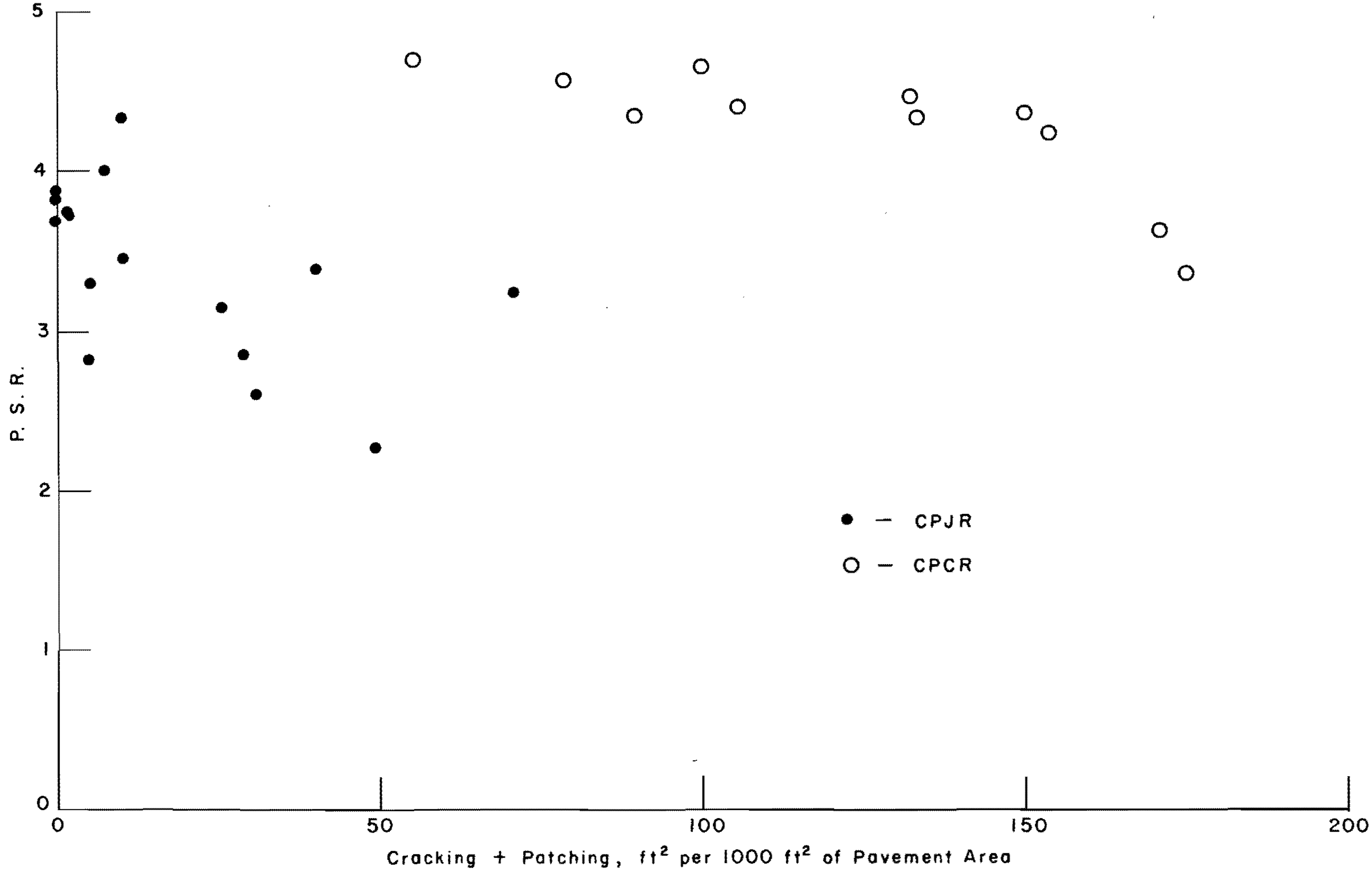


Fig 37. PSR versus cracking plus patching for 28 rigid pavements.

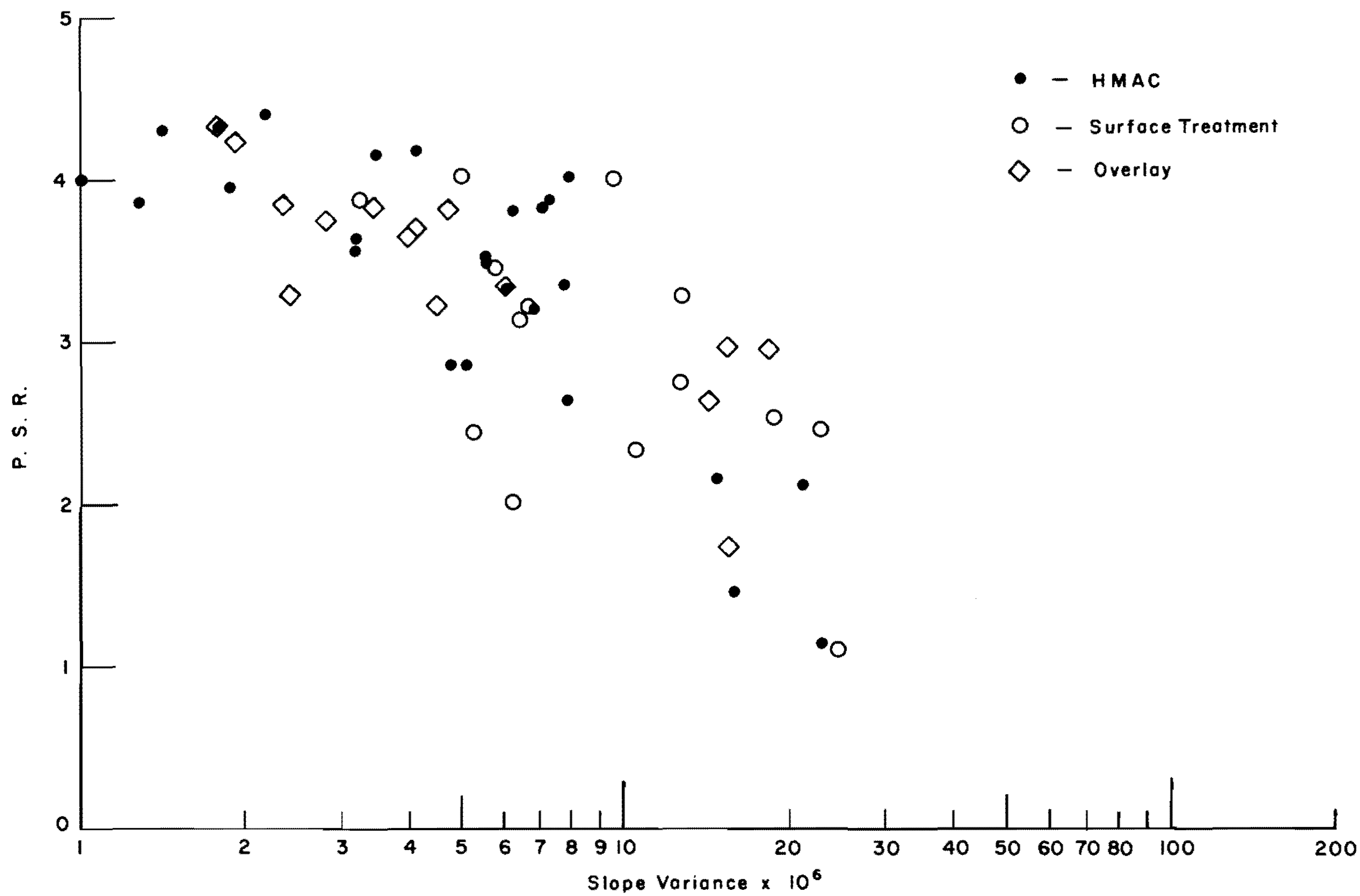


Fig 38. PSR versus log slope variance for 56 flexible pavements measured at 20 miles per hour.

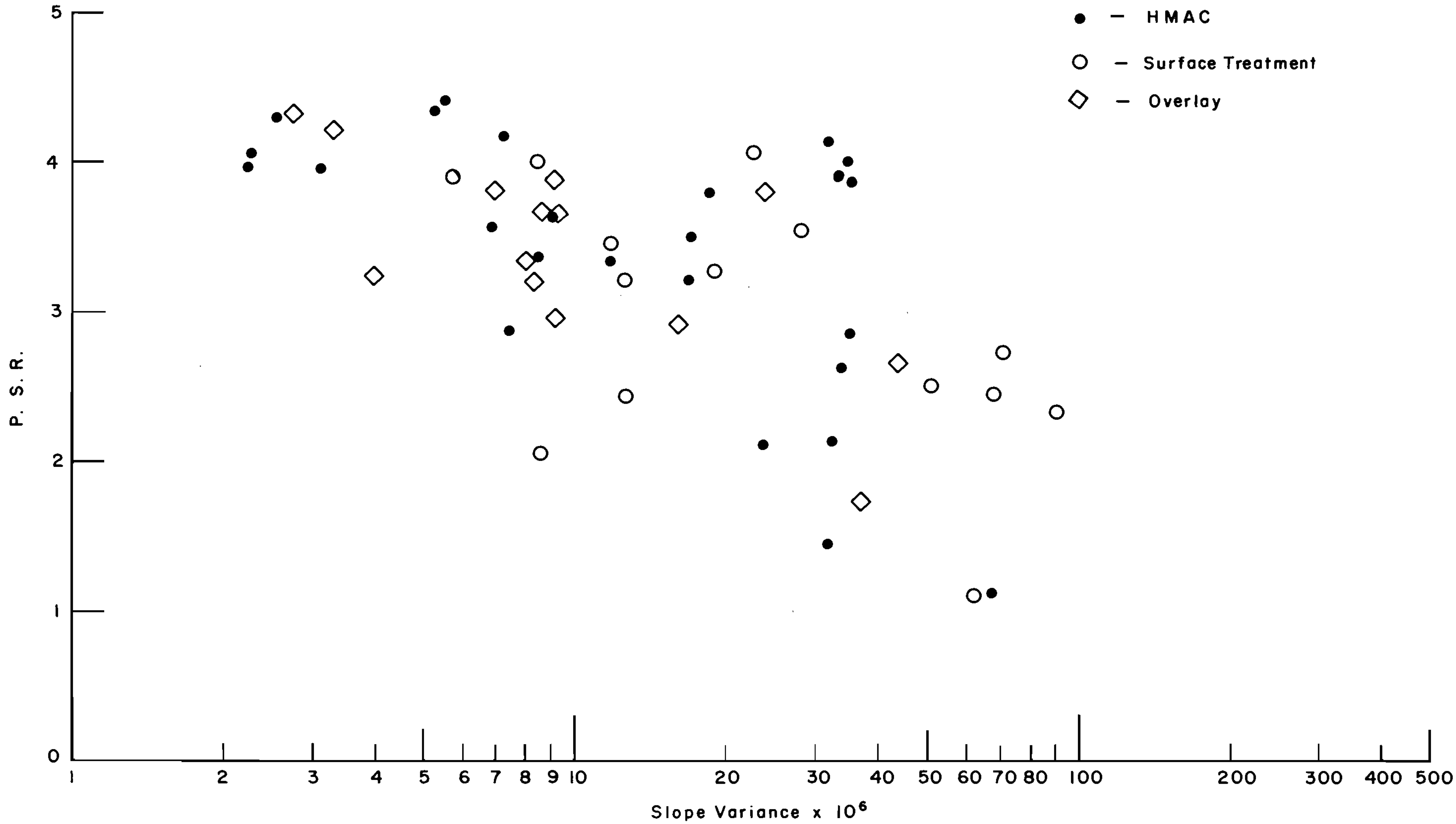


Fig 39. PSR versus log slope variance for 53 flexible pavements measured at 34 miles per hour.

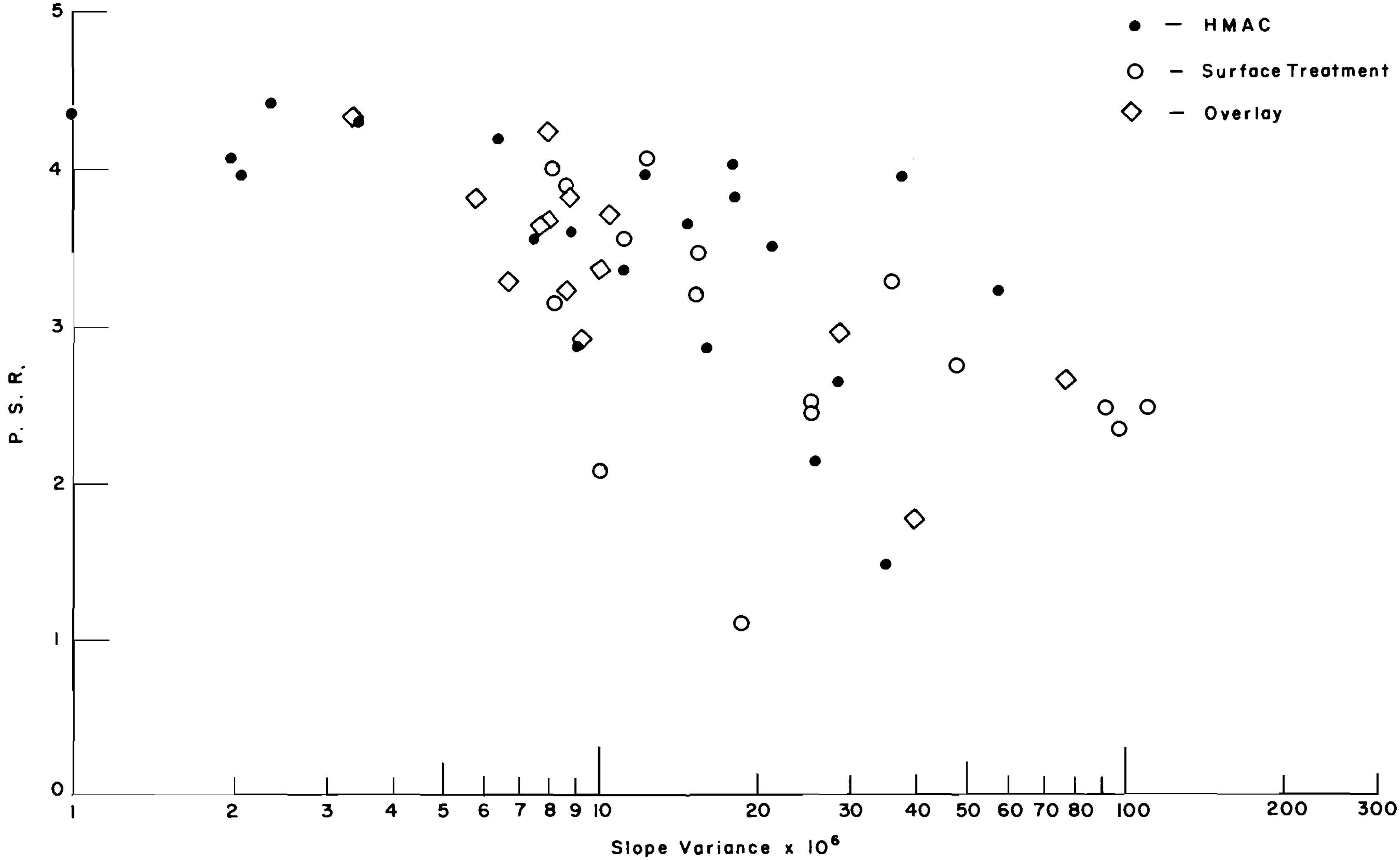


Fig 40. PSR versus log slope variance for 51 flexible pavements measured at 50 miles per hour.

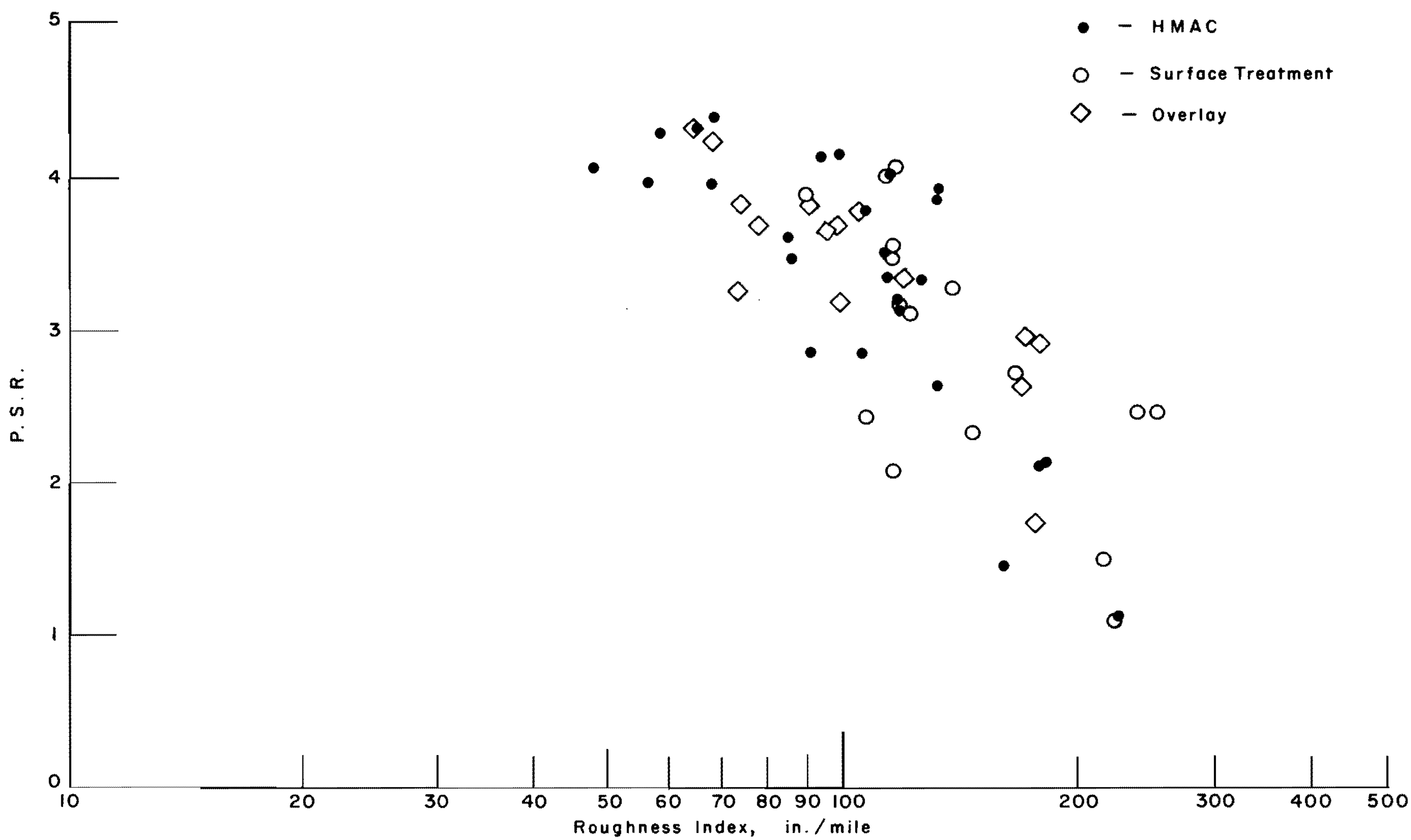


Fig 41. PSR versus log roughness index for 56 flexible pavements measured at 20 miles per hour.

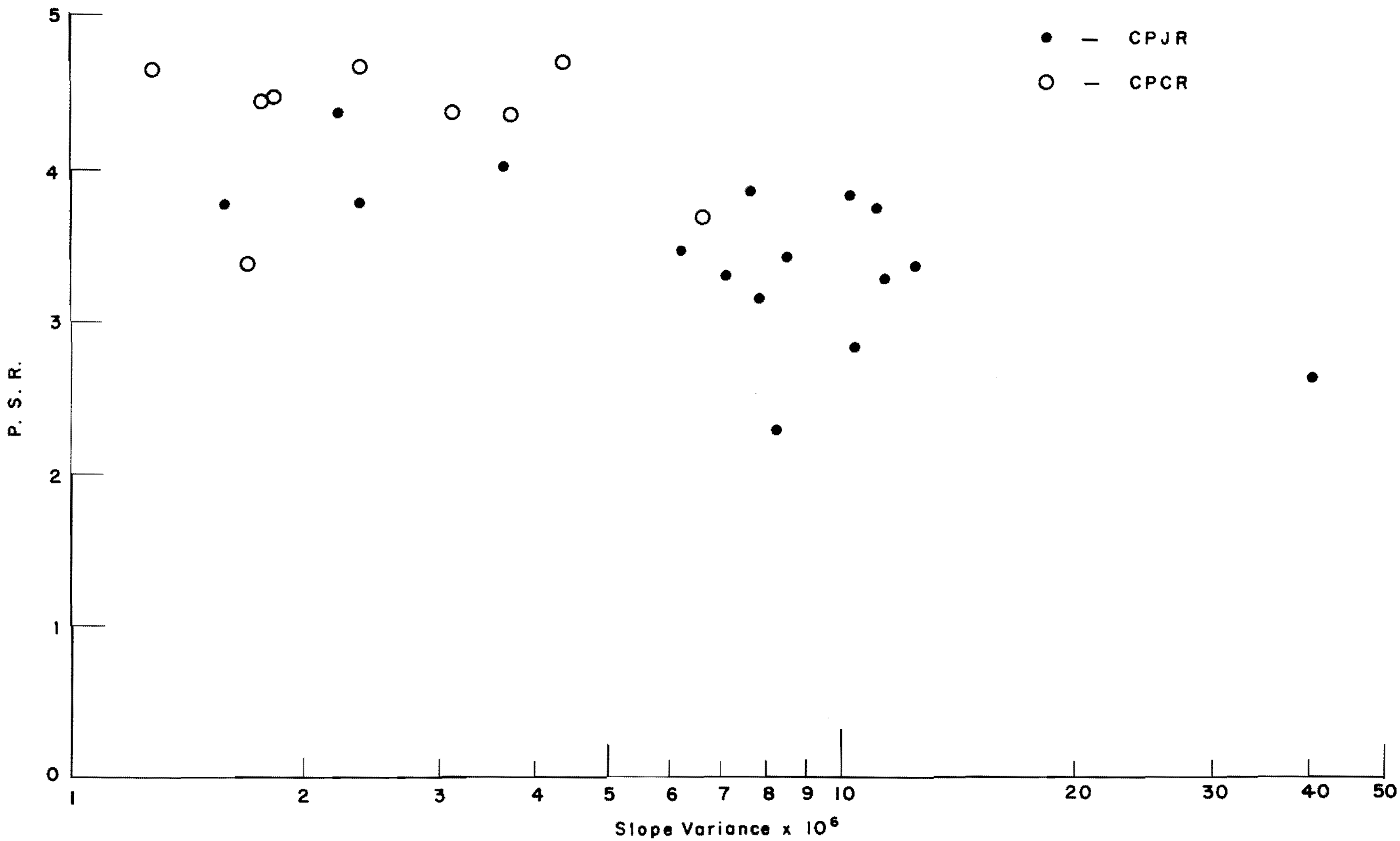


Fig 42. PSR versus log slope variance for 25 rigid pavements measured at 20 miles per hour.

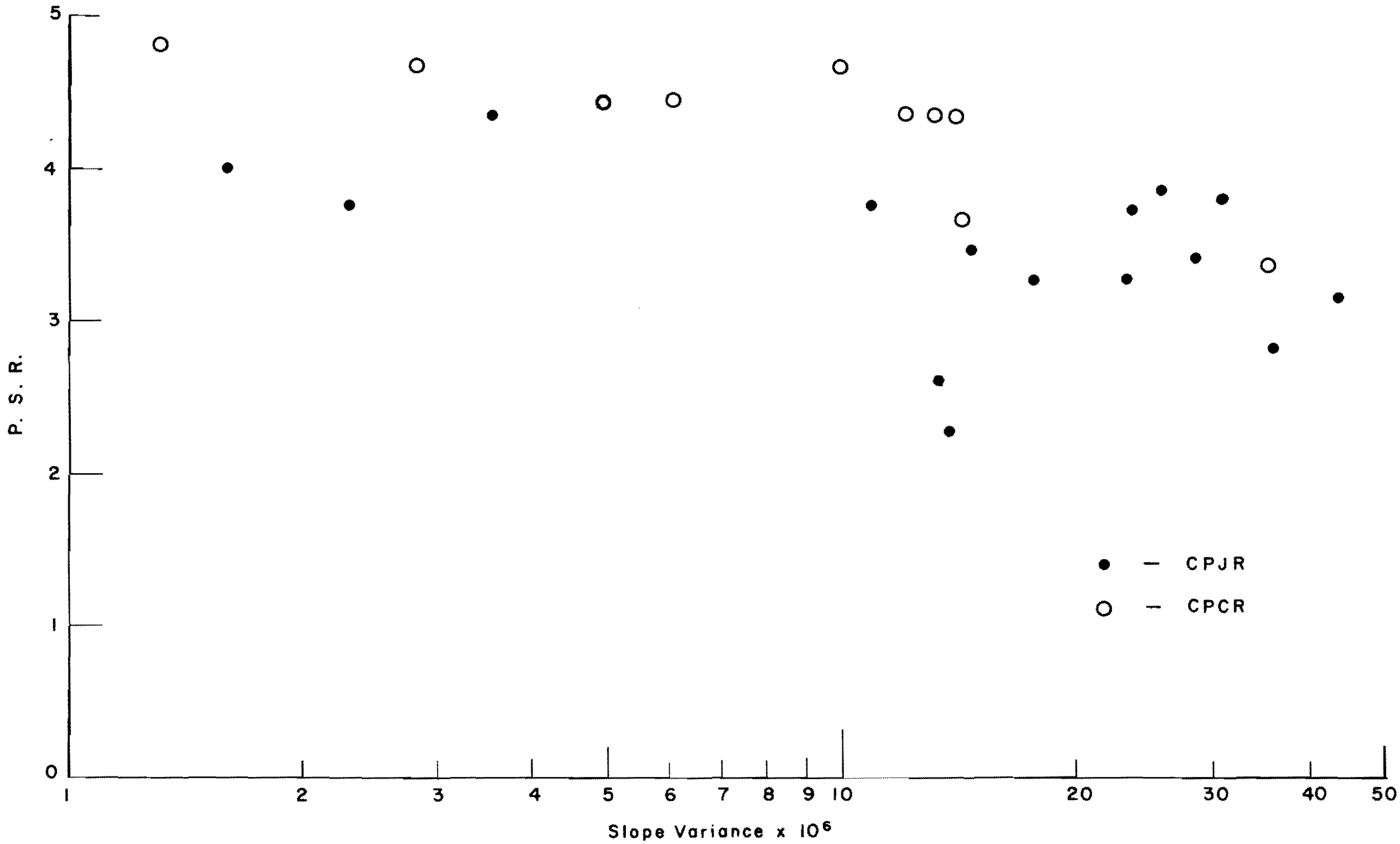


Fig 43. PSR versus log slope variance for 25 rigid pavements measured at 34 miles per hour.

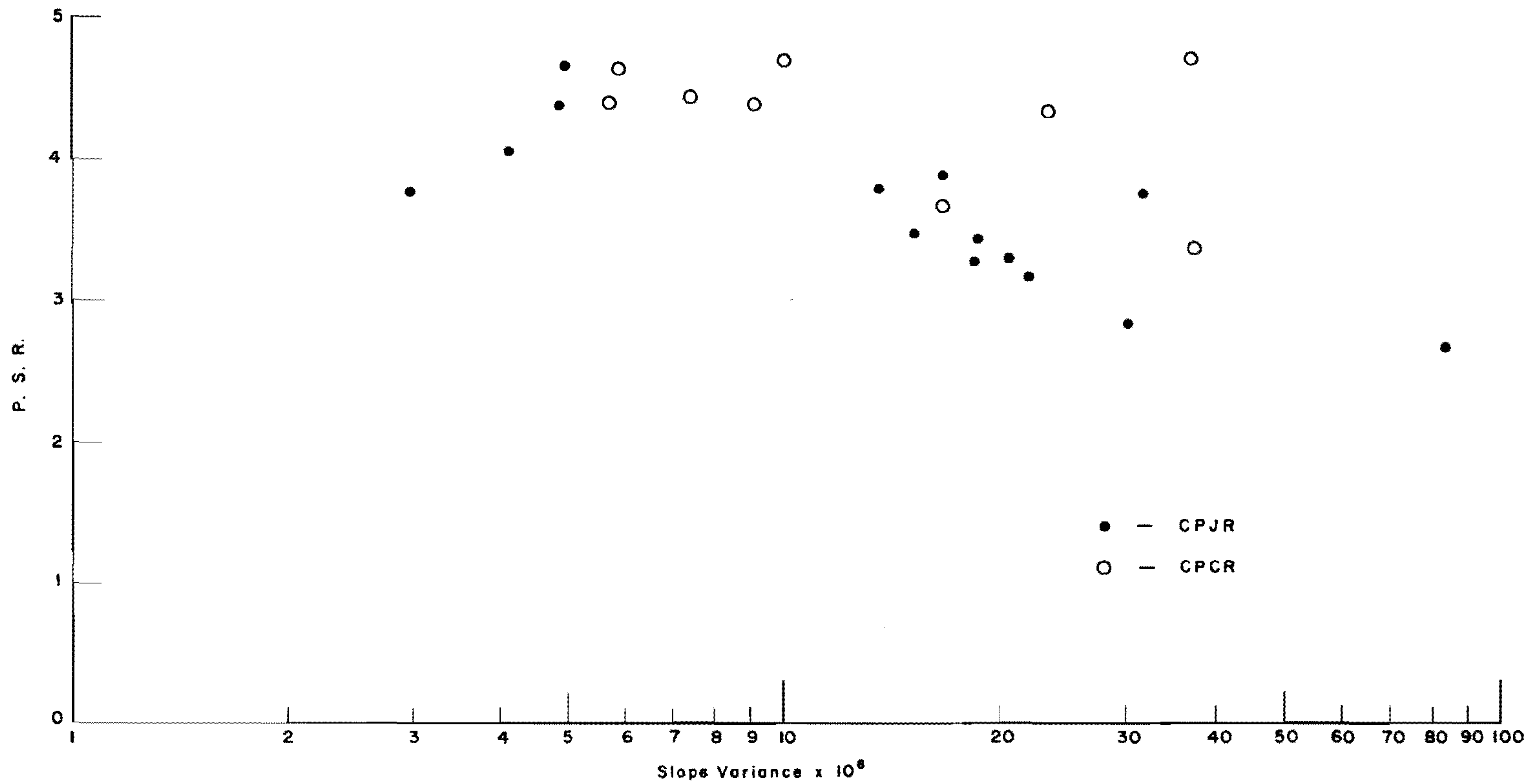


Fig 44. PSR versus log slope variance for 23 rigid pavements measured at 50 miles per hour.

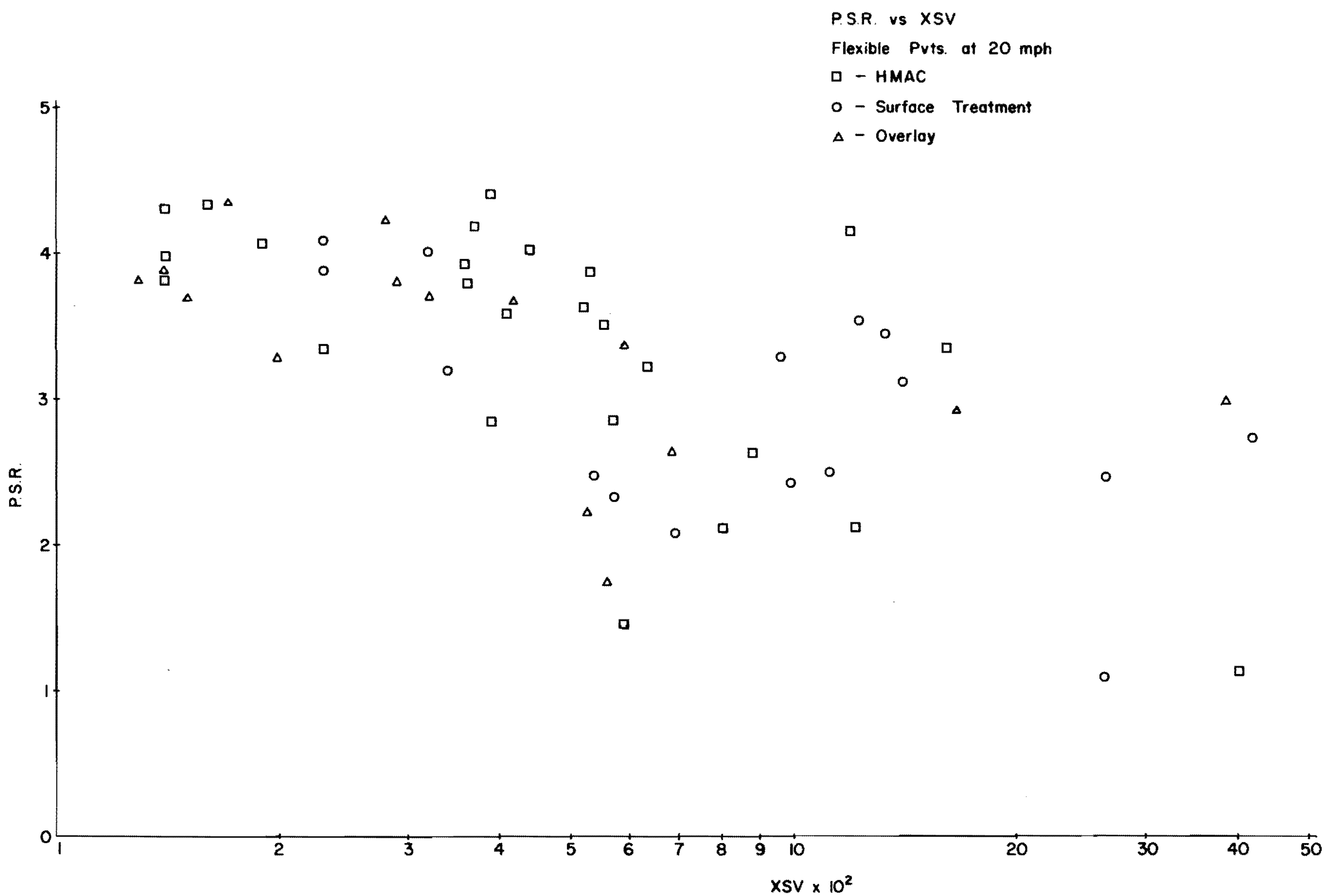


Fig 45. PSR versus cross slope variance for 25 flexible pavements measured at 20 miles per hour.

β_0 , β_1 , and β_2 are defined as the parameters of the model. When referring to the linearity of a model, the reference is to whether the parameters are linear or nonlinear.

Model Development

The regression analyses follow after linearizing the independent variables as carefully as possible. Ten regression analysis problems were run using the flexible pavement roughness variables and condition survey information and eight problems were run using the rigid pavement data.

Eight of the flexible pavement regression problems involved two summary statistics (either RI or SV and XSV as discussed in Chapter 4) as well as cracking (C), patching (P), rut-depth variance (RDV), average rut depth (RD), average texture (T), C + P, and all the interactions. The other two regression analyses involved only one summary statistic and selected condition survey variables. These two will be discussed later in the section on validation of the model. The summarized results of these analyses are shown in Table 25. In this table the problem number designation is used to specify the particular combination of roughness summary statistics which were used for that problem. For example, Problem No. 20-7 involved a regression analysis using data run at 20 miles per hour with Filter 1 and the summary statistics were log slope variance and log cross slope variance.

The best predictive equation can be chosen on the basis of the highest correlation coefficient and smallest standard error of estimate if there is a sufficient number of degrees of freedom in the residual sum of squares. This study provides such a case since the degrees of freedom for residuals of the flexible pavements is at least 45 while the degrees of freedom per the rigid pavements residual is at least 18. From Table 25 the best predictive equation for flexible pavements is that for Problem No. 50-7 and involves log SV and log XSV for measurements made with Filter 2 at 50 miles per hour. This equation is selected over Problem No. 50-8 because it involves fewer terms in the model. For flexible pavements, the best equation is

$$\begin{aligned} PSI = {} & 4.57 - 0.27 (\log SV) - 0.41 (\log XSV) + 0.08 (T) \\ & + 0.24 (\log SV)(RD) - 0.11 (\log SV)(T) - 0.00001 (C)(P) \\ & - 0.00069 (P)(T) \end{aligned} \tag{5.1}$$

TABLE 25. SUMMARY OF 10 REGRESSION ANALYSES FOR FLEXIBLE PAVEMENTS MEASURED AT 20, 34, AND 50 MPH

Problem No.	Filter No.	Vehicle Speed, mph	Roughness Variables	Correlation Coefficient	Standard Error of Estimate	Number of Terms in the Model
20-7	1	20	Log SV, Log XSV	0.88	0.41	5
34-7	1	34	Log SV, Log XSV	0.84	0.49	5
50-7	2	50	Log SV, Log XSV	0.88	0.40	7
20-8	1	20	RI, Log XSV	0.88	0.42	6
34-8	1	34	RI, Log XSV	0.84	0.48	5
50-8	2	50	RI, Log XSV	0.88	0.40	8
20-9	1	20	SV, Log XSV	0.88	0.43	8
20-11	1	20	Log RI, Log XSV	0.87	0.43	4
50-7L	2	50	(Log SV) Left	0.81	0.48	5
50-7LV	2	50	(Log SV) Left	0.75	0.54	4

where

PSI = present serviceability index (predicted PSR);

log SV = $\log_{10}$ (slope variance $\times 10^6$);

log XSV = $\log_{10}$ (cross slope variance $\times 10^3$);

T = average texture, 0.001 in.;

RD = average rut depth, 0.1 in.;

C = cracking, $ft^2/1,000\ ft^2$ of pavement area;

P = patching, $ft^2/1,000\ ft^2$ of pavement area.

For this equation $R = 0.88$ and the standard error of estimate is 0.40.

The standard error of estimate is an estimate of the standard deviation. This means that the PSI will be within ±0.40 of the PSR 68 percent of the time and ±0.80 of the PSR 95 percent of the time. An examination of the residuals (γ - γ estimated or PSR - PSI) was conducted and an example plot is shown in Fig 46. This plot shows the PSI versus the residuals and the plot exhibits no abnormalities.

One other equation will be presented which is represented by Problem No. 50-7L. This equation is provided for the possibility that instrumentation problems incapacitate one of the measurement channels. Since the right profile data channel is more frequently subjected to noise than the left profile, the left profile data channel was used in this analysis. The summary statistic and condition survey data utilized in this model are those used in Problem No. 50-7 which was the best equation for the flexible pavements. The equation was developed using the log SV, the condition survey variables, and their interactions. This equation for the left profile data are

$$\text{F. LEFT (PSI)} = 4.19 - 0.74\ (\log SV) - 0.0023\ (C)$$

$$- 0.020\ (\log SV)(T) - 0.0013\ (P)(T) \qquad (5.2)$$

where F. LEFT (PSI) = PSI for the left profile for flexible pavements, and the other variables are as defined in Eq 5.1. For this equation $R = 0.81$ and the standard error of estimate is 0.48.

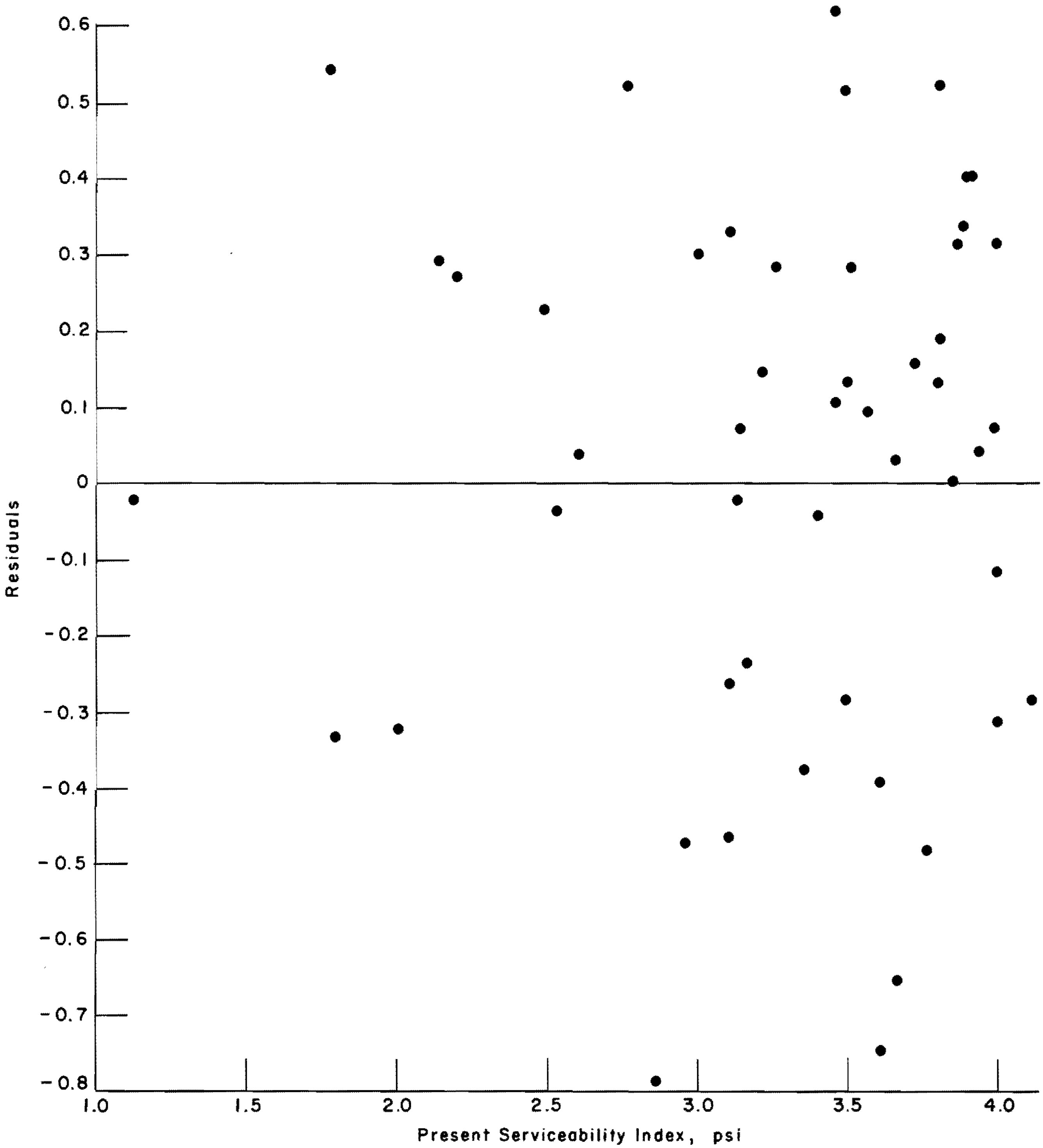


Fig 46. Residuals versus PSI for 51 flexible pavements measured with Filter 2 at 50 miles per hour.

Eight regression analysis problems were run using the rigid pavement roughness variables and condition survey data. Seven of the problems were run using two roughness statistics, condition survey variables, and interactions. Table 26 includes a summary of these runs. From this table it is evident that Problem No. 50-3 provides the best predictive equation. This equation involves roughness data measured with Filter 2 at 50 miles per hour. The best rigid pavement equation is

$$\mathrm{PSI} = 4.53 - 1.21\ (\log \mathrm{SV}) - 0.00004\ (C + P)_C^2 + 1.21\ (\mathrm{PT})$$

$$- 0.0067\ (\log \mathrm{SV})(C + P)_J + 0.39\ (\log \mathrm{SV})(\log \mathrm{XSV}) \qquad (5.3)$$

where

PSI = present serviceability index (predicted PSR),

log SV = $\log_{10}$ (slope variance $\times 10^6$),

log XSV = $\log_{10}$ (cross slope variance $\times 10^3$),

$(C + P)_C$ = cracking plus patching for concrete pavements continuously reinforced (CPCR),

$(C + P)_J$ = cracking plus patching for concrete pavement with joints reinforced (CPJR),

PT = pavement type and equals 1.0 for CPCR and 0.0 for CPJR.

In this equation $R = 0.94$ and the standard error of estimate is 0.23.

The correlation coefficient is equal to 0.94 and the estimated standard deviation is equal to 0.23. These values for the rigid pavements indicate a better correlation among PSR and the roughness and condition survey variables for the rigid pavements than for the flexible pavements as evidenced from the plots of Chapter 4 and Appendix 6. An examination of the residuals for this model was conducted. Figure 47 shows PSI versus the residuals. These data exhibit no abnormalities.

One other equation represented by Problem No. 50-3L will be presented. This equation involves the left profile slope variance data from Problem No. 50-3. It will provide an estimate of the PSR in the case of an instrumentation failure which does not incapacitate both profile channels. This equation is

TABLE 26. SUMMARY OF 8 REGRESSION ANALYSES FOR RIGID PAVEMENTS MEASURED AT 20, 34, AND 50 MPH

Problem No.	Filter No.	Vehicle Speed, mph	Roughness Variables	Correlation Coefficient	Standard Error of Estimate	Number of Terms in the Model
20-3	1	20	Log SV, Log XSV	0.92	0.31	6
34-3	1	34	Log SV, Log XSV	0.91	0.31	4
50-3	2	50	Log SV, Log XSV	0.94	0.23	5
20-8	1	20	RI, Log XSV	0.90	0.32	4
34-8	1	34	RI, Log XSV	0.89	0.33	5
50-8	2	50	RI, Log XSV	0.93	0.26	5
20-9	1	20	SV, Log XSV	0.88	0.35	4
50-3L	2	50	(Log SV) Left	0.92	0.27	5

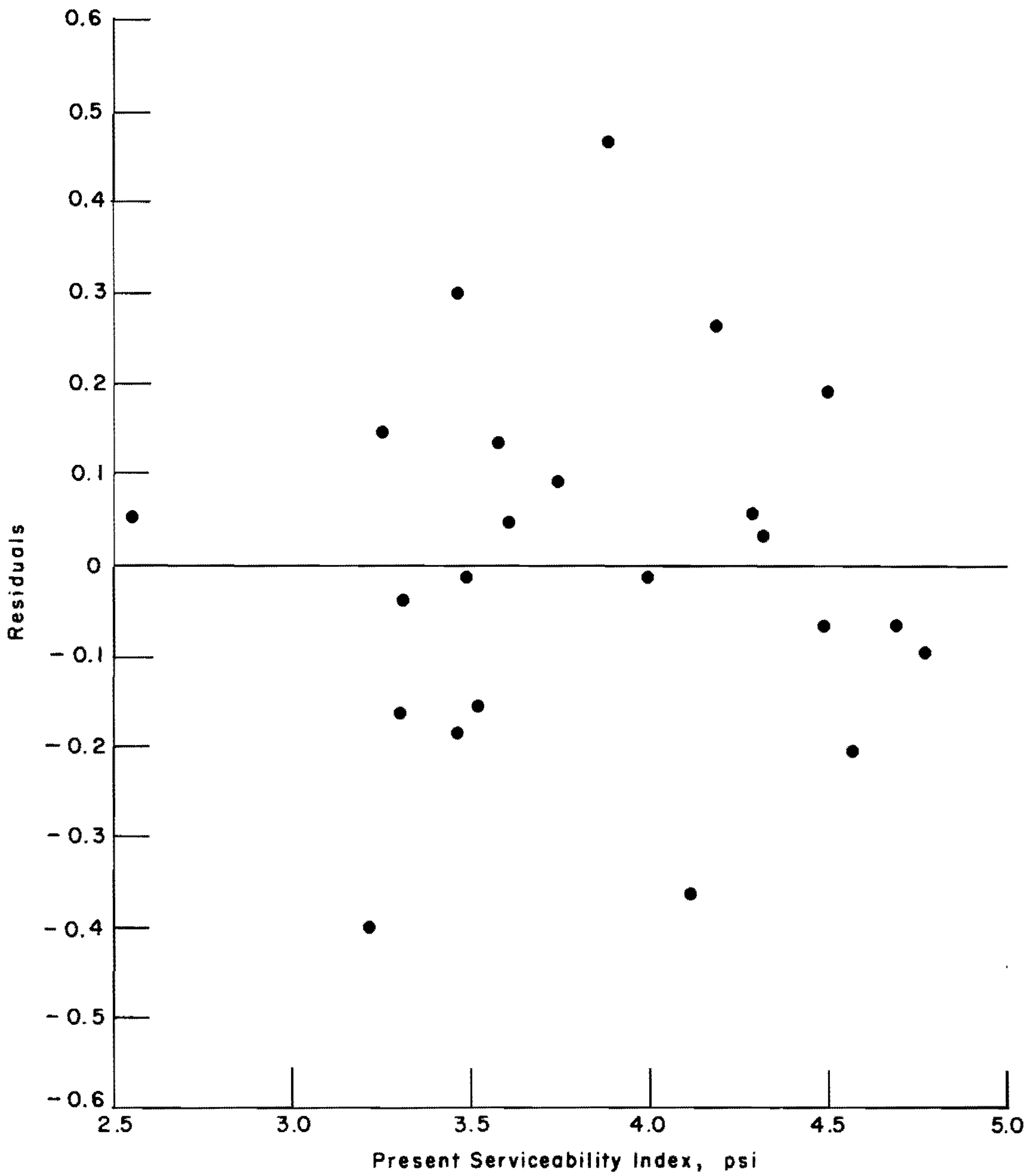


Fig 47. Residuals versus PSR for 23 rigid pavements measured with Filter 2 at 50 miles per hour.

$$\text{R. LEFT (PSI)} = 3.87 - 0.31\,(\log SV) - 0.00004\,(C + P)^2_C$$

$$+ 0.018\,(C + P)_J + 1.298 - 0.026\,(\log SV)(C + P)_J \qquad (5.4)$$

where R. LEFT (PSI) = PSI for the left profile for rigid pavements, and the other variables are as defined in Eq 5.3. In the above equation $R = 0.92$ and the standard error of estimate is 0.27.

In the above regression analyses no test was made for lack of fit for the model. This test was not made because the basic assumption of no error in the independent variables was not met. It was felt that since the regression procedure assumes that all errors are in the Y's , i.e., the PSR values, when in fact these replicate rating errors are very small, this test would not be meaningful. This does mean that the use of these equations outside the range of data used in this analysis should be avoided.

Validation of the Models

An estimate as to the predictive quality of the flexible pavement equation may be found by using the preliminary rating session data as a check. This was accomplished by taking the left profile data for the two summer rating sessions and the condition survey information, except for texture, and performing a regression analysis to develop one additional predictive equation. The roughness variable used in this regression analysis was log SV which is the same one used in the best predictive equation for flexible pavements (Problem No. 50-7). This equation was developed for preliminary rating session data run with Filter 2 at 50 miles per hour and is designated in Table 25 as Problem No. 50-7LV. The resulting equation is

$$\text{PSI} = 4.32 - 1.06\,(\log SV) - 0.0052\,(C + P)$$

$$+ 0.0029\,(\log SV)(C + P) \qquad (5.5)$$

In this equation $R = 0.75$ and the standard error of estimate is 0.54.

Using the log slope variance and condition survey information for the 17 sections of the preliminary rating session as input values for Eq 5.5, these predicted PSI values are shown in Table 27. The differences between the predicted value (PSI) and the mean panel rating for each of the 17 sections are also shown in Table 27. It can be shown from the tabulated data that five of the values have differences greater than one standard deviation and two have differences greater than two standard deviations. The existence of these differences may be explained partly by a change which was made in the profile computer between the runs made for the preliminary rating session in February, and rating periods one and two in the following summer. The high frequency range of the profile computer was extended from about 75 cps (for preliminary rating session) to 250 cps (for rating periods one and two). This extension of the range exceeded the natural frequency of the road-following wheel and probably affected the subsequent data.

As another check on the equation for flexible pavements, a group of six raters who had rated during some or all of the previous sessions rated five flexible pavements of various quality in the Austin area. The SD Profilometer was used to make profile measurements and condition survey data were recorded for these sections. These data are shown in Table 28.

Summary statistics were run on these data and the resulting statistics and condition survey information were substituted into Eq 5.5 for the computation of PSI's. Equation 5.5 was used because only the left profile data were available at the time of measurement. One of the accelerometers was being repaired by the manufacturer. The resulting PSR values are also shown in Table 28. The residual column shows that two out of the five residuals (difference between PSR and PSI) are greater than 0.5 (the estimated standard deviation). This means that 60 percent of the values are within 0.5 of the proper value which is not abnormal. These results would then suggest that the predicted values for flexible pavements are within a reasonable range.

No rigid pavements were included in either the preliminary rating session or in the five test sections in the Austin area. Therefore, no checks are available on the rigid pavement equation at the present time and the checks which have been proposed for the flexible pavements are not rigorous.

The validity of the equations presented in this report cannot be assured until several sections of both the flexible and rigid type are measured while all equipment is operational with the SD Profilometer and then rated by a small panel of raters and the differences compared. Such validation should be accomplished as soon as possible.

TABLE 27. COMPARISON BETWEEN PSI AND PSR FOR THE PRELIMINARY RATING SESSION DATA MEASURED WITH FILTER 2 AT 50 MPH

Sect. No.	Avg. Slope Variance x 10^6	Log SV	Cracking Plus Patching	PSR	PSI	Difference (PSR-PSI)
1	4.61	0.66	475	3.0	2.0	1.0
2	5.48	0.74	0	3.0	3.6	-0.6
3	5.01	0.70	50	3.7	3.4	0.3
4	17.25	1.24	0	3.0	3.0	0
5	5.16	0.71	0	4.0	3.6	0.4
6	13.41	1.13	23	2.3	3.1	-0.8
7	8.56	0.93	0	3.4	3.3	0.1
8	12.27	1.09	0	3.2	3.1	0.1
10	9.67	0.99	0	2.2	3.3	-1.1
11	4.63	0.67	7	3.9	3.6	0.3
12	20.59	1.31	340	1.8	2.6	-0.8
14	3.20	0.51	0	3.7	3.8	-0.1
16	14.29	1.16	0	3.0	3.1	-0.1
17	19.93	1.30	28	2.5	2.9	-0.4
18	2.41	0.38	0	3.8	3.9	-0.1
19	3.97	0.60	0	3.9	3.7	0.2
20	3.02	0.48	0	4.1	3.8	0.3

TABLE 28. ROUGHNESS DATA FOR 5 FLEXIBLE PAVEMENT TEST SECTIONS IN THE AUSTIN AREA

Section No.	Average SV	Log SV	C	P	PSI	PSR	Residual PSR-PSI
1	255.7	2.408	3.6	48.3	1.00	1.75	0.75
2	45.1	1.654	0.5	0	2.75	2.37	-0.38
3	9.4	0.973	0	200.0	2.34	2.97	0.63
4	23.6	1.372	60.5	0	2.31	2.10	-0.21
5	8.8	0.944	69.4	0	3.44	3.87	0.43

Reproducibility of SD Profilometer Measurements

The variability of summary statistics obtained from the SD Profilometer is of importance in determining the usefulness of these measurements in estimating the change of PSI with time on roadway sections of interest. Since the most useful application of the SD Profilometer will be in evaluating roughness to determine PSI, the variability of the log of slope variance (SV) was investigated. The log transformation on SV was used in Eqs 5.1 and 5.3 for flexible and rigid pavements, respectively. The standard derivations of the log SV values for both the flexible and rigid pavements were calculated. The standard deviation for the log SV of the rigid pavements was 0.085. To determine the effect of these variations on the PSI values for a typical flexible and rigid section, two sections were selected for which the PSI was calculated from Eqs 5.1a and 5.3. Using the measured SV and condition survey data then, the standard deviation of the log SV was added to each and the new PSI calculated. These values are shown below:

Flexible Pavement		Rigid Pavement	
PSI with log SV	= 4.09	PSI with log SV	= 4.04
PSI with log SV + σ_{SV}	= 4.08	PSI with log SV + σ_{SV}	= 3.98

As can be noted there are practically no differences between the values calculated using SV and the values calculated using SV plus one standard deviation.

To obtain an indication of the repeatability of the PSI values calculated using Eqs 5.1 and 5.3 versus the PSR values, 10 sections which were rated twice by the rating panel and run twice with the SD Profilometer were selected for a correlation study. To make this study, the PSI's were calculated for data from each run of the profilometer and the condition survey information. The correlation of the PSI for the first run with the PSI from the second run was 92 percent while the correlation of the first PSR value with the second PSR was 96 percent. From this information it can be concluded that the rating panel can repeat its rating value with slightly more accuracy than can the SD Profilometer. However, it is quite likely that variation between two different panels would be much higher. Run to run variation would also be higher for a smaller panel. The implication of such information is that data from the SD Profilometer can be used for estimating present serviceability rating values using the developed equations with about the same accuracy as can a rating panel. However, since it would be impractical to use such a large rating panel for routine work, we can conclude that the profilometer is the better approach to the problem.

CHAPTER 6. DISCUSSION OF FINDINGS AND RECOMMENDATIONS

Discussion of Findings

The analyses involving the rating values from the panel showed that

(1) The average of all rating values could be used to represent the collective opinion of the panel for each test section.

(2) The PSR value is not affected by the position in the vehicle that the rater occupied.

(3) There were no significant differences between the rating values of the men and the women.

(4) There were no significant differences between the average rating values of the drivers and the panel.

(5) The raters were able to rerate several sections with no significant differences between the first and second rating.

A set of programs was developed for computing the summary statistics of slope variance, cross slope variance, and roughness index. These programs use input data which were digitized using an A-D program developed in Ref 47. The digitized data were processed through a compatability program, included in this report, before being used to compute the summary statistics. This is the first set of general programs which has been developed for this purpose.

A set of equations for predicting the present serviceability rating for both flexible and rigid pavements using slope variance and condition survey variables has been developed. Neither equation has been rigorously checked but comparisons of results on a few test sections indicate that the predicted (PSI) values are reasonable. One additional check on several sections which were rated at two different times by the rating panel and run twice with the SD Profilometer indicates that the two predicted (PSI) values are in agreement as are the two PSR values given by the rating panel. This would indicate that the repeatability of the PSI values using profilometer data is about the same as the repeatability of the rating panel itself.

The profilometer provides an accurate analog signal which represents the road profile. These data in digital form are amenable to many statistical or nonstatistical analyses. This type of data is available for the first time.

The digitized profile data have been used as input values of road profile in a model to predict dynamic forces on the pavement surface caused by pavement roughness. Comparisons of these predicted dynamic loads to measured dynamic loads on a test section where both roughness measurements via the SD Profilometer and dynamic loads via a scale for weighing vehicles in motion were obtained, showed very close agreement (Ref 1).

However, many difficulties have been encountered with the equipment and operation of the data collection and analyses phases of the study. The major factors have been:

(1) Maintenance on the profilometer and associated equipment is expensive and repairs require the services of a skilled technician and a graduate electrical engineer. Typical problems encountered are

   (a) frequent adjustments of the raise-lower electromechanical circuit for the sensor wheels,

   (b) rebuilding the linear potentiometers when damaged,

   (c) isolating noise sources and redesign of elements to eliminate them,

   (d) isolating causes for periodic loss of sampling signal,

   (e) altering the interface unit between recording and processing systems, and

   (f) repairing the Honeywell tape recorder and Brush strip-chart recorder when necessary.

(2) Replacement parts such as the recording wheel, linear potentiometer, and accelerometer are very expensive and a long time delay in delivery results because they are specially built equipment. The typical life of a recording wheel is between 200 and 500 miles and the cost ranges from \$400 to \$500. This means that at best 500 miles of run time or about 300 miles of road profile will cost at least \$800. The number of profile miles are less than the run miles because the wheels must be on the road surface as the truck accelerates to the desired measurement speed.

   The potentiometer life appears to be about twice that of the road-following wheels. The cost of a potentiometer is approximately \$600. This adds an additional increment of cost which ranges from \$100 to \$400 per 300 miles of road profile depending on the damage to the potentiometer.

   To date the project has lost only one accelerometer (\$755) but the difficulty in determining when an accelerometer is on the verge of failure presents a very significant problem in validating the recorded data.

   Considering the above equipment alone the cost of obtaining road profiles ranges from \$3.50 to \$5.00 per mile. Such costs could severely restrict the usefulness of this device.

(3) In order to obtain noise free profiles, extreme care must be exercised at all steps in the recording process. The computer must be properly calibrated and checked at least twice each day of continuous operation. After a series of runs have been completed, each profile for each run must be checked for noise in the field by playing back the recorded profile data through an oscilloscope. However, use of this process is not foolproof. Eye fatigue of the observer is a significant obstacle and even if some noise is present no method has yet been devised to determine how much noise must be present before the run is no longer usable.

(4) Before the data can be digitized, a thorough check of the analog data is made in the laboratory. This consists of playing back the recorded data through a high frequency response oscillograph. The hard copy of the analog signal is utilized to determine the amount of noise present on the recorded road profile. The problem of determining how much noise is judged to invalidate a run enters at this point. No clear-cut procedure has yet been developed for making this decision.

(5) The analog-to-digital (A-D) processing requires the services of a technician to set up the necessary interface equipment and to operate the analog tape recorder and the computer. If all systems are operating properly, the analog data can be digitized rather quickly.

(6) The digitized profile data must then be rewritten in a form acceptable to the CDC 6600 which is presently used for data analysis. This process takes at least one day and possibly more depending on computer conditions. Once these are rewritten in CDC 6600 form, the scale factors for each profile run next must be calculated. These are computed using an existing computer program. An additional day is required for this operation.

(7) The data analysis programs which have been used thus far can be run with the digitized data rewritten in CDC 6600 form in another two days. At least four days are required to obtain this first set of summary statistics after the data have been obtained from the field. However, at the present time processing has always taken more than this minimum time period for any set of data runs.

Problems have always been encountered somewhere in the processing system.

Most of the these difficulties have been associated with noise problems from tape flutter and photocell crosstalk and maintenance problems with the sensor wheels and potentiometers. The noise problems have been minimized: (1) by placing a switch in the photocell circuit to break the circuit after the initial begin-of-section signal is obtained and (2) by removing the tape recorder from the shock mounts and placing it on an air cushion. The maintenance problems with the sensor wheels and potentiometers could be eliminated if a noncontact probe were developed. Technology now seems to be available for developing such a noncontact probe and several organizations are conducting research in this area.

Recommendations

As with any empirical finding the equations developed in Chapter 5 should be verified with additional data. This could be accomplished by selecting several test sections of both flexible and rigid type for obtaining profilometer measurements and at the same time selecting several of the original panel members to drive over and rate the same pavement sections. The differences between the predicted PSI and the mean panel PSR should be within plus or minus one standard deviation 67 percent of the time.

An investigation into the possibility of replacing the present road-following wheel and linear potentiometer with a noncontact probe for measurement of the relative displacement between the road surface and the profilometer vehicle might help eliminate the major source of equipment difficulty. A re-evaluation of the rating session profile data with a noise filter would be desirable.

REFERENCES

1. Al-Rashid, Nasser I., and Clyde E. Lee, "A Theoretical and Experimental Study of Dynamic Highway Loading," Research Report No. 108-1, Center for Highway Research, The University of Texas at Austin, March 1970.

2. Anderson, Virgil L., "Designs and Optimum Techniques for Consulting Statisticians and Experimenters," unpublished personal manuscript, Purdue University, Lafayette, Indiana, 1968.

3. Blackman, R. B., and J. W. Tukey, The Measurement of Power Spectra, Dover Publications, 1958.

4. Carey, W. N., Jr., H. C. Huckins, and R. C. Leathers, "Slope Variance as a Measure of Roughness and the CHLOE Profilometer," Special Report 73, Highway Research Board, 1962.

5. Carey, W. N., Jr., and P. E. Irick, "The Pavement Serviceability-Performance Concept," Bulletin 250, Highway Research Board, 1960.

6. Cochran, W. T., et al, "What is the Fast Fourier Transform?," Proceedings, Vol 55, No. 10, Institute of Electronic and Electrical Engineers, October 1967.

7. Cooley, J. W., P. A. W. Lewis, and P. D. Welch, "Application of the Fast Fourier Transform to Computation of Fourier Integrals, Fourier Series, and Convolution Integrals," Transactions on Audio and Electroacoustics, Vol AU15, No. 2, Institute of Electronic and Electrical Engineers, June 1967.

8. Cooley, J. W., P. A. W. Lewis, and P. D. Welch, "Historical Notes on the Fast Fourier Transform," Proceedings, Vol 55, No. 10, Institute of Electronic and Electrical Engineers, October 1967.

9. Darlington, J. R., and P. Milliman, "A Progress Report on the Evaluation and Application Study of the General Motors Rapid Travel Road Profilometer," Highway Research Record No. 214, Highway Research Board, 1968.

10. Dixon, W. J., Editor, BMD Biomedical Computer Programs, University of California Press, Berkeley and Los Angeles, 1968.

11. Draper, N. R., and H. Smith, Applied Regression Analysis, 1st Edition John Wiley and Sons, January 1967.

12. Getekunst, Ralph M., Jr., "A Study of the Subjective Experience of Riding Quality," Applied Psychology Corporation, Arlington, Virginia, October 1965.

13. Gossard, E. E., "A Review of Power Spectrum and Cross Analysis by Digital Methods," Technical Memorandum 600, Naval Electronics Laboratory Center, San Diego, California.

14. Gossard, E. E., and V. R. Noonkester, "A Guide to Digital Computation and Use of Power Spectra and Cross-Power Spectra," Technical Document 20 (TD 20 (Rev)), Naval Electronics Laboratory Center, November 3, 1967, (revised April 1968), San Diego, California.

15. Helms, H. D., "Fast Fourier Transform Method of Computing Difference Equations and Simulating Filters," Transactions on Audio and Electroacoustics, Vol Au-15, No. 2, Institute of Electronic and Electrical Engineers, June 1967.

16. Houbolt, John C., "Runway Roughness Studies in the Aeronautical Field," Journal of the Aero-Space Transport Division, No. AT1, Proceedings of the American Society of Civil Engineers, March 1961.

17. Housel, W. S., "Cumulative Changes in Rigid Pavements with Age in Service," Bulletin 328, Highway Research Board, 1962.

18. Hudson, W. Ronald, "Determination of Present Serviceability Index with the Illinois Highway Roadometer," Special Report, AASHO Road Test, 1960.

19. Hudson, W. Ronald, "High-Speed Road Profile Equipment Evaluation," Research Report No. 73-1, Center for Highway Research, The University of Texas, Austin, October 1965.

20. Hudson, W. R., et al, "Systems Approach to Pavement Design," Final Project 1-10, National Cooperative Highway Research Program, March 1968.

21. Hudson, W. Ronald, and Robert C. Hain, "Calibration and Use of the BPR Roughometer at the AASHO Road Test," Special Report 66, Highway Research Board, 1961.

22. Hudson, W. Ronald, and Frank H. Scrivner, "A Modification of the AASHO Road Test Serviceability Index to Include Surface Texture," a technical report for Research Project 2-8-62-32, Center for Highway Research, The University of Texas, Austin, 1964.

23. Hulbert, Slade, "Motion Systems for Automobile Driving Simulators," a paper prepared for Human Factors Society Symposium, Human Factors Society Annual Meeting, Chicago, Illinois, October 30, 1968.

24. Hutchinson, B. G., "Analysis of Road Roughness Records by Power Spectral Density Techniques," a final report to Ontario Joint Highway Research Programme, prepared by the Department of Civil Engineering, University of Waterloo, Ontario, January 1965.

25. Hutchinson, B. G., "Digital Computation of Pavement Roughness Power Spectra," a paper presented at Mid-Year Meeting, Department of Design, Highway Research Board, August 1967.

26. Hutchinson, B. G., "Principles of Subjective Rating Scale Construction," Highway Research Record No. 46, Highway Research Board, 1964.

27. Hveem, F. W., "Devices for Recording and Evaluating Road Roughness," Bulletin 264, Highway Research Board, 1960.

28. LeClerc, R. V., and T. R. Marshall, "A Pavement Condition Rating System and its Use," Washington State Highway Commission, Department of Highways, Olympia, Washington.

29. McCullough, B. F., and C. L. Monismith, "Application of a Pavement Design Overlay System," Special Report No. 1, Center for Highway Research, The University of Texas at Austin, October 1969.

30. Miller, K. S., "Stochastic Processes in Engineering Problems," Technical Report No. 6, Electro-Mechanical Laboratories Division, White Sands Proving Ground, Las Cruces, New Mexico, August 1953.

31. Nakamura, Velma F., and Harold L. Michael, "Serviceability Ratings of Highway Pavements," Highway Research Record No. 40, Highway Research Board, 1963.

32. Ostle, Bernard, Statistics in Research, 2nd Edition, The Iowa State University Press, Ames, 1963.

33. Painter, L. J., "An Alternate Analysis of the Present Serviceability Index," International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, August 1962.

34. Painter, Lewis J., "Analysis of AASHO Road Test Data by the Asphalt Institute," International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, 1962.

35. "Pavement Evaluation Studies in Canada," Special Committee on Pavement Design and Evaluation, Canadian Good Roads Association, E. B. Wilkins, Chairman, International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, August 1962.

36. Plantema, F. J., and J. Buhrman, "Some Experimental Investigation on Runway Waviness," Nat. Lucht-en Ruimtev. Lab (NLR), National Aeronautics and Astronomical Research Institute, Publication No. MP. 218, Amsterdam.

37. Quinn, Bayard E., and David R. Thompson, "Effect of Pavement Condition on Dynamic Vehicle Reactions," Bulletin 328, Highway Research Board, 1962.

38. Quinn, Bayard E., and Thomas W. DeVries, "Highway Characteristics as Related to Vehicle Performance," Bulletin 250, Highway Research Board, 1960.

39. Quinn, B. E., and J. L. Zable, "Evaluating Highway Elevation Power Spectra from Vehicle Performance," a paper presented at Highway Research Board, 1965.

40. Rizenbergs, Rolands L., "Accelerometer Method of Riding Quality Testing," Interim Research Report, KY HPR-64-25; HPS-HPR-1(26), Kentucky Department of Highways, Lexington, February 1965.

41. Scrivner, Frank H., "A Modification of the AASHO Road Test Serviceability Index Formula," Report No. 1 for Research Project 2-8-62, Texas Transportation Institute, May 1963.

42. Singleton, R. C., "A Method for Computing the Fast Fourier Transform with Auxiliary Memory and Limited High-Speed Storage," Transactions on Audio and Electroacoustics, Vol AU-15, No. 2, Institute of Electronic and Electrical Engineers, June 1967.

43. Spangler, Elson B., and William J. Kelly, "GMR Road Profilometer - A Method for Measuring Road Profiles," Research Publication GMR-452, Engineering Mechanics Department, General Motors Corporation, December 1964.

44. Spangler, Elson B., James W. Strong, and Gordon R. Brown, "Evaluation of the Surface Dynamics Profilometer for Runway Profile Measurement," Technical Report No. AFWL-TR-68-43, Air Force Weapons Laboratory, Kirkland Air Force Base, Albuquerque, New Mexico, December 1968.

45. "The PCA Road Meter Measuring Road Roughness at 50 Miles Per Hour," Report No. IR26, Department of Highways, Ontario, January 1969.

46. Vyce, J. M., "Evaluation of Flexible Pavements in New York," a paper presented to Highway Research Board Committee D-B5, Pavement Condition Evaluation.

47. Walker, Roger S., Freddy L. Roberts, and W. Ronald Hudson, "A Profile Measuring, Recording, and Processing System," Research Report No. 73-2, Center for Highway Research, The University of Texas at Austin, May 1969.

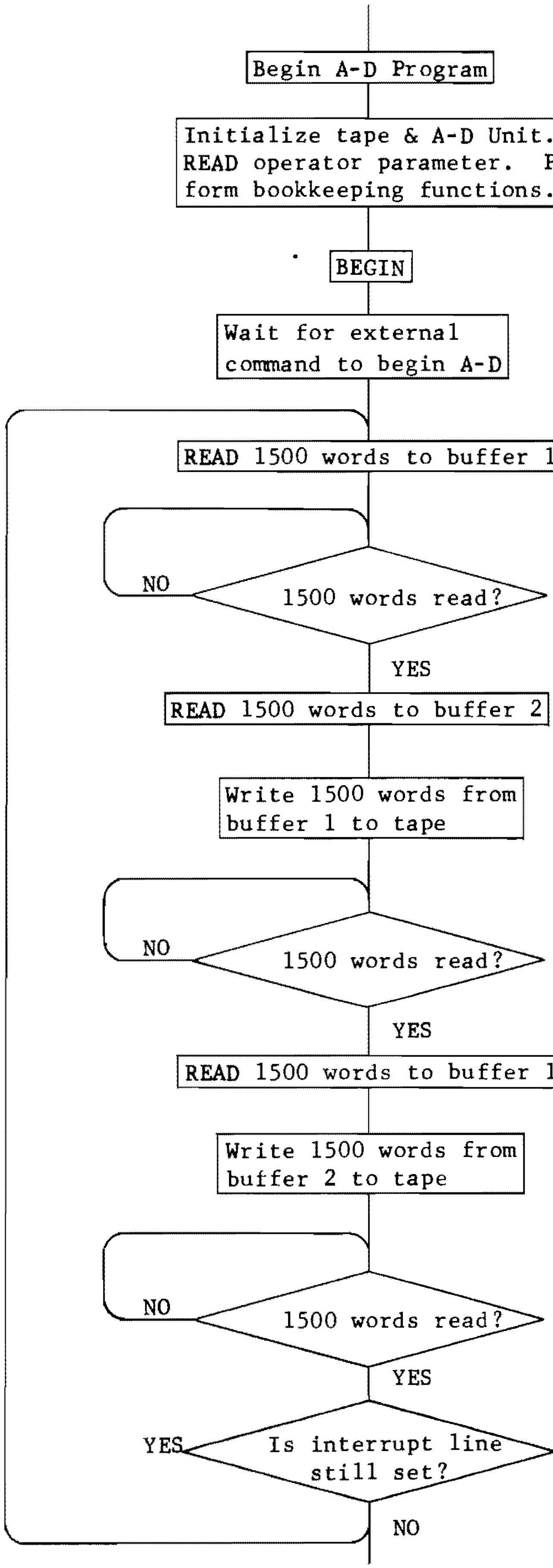
48. Welch, P. D., "The Use of Fast Fourier Transform for the Estimation of Power Spectra: A Method Based on Time Averaging over Short Modified Periodograms," Transactions on Audio and Electroacoustics, Vol AU-15, No. 2, Institute of Electronic and Electrical Engineers, June 1967.

49. Yoder, E. J., and R. T. Milhous, "Comparison of Different Methods of Measuring Pavement Condition," a paper presented at Highway Research Board, January 1965.

APPENDICES

APPENDIX 1

ANALOG-TO-DIGITAL PROGRAM FOR THE SDS COMPUTER


Begin A-D Program
Initialize tape & A-D Unit. READ operator parameter. Perform bookkeeping functions.
BEGIN
Wait for external command to begin A-D
READ 1500 words to buffer 1
NO
1500 words read?
YES
READ 1500 words to buffer 2
Write 1500 words from buffer 1 to tape
NO
1500 words read?
YES
READ 1500 words to buffer 1
Write 1500 words from buffer 2 to tape
NO
1500 words read?
YES
YES
Is interrupt line still set?
NO

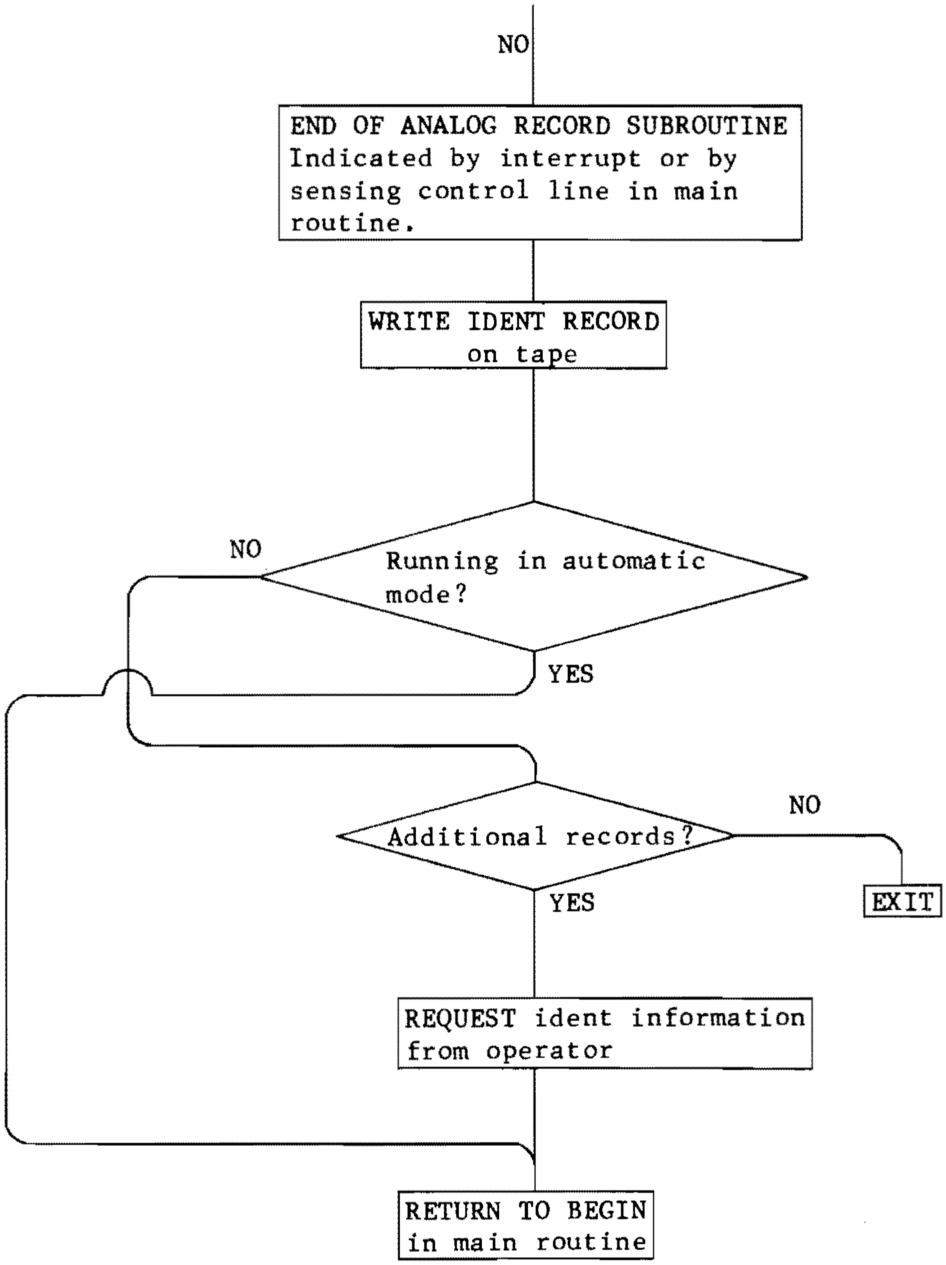


Fig A1.1. Analog-to-digital program for SDS computer.

APPENDIX 2

PROGRAM STEP

APPENDIX 2. PROGRAM STEP

Purpose

The purpose of this program is to compute the magnitude of 1-inch steps in terms of the units in which the data were recorded.

Method

A threshold is set which depends upon the resolutions used to generate the data and the individual data points in the 1-inch step file are processed until 20 consecutive points are found which are above the threshold. Call the first point of these 20 consecutive points above the threshold X(1) . The 100 points X(I-300) , X(I-299) , and X(I-201) are averaged to get the value of the base from which the jump of the 1-inch step was made, and this average is called L . Then the 100 points X(I+201) , X(I+202) , ..., and X(I+300) are averaged to obtain the value which is reached after the 1-inch step was made, and this average is called U . Therefore, the magnitude of the 1-inch step is determined by U-L .

Input

The first data card should contain the following:

(1) Columns 1 through 3: NF = the number of files to be input. This is not the number of 1-inch step file, but the number of files on the data tape up to and including the last 1-inch step file to be processed. NF is in I3 format.

(2) Column 4: an R or L to indicate whether the data is from the right or left profile.

(3) Columns 6 through 10: a number indicating from which reel of tape the data were taken. This is in I5 format.

Following this card are sufficient number of cards to input the file numbers of the 1-inch step files in the order they are found on the tape, with the format being 20I4.

Output

For each 1-step file, the magnitude of the 1-inch step will be printed and punched.

Error Messages

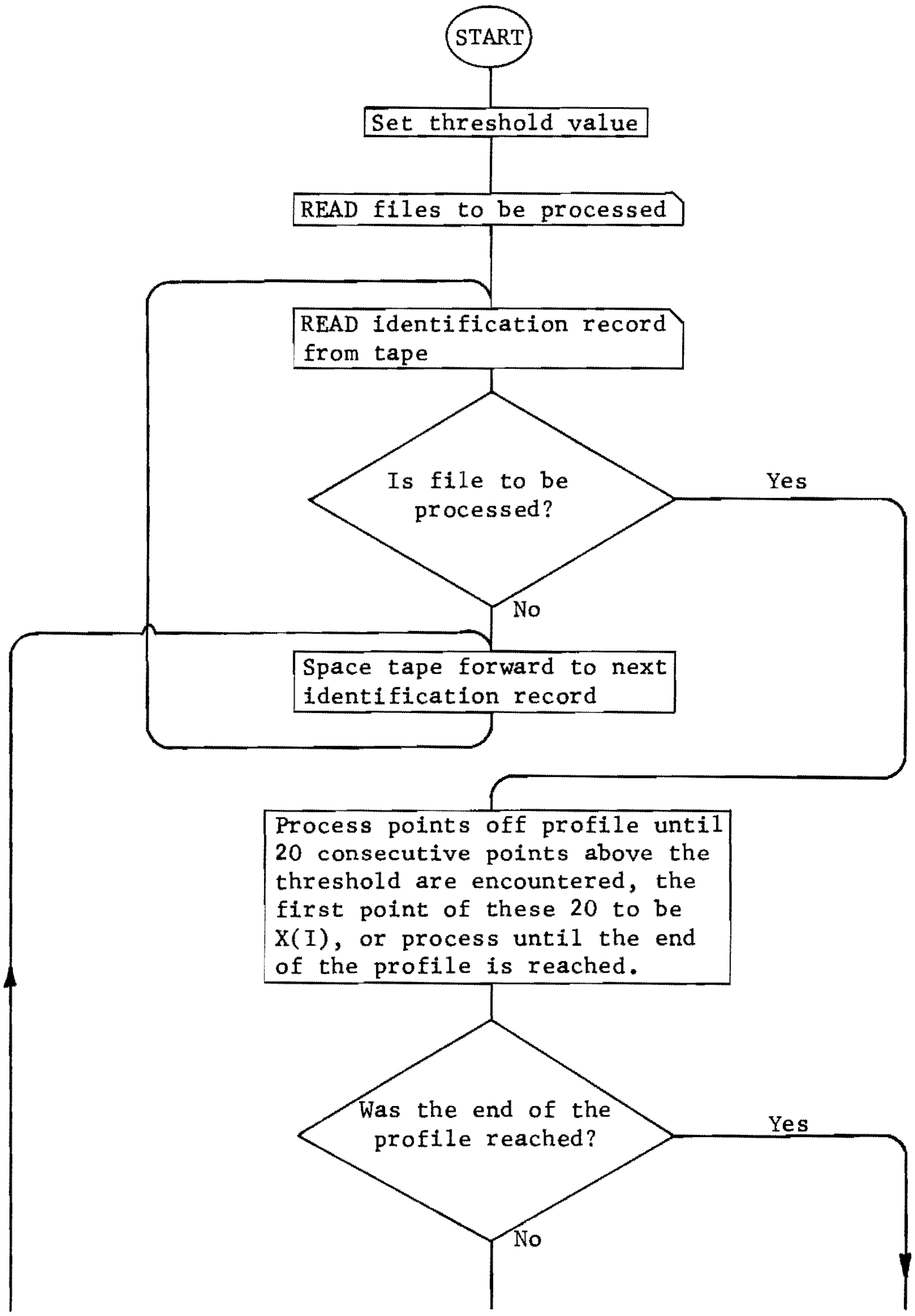
If 20 consecutive points above the threshold are not found during the processing of a 1-inch step file, then the message "BAD" will be printed. If there are not enough points either before or after the point where the 1-inch step was made, then "THIS SHOULD NOT HAPPEN" is printed.

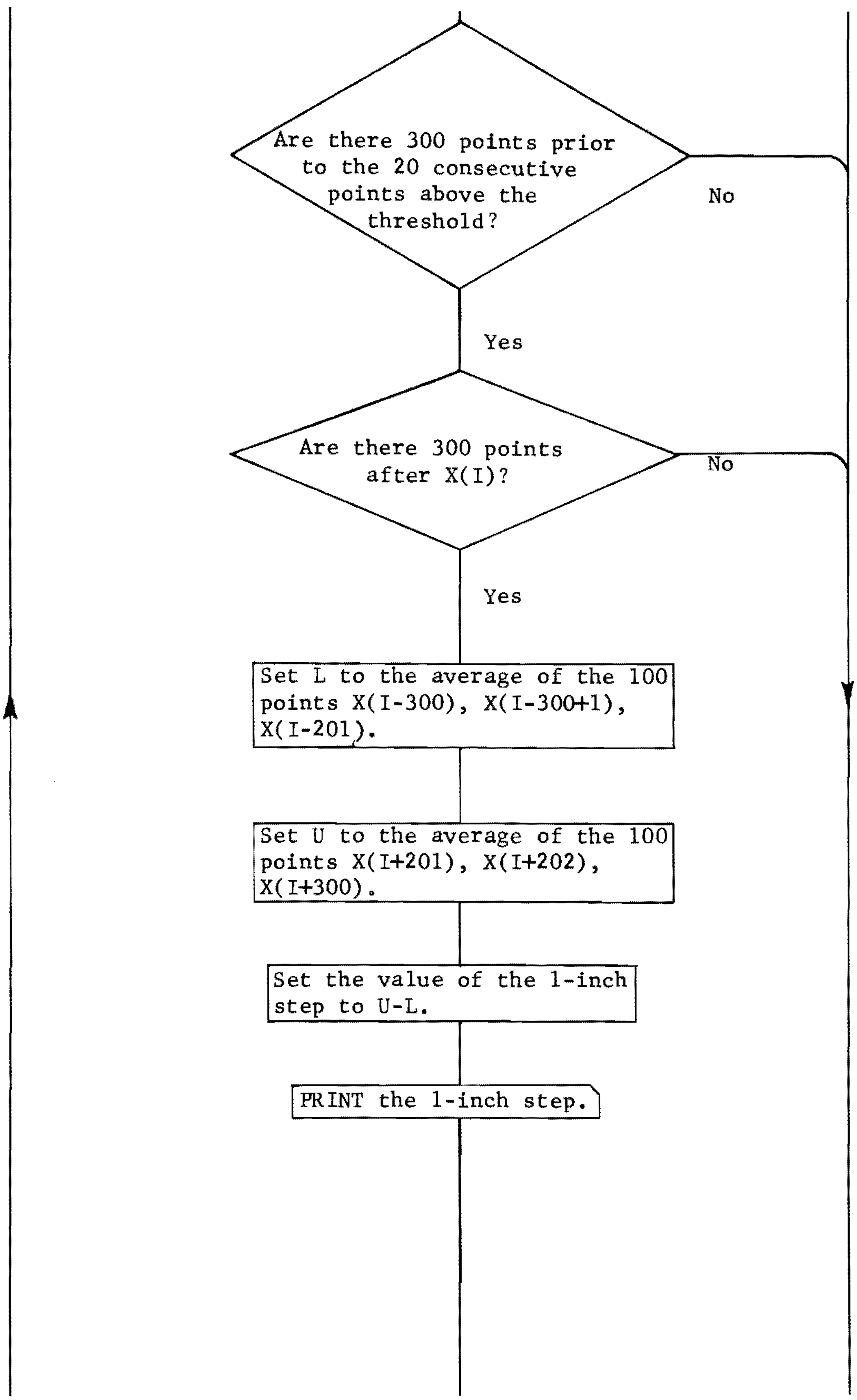
Conditions, Limitations, and so forth

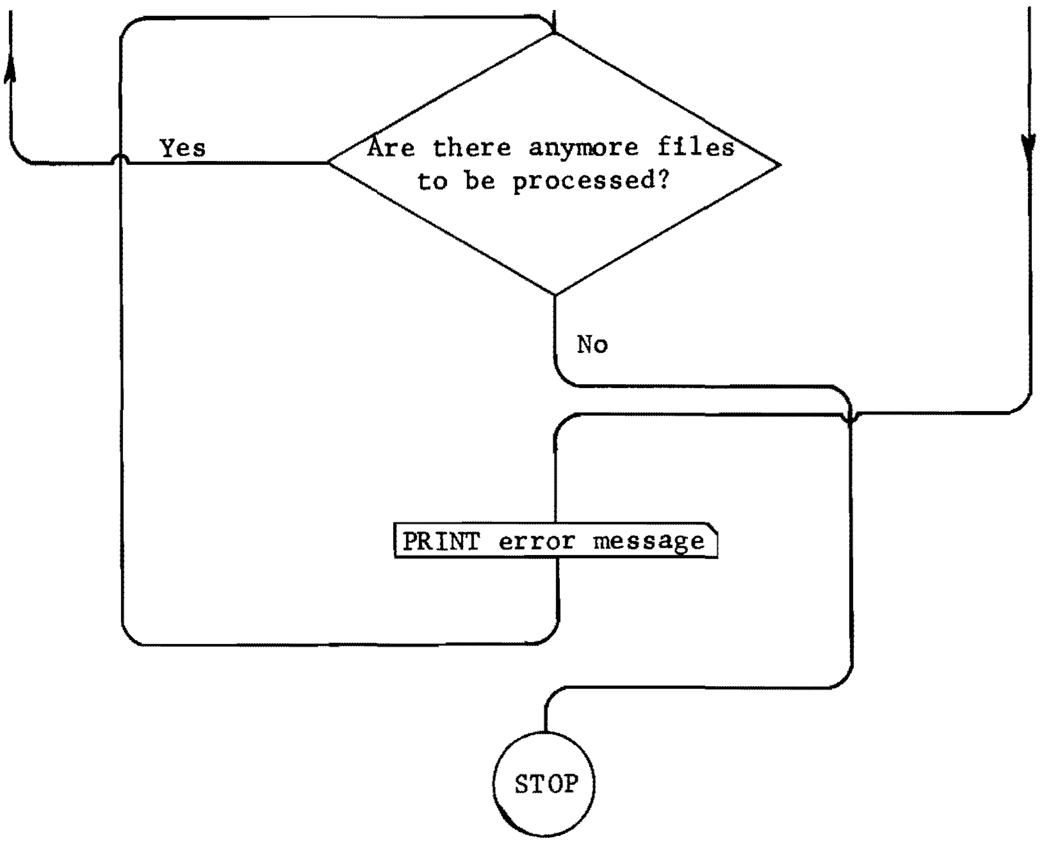
The number of points used to compute the upper and lower averages can be changed by changing the value of the variable NP . This cannot be changed to a number larger than 750, however.

The maximum number of 1-inch steps that can be processed is 120, determined by the dimensioning of the array NS .

SUMMARY FLOW CHART FOR PROGRAM STEP




Are there 300 points prior to the 20 consecutive points above the threshold?
No
Yes
Are there 300 points after X(I)?
No
Yes
Set L to the average of the 100 points X(I-300), X(I-300+1), X(I-201).
Set U to the average of the 100 points X(I+201), X(I+202), X(I+300).
Set the value of the 1-inch step to U-L.
PRINT the 1-inch step.


Yes
Are there anymore files to be processed?
No
PRINT error message
STOP

APPENDIX 3

CONDITION SURVEY INFORMATION
FOR 89 TEST SECTIONS

TABLE A3.1. CONDITION SURVEY DATA FOR 61 FLEXIBLE PAVEMENTS

Section No.	Pavement Type	Cracking: Longit. and Transv. $\frac{ft}{1000ft^2}$	Cracking: Alligator and/or Map, $\frac{ft^2}{1000ft^2}$	Patching $\frac{ft^2}{1000ft^2}$	Rut Depth: Mean RD, 0.1 in.	Rut Depth: σ^2_{RD}, 0.01 in.	Texture, 0.001 in.	PSR
1	HMAC	---	2.65	---	0.15	0.13	0.65	4.307
2	HMAC	---	239.39	---	-0.50	1.23	.85	3.214
4	HMAC	36.47	---	---	0.04	0.04	1.30	3.986
5	ST	---	---	.92	.27	1.50	28.70	2.086
6	HMAC	1.79	113.26	---	0.23	0.18	58.90	3.350
7	HMAC	97.30	---	61.66	1.03	1.82	15.20	1.464
11	OVLY	101.00	---	---	.45	.95	13.00	3.286
12	ST	---	104.16	---	2.13	1.99	29.80	2.086
13	OVLY	19.61	---	---	.30	.29	17.55	3.943
14	OVLY	46.66	---	---	.12	.45	2.05	4.071
15	ST	---	130.55	11.11	2.63	9.25	32.40	3.114
16	ST	---	46.50	88.25	1.57	8.18	---	2.421
17	OVLY	39.79	---	---	.19	.15	9.10	3.836
18	OVLY	---	---	---	.30	.21	6.10	4.343
24	ST	---	---	.11	.04	.77	7.55	3.293
25	HMAC	---	---	---	1.00	.23	2.15	3.964
28	ST	---	---	---	.20	.22	2.55	3.893
30	ST	---	159.25	8.66	2.27	2.12	26.90	2.436
32	HMAC	---	---	---	.85	.35	2.55	4.071
34	HMAC	---	---	---	.45	.25	5.70	4.400
35	HMAC	---	47.63	16.77	.88	.73	3.20	2.864
36	ST	---	403.26	365.76	1.77	6.72	2.90	1.107
37	OVLY	29.75	---	---	.38	1.63	16.70	3.371
38	HMAC	---	7.15	15.27	1.11	1.30	1.10	2.143
39	OVLY	178.91	---	22.11	-0.65	1.61	11.40	1.750
40	HMAC	28.25	---	48.33	.45	2.33	3.20	2.114
44	ST	---	---	---	.73	.35	9.50	3.207
46	HMAC	4.72	9.72	---	.54	.32	5.40	3.636
49	OVLY	8.48	39.62	---	1.04	.11	1.65	4.236
64	OVLY	94.83	---	.12	1.07	.47	5.50	3.700
66	HMAC	---	1.94	---	.30	.21	.96	3.358
70	OVLY	144.91	---	1.87	.30	.21	3.34	2.933
71	HMAC	13.01	---	---	-0.04	.19	.81	3.883
72	OVLY	84.55	3.07	---	.15	.36	2.39	3.217
73	OVLY	3.03	---	---	.45	.26	1.00	3.858
74	OVLY	38.33	---	4.48	-0.12	.11	3.31	3.708
75	OVLY	40.76	---	9.23	-0.08	.14	4.97	2.983
81	HMAC	---	---	---	.30	.22	3.04	3.808

(Continued)

TABLE A3.1. (CONTINUED)

Section No.	Pavement Type	Cracking: Longit. and Transv. $\frac{ft}{1000ft^2}$	Cracking: Alligator and/or Map, $\frac{ft^2}{1000ft^2}$	Patching $\frac{ft^2}{1000ft^2}$	Rut Depth: Mean RD, 0.1 in.	Rut Depth: σ^2_{RD}, 0.01 in.	Texture, 0.001 in.	PSR
82	ST	---	---	---	.54	.39	10.46	4.083
83	ST	---	77.84	482.70	.50	1.44	2.12	2.325
84	ST	---	2.50	---	.38	.47	13.16	2.500
85	HMAC	---	5.76	89.69	-0.42	1.24	.50	2.633
86	ST	---		---	-0.04	.65	.31	2.483
87	HMAC	---	138.88	327.08	.81	2.45	---	2.858
88	ST	---	2.29	---	-0.38	.86	1.58	3.450
89	OVLY	---	116.53	219.37	-0.73	.74	.31	2.658
90	HMAC	---	69.44	---	-0.66	.90	.58	3.583
93	HMAC	---	4.30	---	.19	.15	.27	4.158
94	OVLY	44.78	---	---	---	---	.62	3.675
95	OVLY	24.66	---	---	1.23	.95	.39	3.808
97	HMAC	---	10.20	9.37	1.77	1.72	.73	3.508
100	HMAC	.90	---	---	-0.19	.30	1.50	4.025
101	ST	---	7.66	3.03	-0.04	1.11	2.70	3.550
103	HMAC	8.26	---	---	.30	.36	.38	3.933
104	ST	---	5.55	3.24	1.81	15.45	7.00	2.475
105	HMAC	---	72.50	4.16	4.03	31.93	4.04	1.133
108	ST	---	8.78	29.16	1.46	7.02	9.93	2.733
109	OVLY	4.04	.41	66.66	.34	.22	1.66	2.650
110	HMAC	---	37.17	---	.34	.30	.46	4.333
111	ST	---	.	---	.92	.45	6.31	4.000
112	HMAC	---	58.02	---	1.11	.58	2.62	4.192

TABLE A3.2. CONDITION SURVEY DATA FOR 28 RIGID PAVEMENTS

Section No.	Pavement Type	Cracking Longitudinal and Transverse, $\frac{ft}{1000ft^2}$	Cracking Area Type, $\frac{ft^2}{1000ft^2}$	Patching, $\frac{ft^2}{1000ft^2}$	Texture, 0.001 in.	PSR
3	CPJR	.86	1.45	1.22	.15	3.764
8	CPCR	60.06	--	--	--	4.700
10	CPJR	71.48	--	--	1.10	3.286
20	CPJR	3.40	.01	--	.10	3.771
26	CPJR	33.54	--	--	.10	2.857
27	CPJR	3.54	--	9.06	.30	2.814
29	CPJR	---	--	--	1.95	3.707
31	CPJR	48.90	--	--	3.40	2.264
33	CPJR	35.75	--	--	5.70	2.621
45	CPJR	14.30	--	--	6.60	4.029
48	CPJR	20.83	--	--	1.85	4.357
65	CPCR	111.94	--	--	.15	4.425
67	CPJR	5.34	--	.16	5.00	3.285
68	CPJR	25.54	--	.17	4.85	3.150
69	CPCR	169.70	--	5.83	1.70	3.375
76	CPCR	150.27	--	--	4.90	4.367
77	CPCR	125.41	--	11.87	.60	4.358
78	CPCR	171.31	--	--	.77	3.667
79	CPCR	127.63	--	6.94	--	4.458
80	CPCR	76.87	--	--	--	4.633
91	CPJR	38.19	--	2.08	.45	3.408
92	CPJR	10.62	--	--	.46	3.483
96	CPCR	132.95	--	20.83	.46	4.242
98	CPCR	89.72	--	--	.17	4.375
99	CPJR	---	--	--	.45	3.808
102	CPJR	2.29	--	--	.77	3.725
107	CPJR	---	--	--	.27	3.850
113	CPCR	98.65	--	1.70	.23	4.683

APPENDIX 4

PROGRAM PDAP

APPENDIX 4. PROGRAM PDAP

Purpose

PDAP is used to obtain the cross slope variance between the two profiles of a data set.

Method

A new profile is generated from each of the input profiles by using running averages of a number of points given by input to the program. The corresponding elements from the new left profile are subtracted from the new right profile elements. This yields a final profile which is used to determine the cross slope variance for the data file.

Let X(R1), X(R2), ..., X(RN) be the elements of the right profile and X(L1), X(L2), ..., X(LN) be the elements of the left profile. Then the new profiles are generated using the average of ILNG points according to

$$X_{Ri} = \sum_{j=i}^{i+ILNG} \frac{X_{Rj}}{SFR \times ILNG}$$

where

$i = 1, 2, \ldots, N + 1 - ILNG$;

ILNG = the number of points averaged;

SFR = the scale factor for the right profile.

$$X_{Li} = \sum_{j=i}^{i+ILNG} \frac{X_{Lj}}{SFL \times ILNG}$$

where

$$i = 1, 2, \ldots, N + 1 - ILNG ;$$

$$SFL = \text{the scale factor for the left profile.}$$

From these two profiles a final profile is generated according to

$$X_{Fi} = X_{Ri} - X_{Li}$$

where $i = 1, 2, \ldots, N + 1 - ILNG$. Then, using the base length IB , the variance XSV is computed

$$XSV = \left\{ \frac{\sum_{i=0}^{N/IB} \left(X_{(i+1)IB+1} - X_{(i)IB+1} \right)^2}{\frac{N}{IB} - 1} - \frac{\left[\sum_{i=0}^{N/IB} \left(X_{(i+1)IB+1} - X_{(i)IB+1} \right) \right]^2}{\frac{N}{IB}\left(\frac{N}{IB} - 1 \right)} \right\}$$

<u>Input</u>

The first card contains

(1) Columns 1 through 3: JI number of files to be processed not including files.

(2) Columns 4 through 5: ILNG number of points to be used in running average.

(3) Columns 6 through 7: IB base length used to compute variance.

(4) Column 8: I2 = 0 if want to use a scale factor of 350/16 for every file, otherwise will read in scale factors.

(5) Column 9: I3 = 0 if want to use every data file, otherwise will read in files to be skipped.

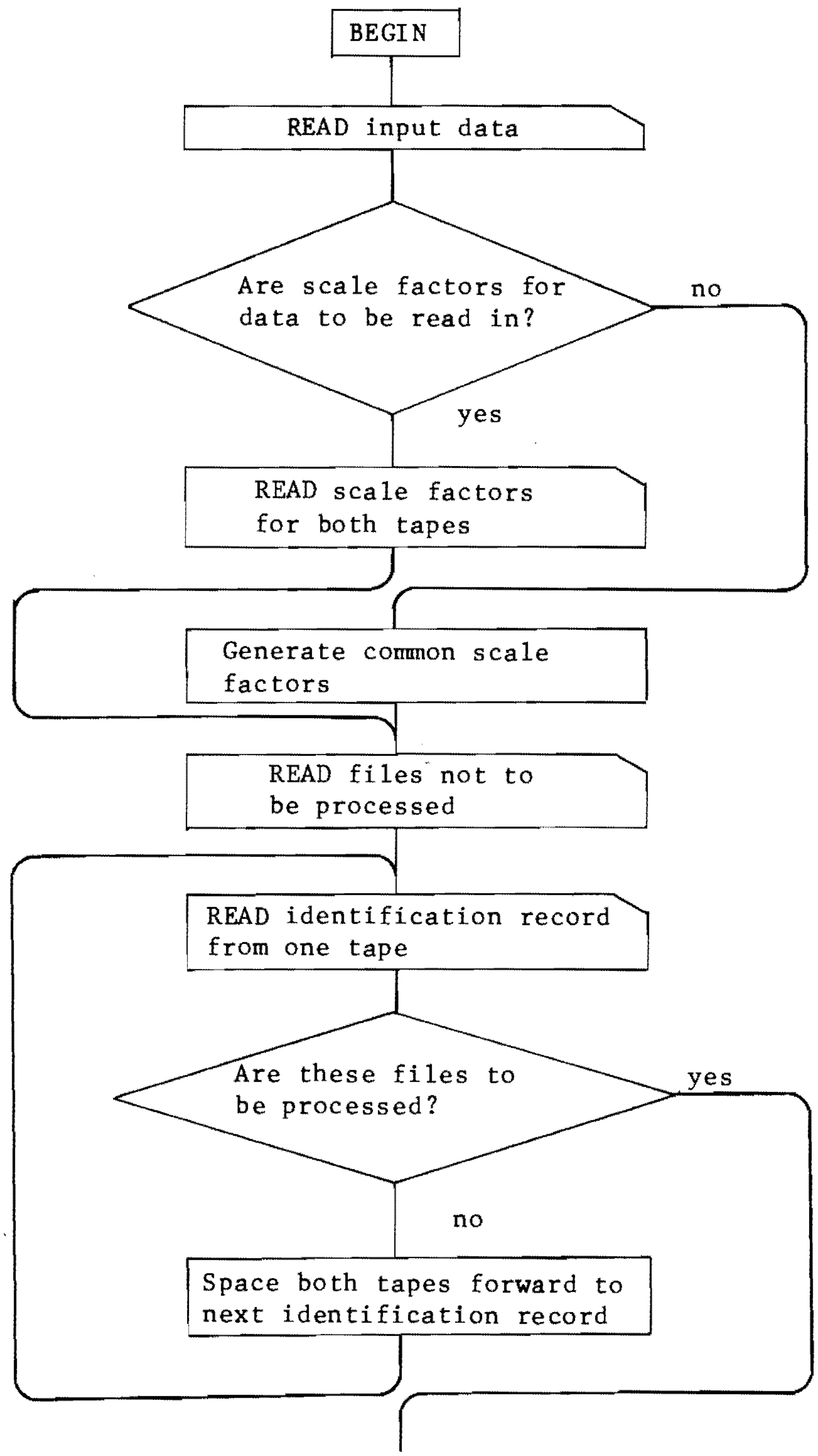
(6) Columns 10 through 11: I5 = 0 if want to use a maximum of 21 data records for computations, otherwise I5 will be the number which is the maximum number of data records to be used in computations.

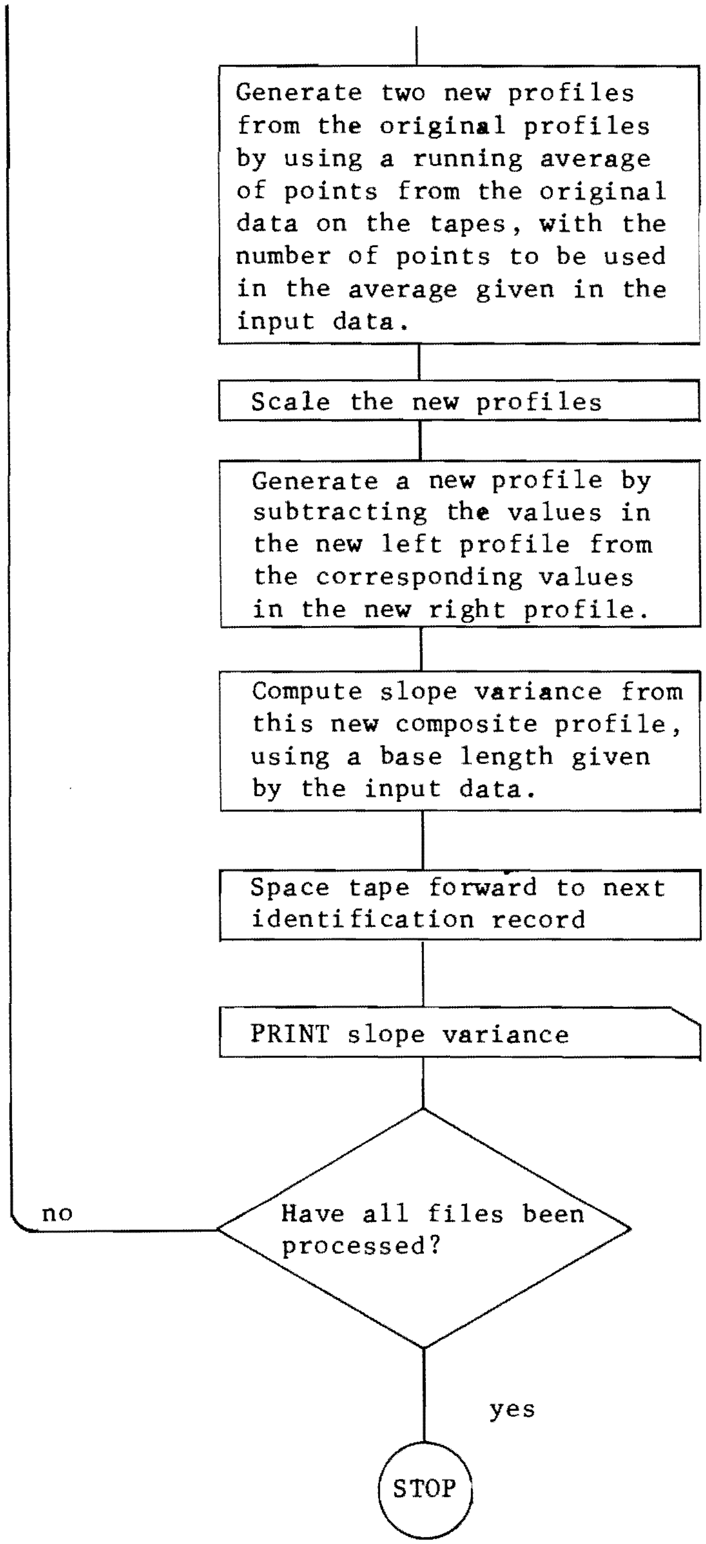
(7) Columns 19 through 23: IREEL number of the data tape reel from which these data were taken.

If I2 $\neq$ 0 then will next have JI cards containing scale factors for right profile files to be operated on (in the order in which they will be processed), then JI more cards containing the scale factors for the corresponding left profile files (10X,F7.3).

If I3 $\neq$ 0 then have file number of the files not to be processed in order they occur on tapes (20I4 format) and have five cards even if some are blank.

SUMMARY FLOW CHART
Program PDAP





Generate two new profiles from the original profiles by using a running average of points from the original data on the tapes, with the number of points to be used in the average given in the input data.
Scale the new profiles
Generate a new profile by subtracting the values in the new left profile from the corresponding values in the new right profile.
Compute slope variance from this new composite profile, using a base length given by the input data.
Space tape forward to next identification record
PRINT slope variance
Have all files been processed?
no
yes
STOP

APPENDIX 5

PROGRAM DAP

APPENDIX 5. PROGRAM DAP

Purpose

The Data Analysis Program calculates the slope variance and roughness index of a road profile or a number of road profiles.

Method

The parameters required in computing the slope variance and roughness index are

(1) the scale factor = (SF) ,

(2) the base length = (IB) , and

(3) the number of points to be used for average (ILNG) .

From the original profile, a new profile is obtained by using averages of ILNG points in the following way: The original profile consists of the points

$$X_1, X_2, X_3, \ldots, X_N$$

The new profile consists of the points

$$\bar{X}_1, \bar{X}_2, \bar{X}_3, \ldots, \bar{X}_{N + 1 - ILNG}$$

where

$$\bar{X}_i = \sum_{j = i}^{i + ILNG - 2} \frac{X_j}{SF \times ILNG}$$

This means that $\bar{X}_1$ is obtained by dividing SF into the average of the points $X_1, X_2, \ldots, X_{ILNG}$, and $\bar{X}_2$ is obtained by dividing SF into the average of the points $X_2, X_3, \ldots, X_{ILNG + 1}$ and so forth. This new profile is used to obtain the roughness index RI (in inches per mile) according to

$$RI = \frac{\left(\sum_{i=0}^{N/IB} \left| \overline{X}_{(i+1)IB+1} - X_{(i)IB+1} \right| \right)}{\frac{N}{12(5280)}}$$

and the slope variance equals SV according to

$$SV = \left\{ \frac{\sum_{i=0}^{N/IB} \left(\overline{X}_{(i+1)IB+1} - X_{(i)IB+1} \right)^2}{\frac{N}{IB} - 1} - \frac{\left[\sum_{i=0}^{N/IB} \left(\overline{X}_{(i+1)IB+1} - X_{(i)IB+1} \right) \right]^2}{\frac{N}{IB} \left(\frac{N}{IB} - 1 \right)} \right\}$$

Tape Input

The road profile is on tape in records of 750 points (words) and the data values are preceded by an identification record of five words that contain the following information:

(1) NID(1) = 1st word: a number associated with the data set, called the file number,

(2) NID(2) = 2nd word: the number of records in the data set.

(3) NID(3) = 3rd word: the number of points in the last data record times two.

(4) NID(4) = 4th word: the total number of data points in the set times two.

(5) NID(5) = 5th word: a number associated with the data set, called the section number.

If there is more than one data set, then the data sets are separated by end-of-file marks.

Card Input

The first two data cards are for comments pertaining to the run and will be printed on the first page of the output.

The next data card contains the following information and is designated as a control card:

(1) Columns 1 through 5: JI = the number of files to be processed, right justified field.

(2) Columns 6 through 10: ILNG = the number of points used for averaging purposes, right justified in the field.

(3) Columns 11 through 15: IB = the base length, right justified.

(4) Column 16: I2 is to be zero if want to use a scale factor of 350/16 for every file; if I2 $\neq 0$ then the scale factors will have to be read in.

(5) Column 17: I3 is zero if no go option (files not to be read) is not desired; if I3 $\neq 0$, then the file numbers of those data files which are to be skipped must be read in.

(6) Column 18: I4 is an R if the right profile was the source of the data and is an L if the left profile was.

(7) Columns 21 through 25: I5 is zero if want to use minimum (21, NID(2)) records for computations; if I5 $\neq 0$, then use minimum (I5, NID(2)) records for computations.

(8) Columns 26 through 30: IREEL is a number associated with the original tape reel from which the data were taken.

If I2 $\neq 0$, then the next JI data cards contain the scale factors for the profiles to be processed in the order in which the profiles will be on the data tape. (The scale factors will be on the cards in the 8X,F7.3 format.)

If I3 $\neq 0$, then following the scale factors, if any, will be five data cards which will contain in order the file numbers of files not to be processed according to the 20I4 format.

The variable I6 in the program DAP is presently assigned the value "21." This indicates that there is a maximum of 21 records per road profile. If this is not true for the data tape, then I6 must be changed to the correct value.

The data card list consists of the following:

(1) two comment cards,

(2) control card,

(3) JI scale factors if I2 $\neq 0$, and

(4) five cards with file numbers of files not to be processed.

Output

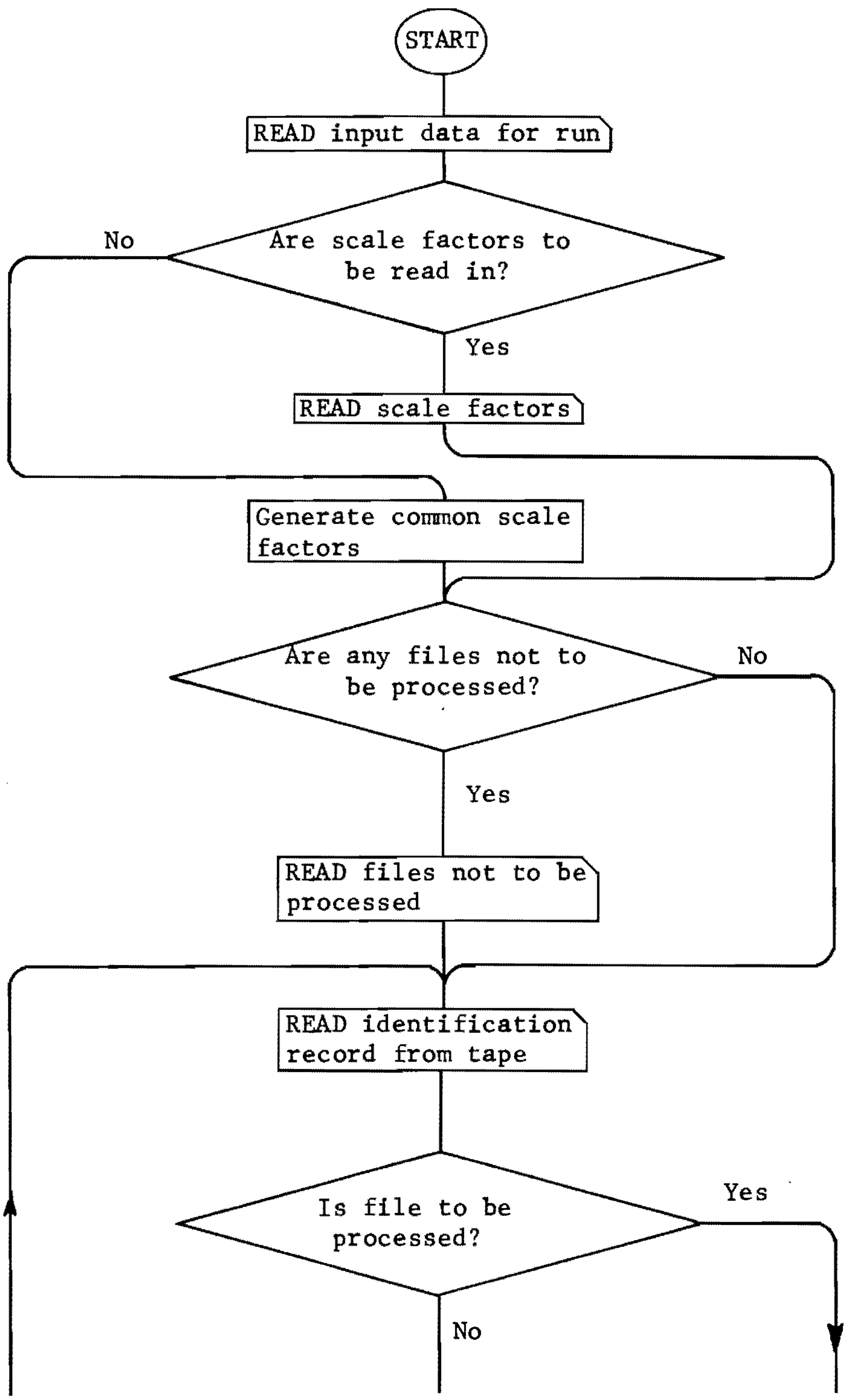
The contents of the two comment cards will be printed on a separate page. Then, for each road profile processed, the following information will be printed:

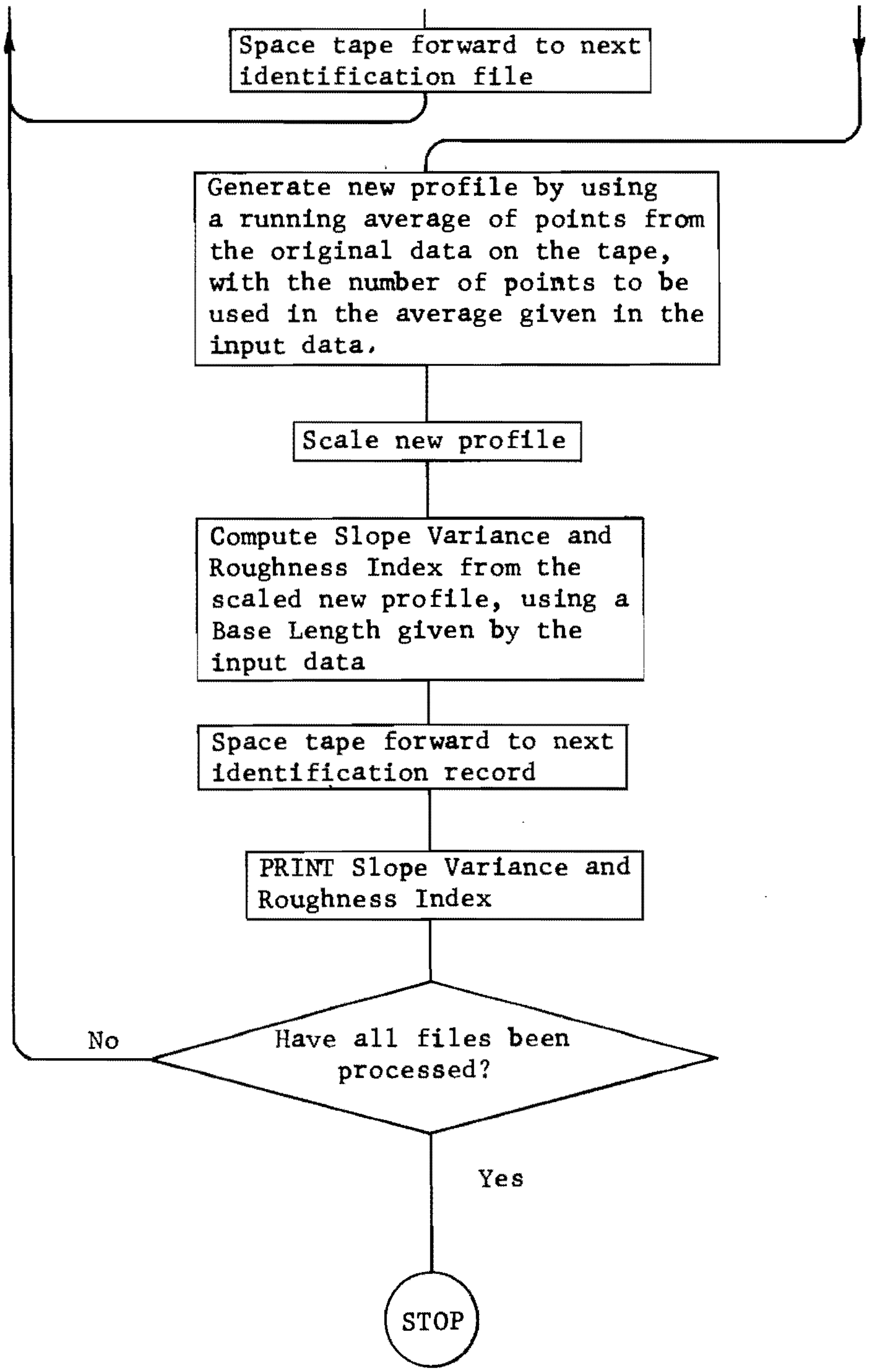
(1) NID(5) ,
(2) NID(1) ,
(3) ILNG ,
(4) IB ,
(5) I4 ,
(6) the scale factor used,
(7) the slope variance of the profile, and
(8) the roughness index of the profile.

Also, the following information will be punched on a card for each file processed:

(1) I4 ,
(2) IREEL ,
(3) NID(5) ,
(4) NID(1) ,
(5) ILNG ,
(6) IB ,
(7) the slope variance, and
(8) the roughness index.

SUMMARY FLOW CHART FOR PROGRAM DAP




Space tape forward to next identification file
Generate new profile by using a running average of points from the original data on the tape, with the number of points to be used in the average given in the input data.
Scale new profile
Compute Slope Variance and Roughness Index from the scaled new profile, using a Base Length given by the input data
Space tape forward to next identification record
PRINT Slope Variance and Roughness Index
Have all files been processed?
No
Yes
STOP

APPENDIX 6

SUMMARY STATISTICS FOR 81 TEST SECTIONS

TABLE A6.1. SUMMARY STATISTICS FOR 56 FLEXIBLE PAVEMENTS

Section No.	Surface Type	Slope Variance x 10^6 20 mph	34 mph	50 mph	Roughness Index, in/mile 20 mph	34 mph	50 mph	Cross Slope Variance 20 mph	34 mph	50 mph	PSR
1	HMAC	1.41	2.56	3.45	58.95	78.83	78.99	.014	.014	.014	4.300
2	HMAC	6.75	16.92	57.90	117.17	189.16	224.73	.063	.093	.072	3.210
4	HMAC	1.28	2.23	2.09	56.33	72.51	70.74	.014	.025	.014	3.980
5	ST	6.18	8.77	10.04	116.71	134.29	135.11	.069	.098	.052	2.080
6	HMAC	6.08	8.52	7.50	114.20	113.78	112.24	.023	.083	.046	3.350
7	HMAC	15.93	30.19	35.08	161.05	188.07	211.88	.059	.119	.056	1.460
11	OVLY	2.45	4.03	6.70	73.84	94.90	119.01	.020	.022	.026	3.280
15	ST	6.46	---	8.22	123.41	---	142.45	.142	--	.191	3.110
17	OVLY	3.41	7.51	5.83	91.62	136.30	115.49	.013	.098	.007	3.830
18	OVLY	1.78	2.79	3.38	64.99	78.17	89.75	.017	.050	.048	4.340
24	ST	12.84	19.06	30.63	139.38	194.01	229.27	.096	.131	.099	3.290
25	HMAC	1.86	3.13	12.27	68.11	88.70	137.04	.014	.020	.014	3.960
28	ST	3.23	5.83	8.76	90.21	120.87	142.24	.023	.035	.025	3.890
30	ST	5.28	12.89	25.76	107.80	175.35	194.94	.099	.107	.061	2.430
32	HMAC	.93	2.28	1.97	48.07	76.23	69.92	.019	.026	.021	4.070
34	HMAC	2.19	5.51	2.37	68.99	116.82	69.83	.039	.054	.024	4.400
35	HMAC	5.12	7.45	9.06	91.08	116.40	115.46	.057	.100	.067	2.860
36	ST	24.96	62.72	18.74	221.79	299.81	170.36	.263	.338	.082	1.100
37	OVLY	6.02	8.17	10.16	120.23	139.91	154.15	.059	.067	.051	3.370
38	HMAC	14.93	32.60	---	182.39	241.66	---	.121	.162	--	2.140
39	OVLY	15.41	37.21	30.98	176.03	276.47	253.23	.056	.068	.053	1.750
40	HMAC	16.03	20.38	25.50	179.51	169.95	202.31	.081	.109	.120	2.110
44	ST	6.77	12.65	15.22	118.18	160.24	179.01	.034	.053	.027	3.200
46	HMAC	3.18	9.12	14.66	85.39	147.23	177.34	.052	.056	.047	3.630
49	OVLY	1.94	3.32	8.15	68.93	88.29	123.13	.028	.050	.033	4.230
64	OVLY	4.18	8.70	10.51	98.82	145.82	152.51	.015	.019	.014	3.700
66	HMAC	7.76	11.95	11.05	126.70	166.35	157.87	.161	.132	.127	3.350

(Continued)

TABLE A6.1. (CONTINUED)

Section No.	Surface Type	Slope Variance x 10^6 20 mph	34 mph	50 mph	Roughness Index, in/mile 20 mph	34 mph	50 mph	Cross Slope Variance 20 mph	34 mph	50 mph	PSR
70	OVLY	18.43	16.25	28.70	180.74	152.33	188.85	.167	.418	.134	2.930
71	HMAC	7.26	35.96	---	132.60	304.09	---	.053	.068	--	3.880
72	OVLY	4.53	8.46	8.72	100.26	136.34	137.50	.053	.056	.041	3.210
73	OVLY	2.37	9.31	7.79	74.33	113.02	137.52	.014	.028	.022	3.850
74	OVLY	2.84	---	8.07	78.42	---	140.57	.032	--	.022	3.700
75	OVLY	15.31	9.35	9.49	173.01	142.55	144.68	.385	.078	.058	2.980
81	HMAC	6.28	18.96	23.30	108.45	203.44	197.97	.036	.030	.038	3.800
82	ST	9.48	22.86	11.71	116.73	238.58	168.78	.023	.020	.034	4.080
83	ST	10.53	91.57	98.12	147.79	405.48	457.62	.057	.269	.411	2.320
84	ST	18.99	51.43	25.70	216.01	349.07	250.67	.112	.189	.102	2.500
85	HMAC	7.89	33.91	28.69	132.26	266.79	206.81	.088	.202	.128	2.630
86	ST	116.26	---	92.31	254.57	---	344.44	.054	--	.501	2.480
87	HMAC	4.78	35.36	16.00	106.13	283.13	175.29	.039	.108	.074	2.850
88	ST	5.81	12.00	15.45	116.33	170.62	167.18	.133	.241	.144	3.450
89	OVLY	14.45	44.83	77.32	170.38	233.04	336.59	.069	.018	.091	2.650
90	HMAC	3.15	6.96	8.88	86.75	130.27	127.32	.041	.075	.035	3.580
93	HMAC	3.48	31.83	---	94.32	282.24	---	.119	.220	--	4.150
94	OVLY	4.04	9.53	7.88	95.97	155.04	135.38	.042	.062	.045	3.670
95	OVLY	4.75	24.02	---	107.76	245.79	---	.029	.041	--	3.800
97	HMAC	5.55	17.00	21.28	114.73	207.65	198.92	.055	.063	.047	3.500
100	HMAC	7.90	34.57	18.00	115.01	290.59	210.31	.044	.041	.034	4.020
101	ST	5.59	28.19	11.29	117.38	213.15	167.13	.123	.224	.115	3.550
103	HMAC	7.15	33.50	38.29	132.94	290.45	312.48	.036	.063	.027	3.930
104	ST	22.98	68.25	110.83	237.19	399.59	467.96	.263	.313	11.004	2.470
105	HMAC	22.73	67.90	---	226.13	396.86	---	.402	.486	--	1.130
108	ST	12.56	71.51	47.88	167.22	363.14	276.48	.410	.455	.302	2.730
110	HMAC	1.80	5.34	5.54	65.64	114.27	114.25	.016	.025	.015	4.330
111	ST	6.08	8.55	8.12	123.35	144.65	141.92	.032	.035	.032	4.000
112	HMAC	4.10	7.33	6.40	99.78	131.72	123.71	.037	.047	.037	4.190

TABLE A6.2. SUMMARY STATISTICS FOR 25 RIGID PAVEMENTS

Section No.	Surface Type	Slope Variance x 10^6			Roughness Index, in/mile			Cross Slope Variance			PSR
		20 mph	34 mph	50 mph	20 mph	34 mph	50 mph	20 mph	34 mph	50 mph	
3	CPJR	1.59	2.30	2.99	59.94	73.43	73.52	.008	.009	.010	3.760
8	CPCR	4.47	1.30	37.29	103.63	57.00	276.55	.011	.047	.022	4.700
10	CPJR	11.43	23.22	20.61	162.93	193.45	203.02	.203	.245	.096	3.280
20	CPJR	2.37	10.90	13.53	75.91	144.69	186.89	.005	.010	.006	3.770
27	CPJR	10.48	35.89	30.16	127.56	204.13	189.64	.009	.055	.012	2.810
31	CPJR	8.25	13.61	---	141.44	178.91	---	.025	.037	--	2.260
33	CPJR	40.12	13.31	83.96	290.81	163.07	358.60	.021	.012	.013	2.620
45	CPJR	3.69	1.62	4.10	78.47	63.40	96.34	.025	.040	.021	4.020
48	CPJR	2.19	3.55	4.84	72.35	93.71	100.70	.009	.019	.012	4.350
65	CPCR	1.79	4.98	7.46	65.53	110.83	136.37	.011	.009	.011	4.420
67	CPJR	7.13	17.64	18.21	134.17	208.92	212.03	.016	.023	.011	3.280
68	CPJR	7.87	43.51	21.93	137.19	333.61	229.54	.019	.023	.017	3.150
69	CPCR	12.40	35.25	37.30	169.46	288.31	303.86	.052	.119	.043	3.370
76	CPCR	3.11	13.12	5.71	87.03	168.98	114.95	.016	.326	.039	4.360
77	CPCR	3.73	12.13	23.37	95.90	176.69	239.57	.009	.012	.079	4.350
78	CPCR	6.66	14.42	16.47	120.30	185.63	203.47	.022	.031	.019	3.660
79	CPCR	1.83	6.15	7.87	67.40	102.50	104.24	.007	.007	.008	4.450
80	CPCR	1.28	2.81	5.88	56.08	85.52	102.61	.004	.005	.004	4.630
91	CPJR	8.51	28.58	18.64	142.70	230.94	204.12	.020	.080	.018	3.400
92	CPJR	6.26	14.78	15.18	123.98	192.93	196.81	.015	.019	.012	3.480
98	CPCR	3.14	14.00	9.16	88.87	178.30	149.64	.010	.933	.009	4.370
99	CPJR	10.19	30.97	---	154.52	261.41	---	.100	2.386	--	3.800
102	CPJR	11.15	23.69	31.54	151.82	233.75	240.45	.025	.046	.034	3.720
107	CPJR	7.60	25.87	16.59	118.25	209.90	200.17	.032	.047	.030	3.850
113	CPCR	2.39	10.04	10.04	75.44	152.95	157.53	.007	.151	.056	4.680

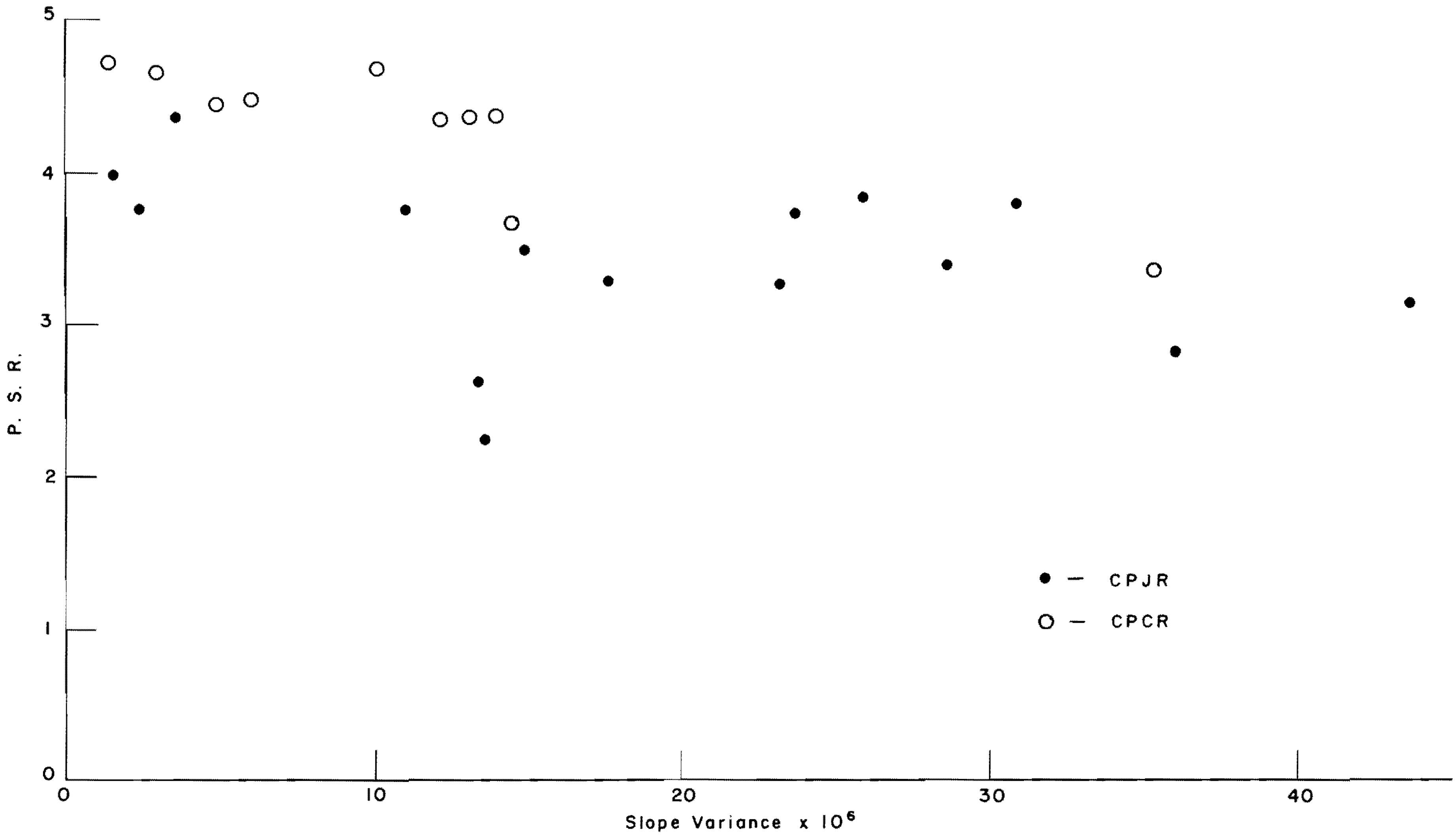


Fig A6.1. PSR versus SV for 25 rigid pavements at 34 miles per hour.

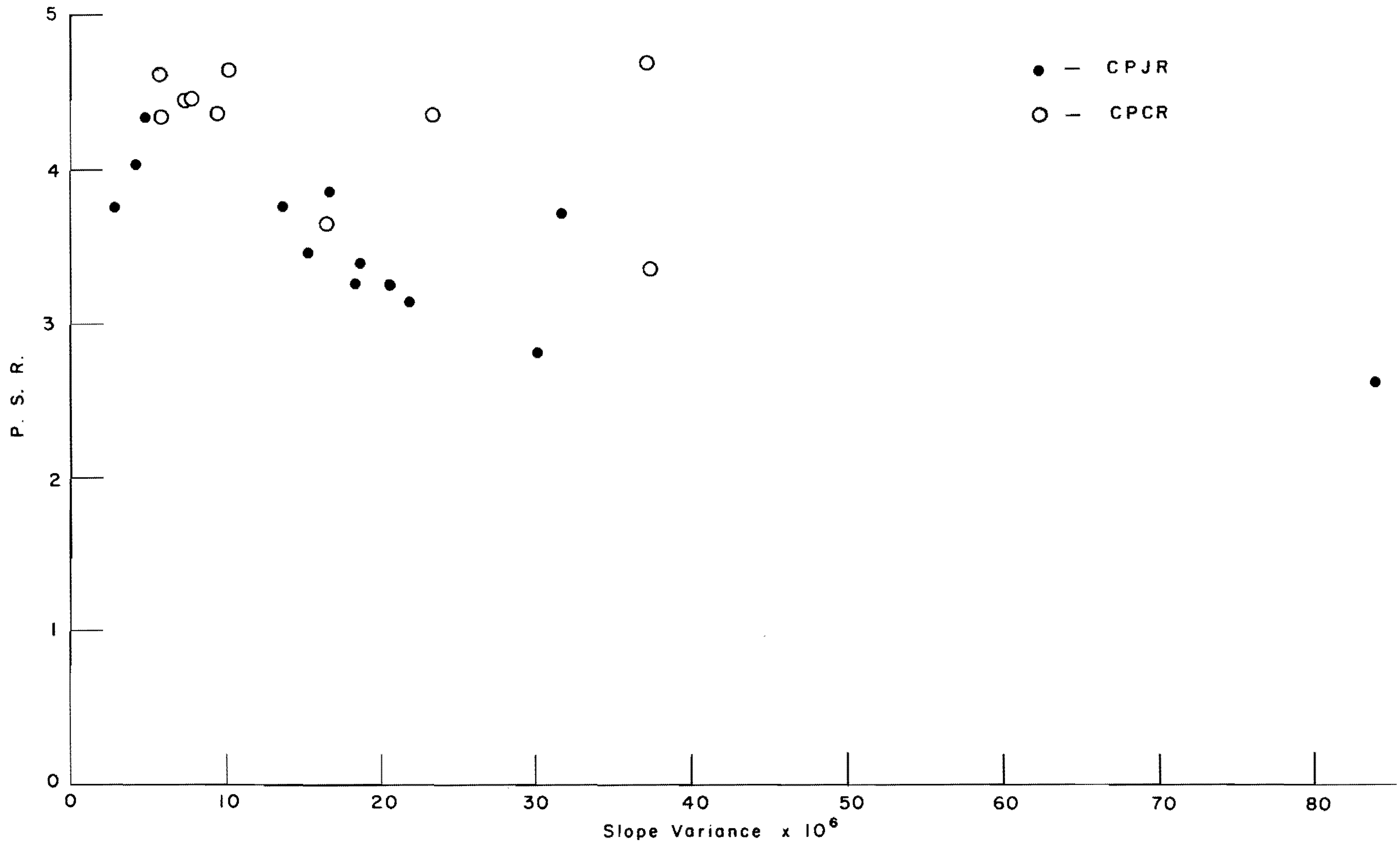


Fig A6.2. PSR versus SV for 23 rigid pavements at 50 miles per hour.

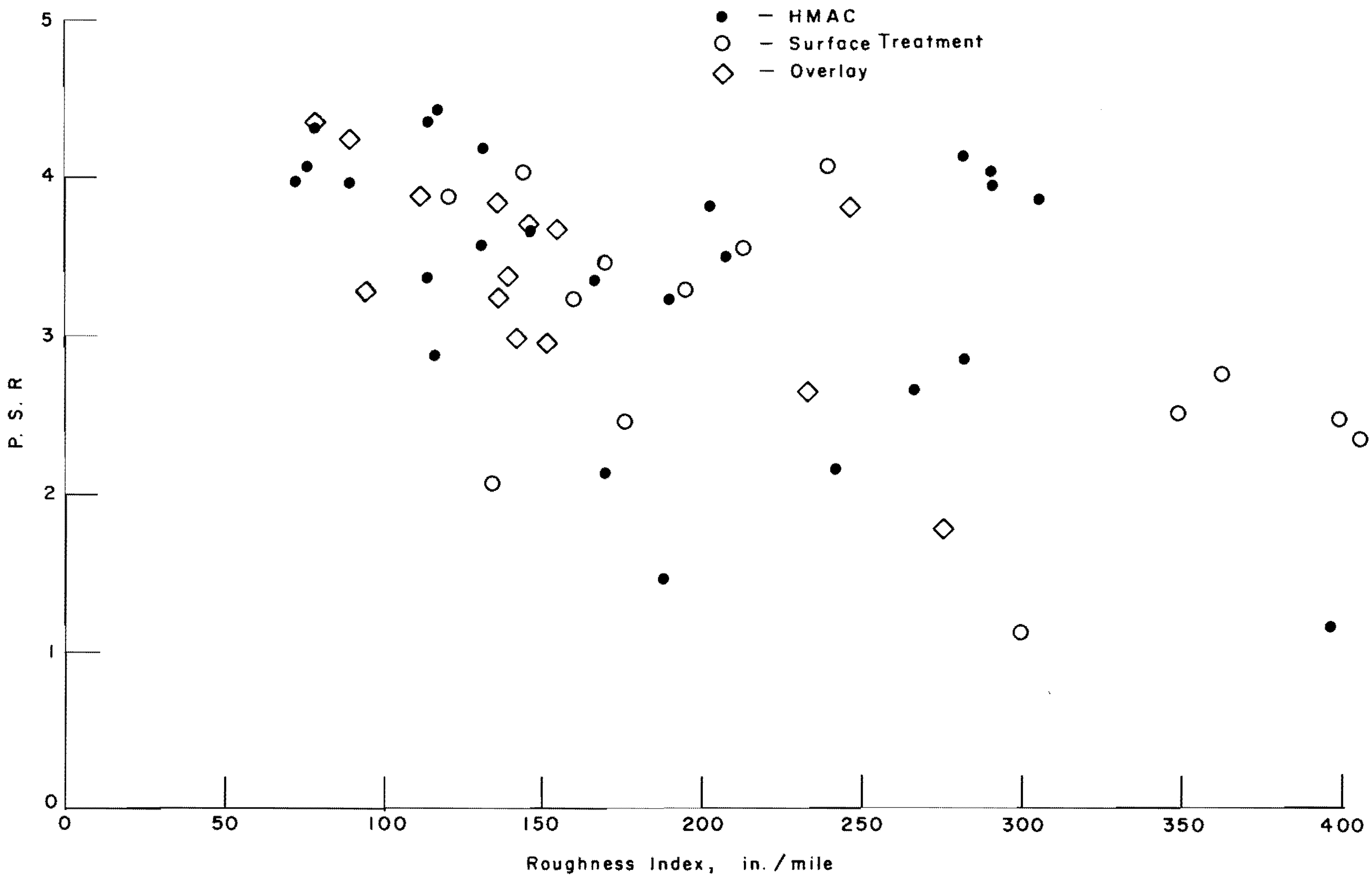


Fig A6.3. PSR versus RI for 53 flexible pavements at 34 miles per hour.

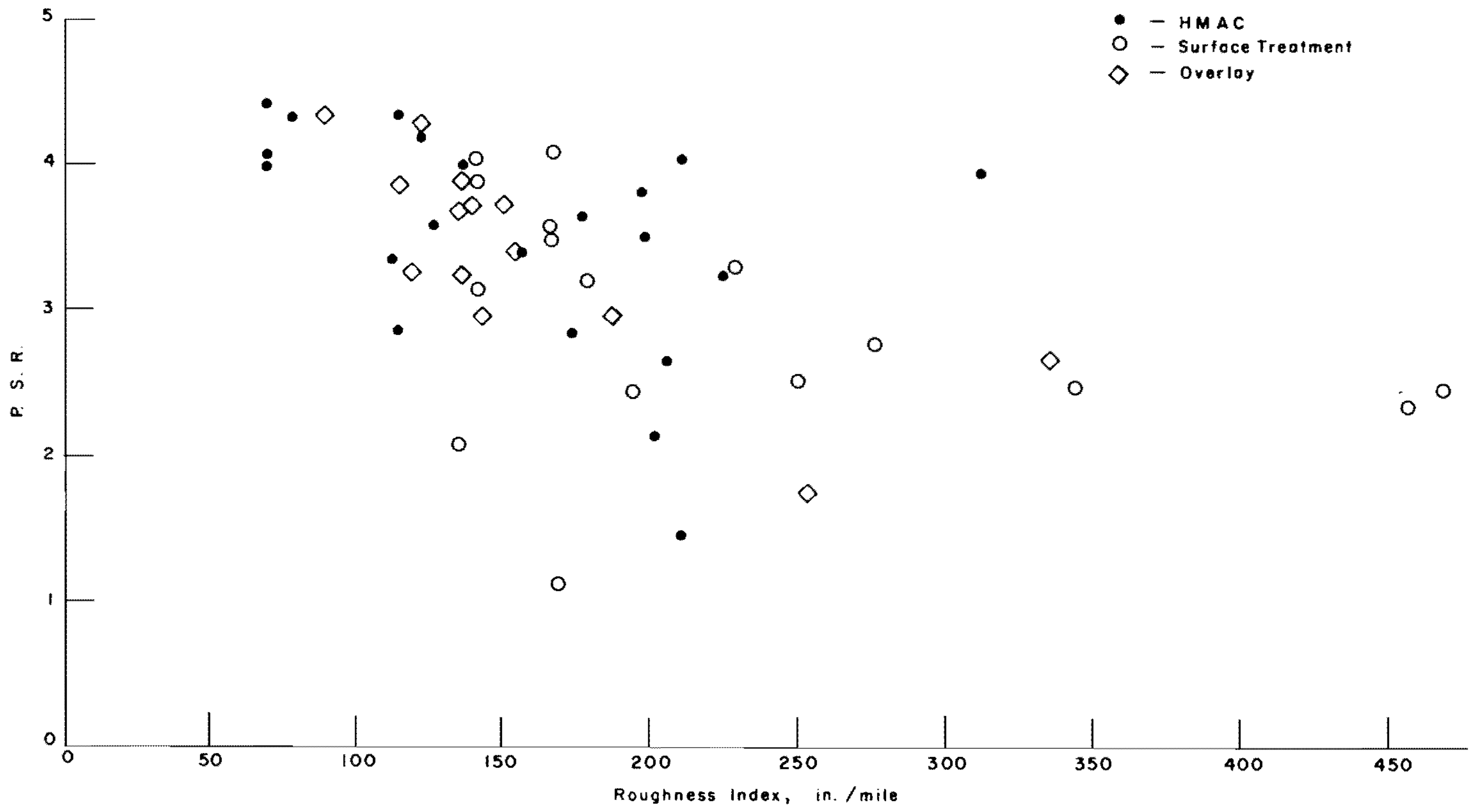


Fig A6.4. PSR versus RI for 51 flexible pavements at 50 miles per hour.

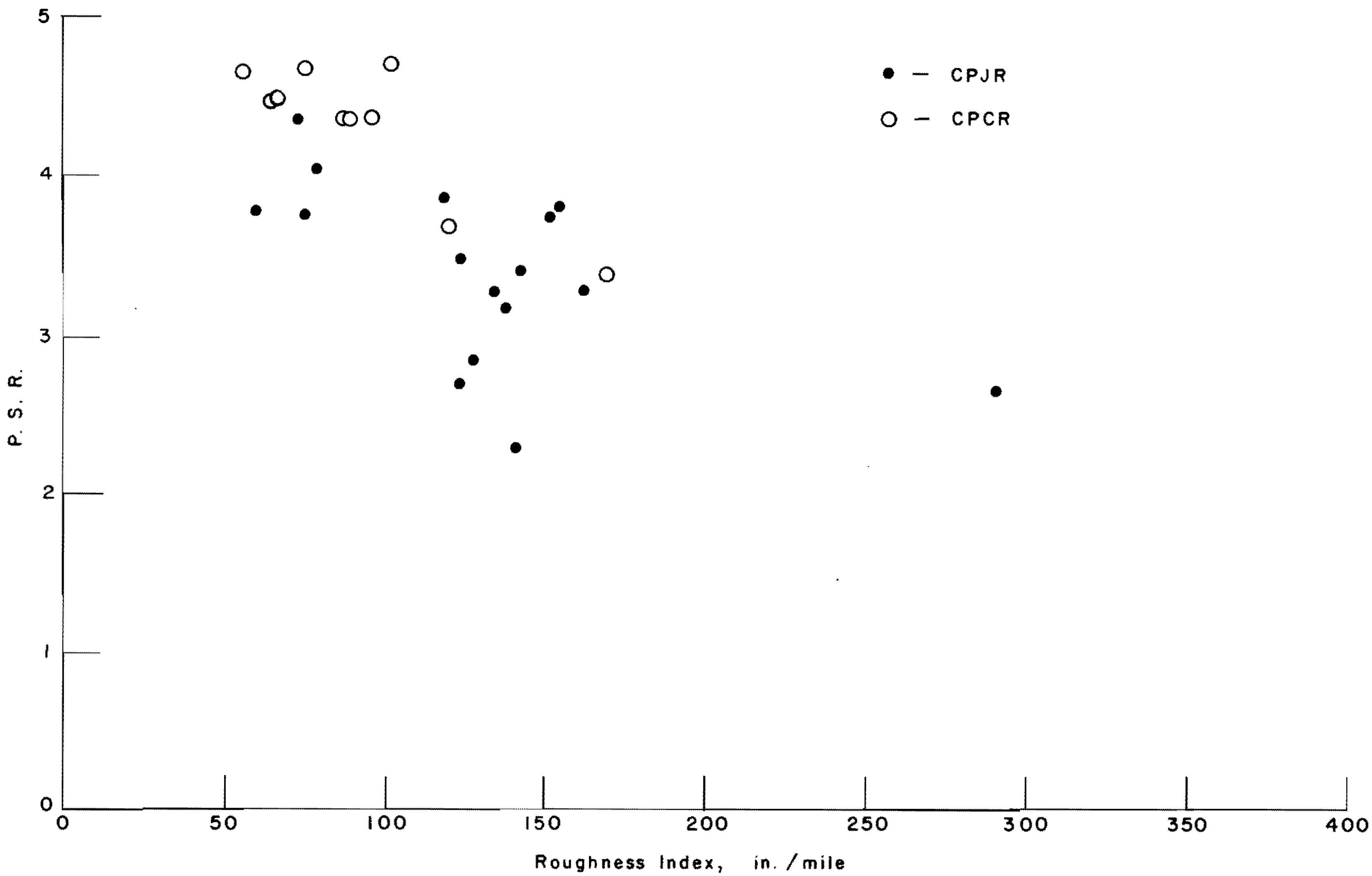


Fig A6.5. PSR versus RI for 25 rigid pavements at 20 miles per hour.

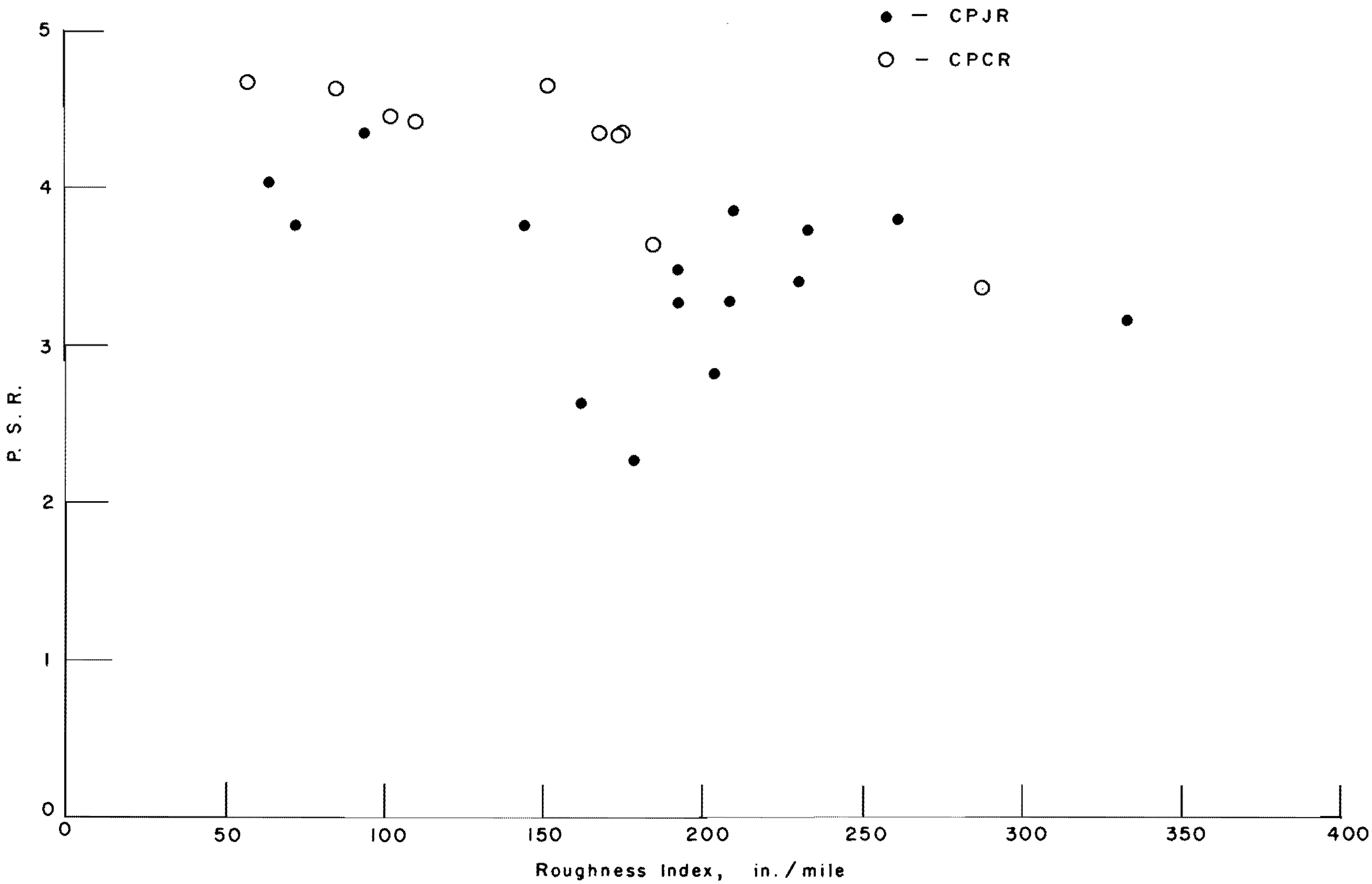


Fig A6.6. PSR versus RI for 25 rigid pavements at 34 miles per hour.

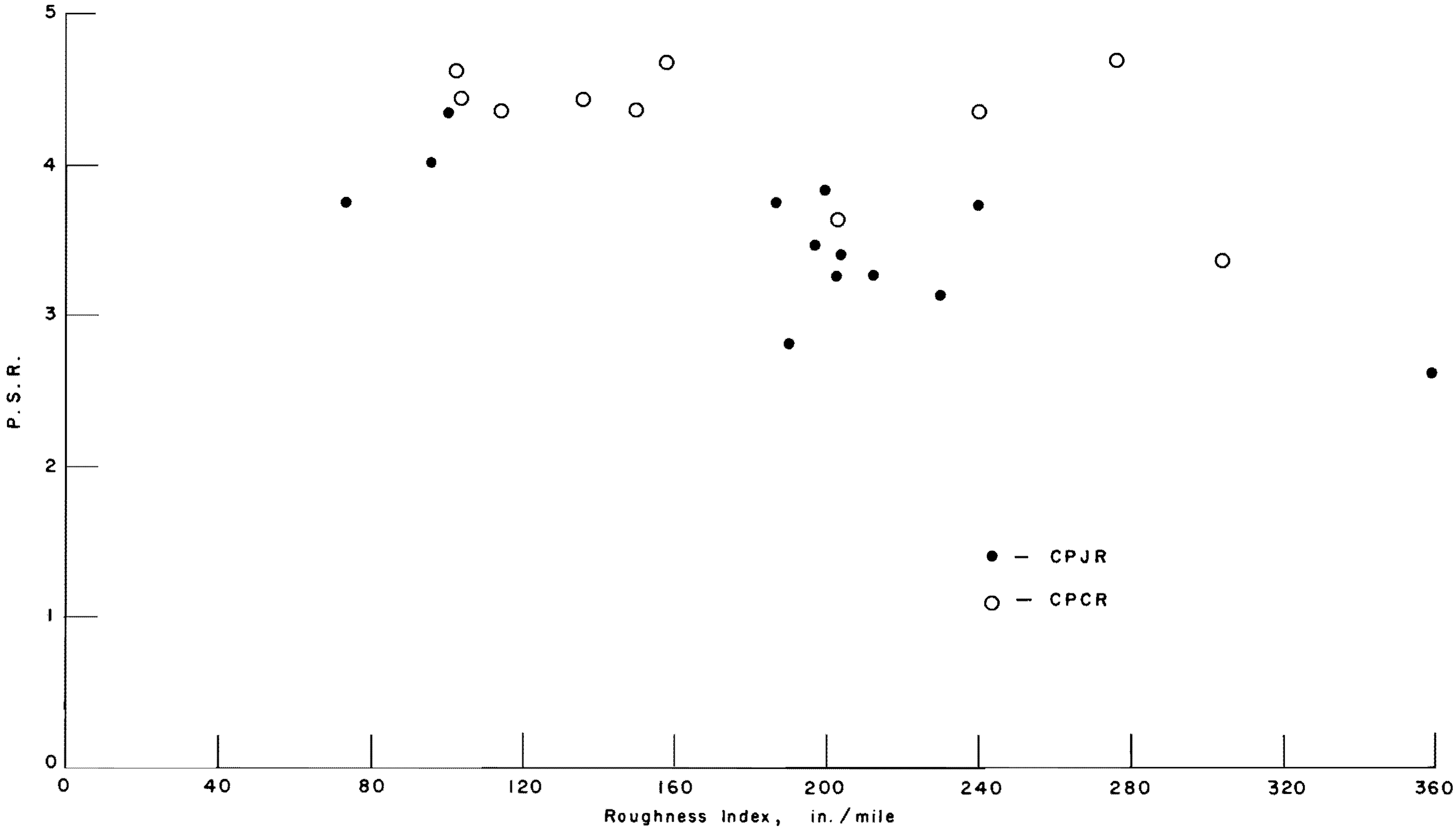


Fig A6.7. PSR versus RI for 23 rigid pavements measured at 50 miles per hour.

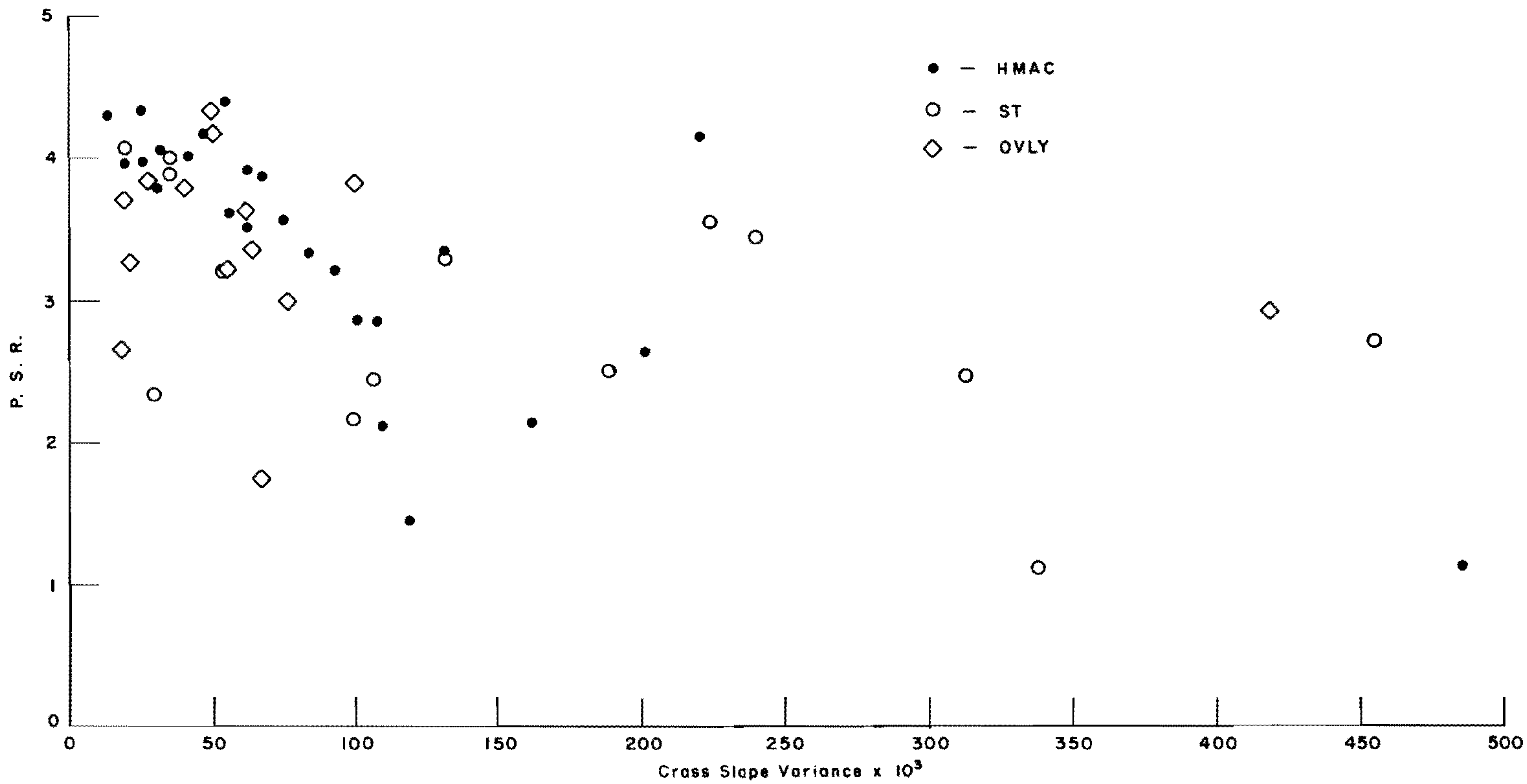


Fig A6.8. PSR versus cross slope variance for 53 flexible pavements at 34 miles per hour.

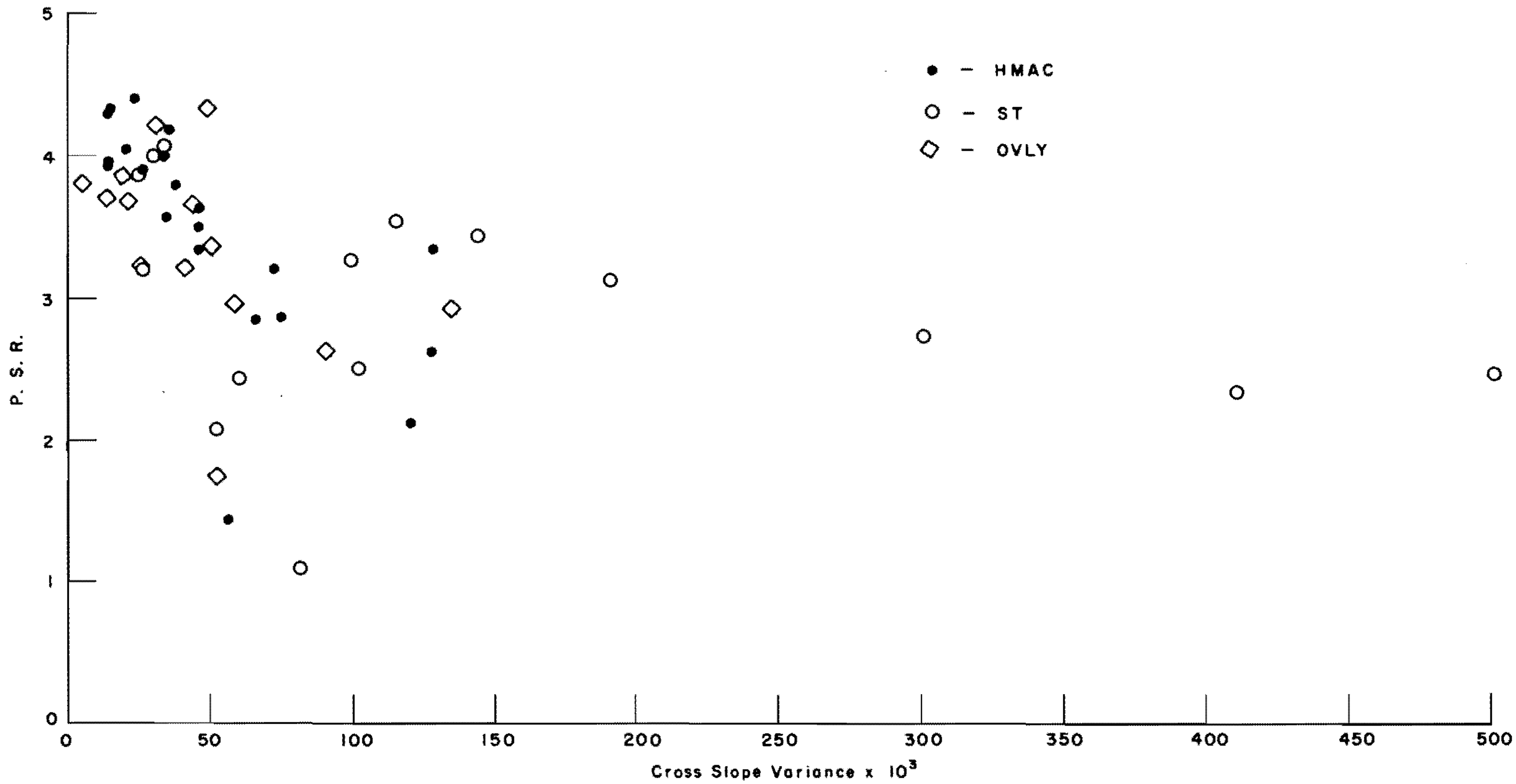


Fig A6.9. PSR versus cross slope variance for 51 flexible pavements at 50 miles per hour.

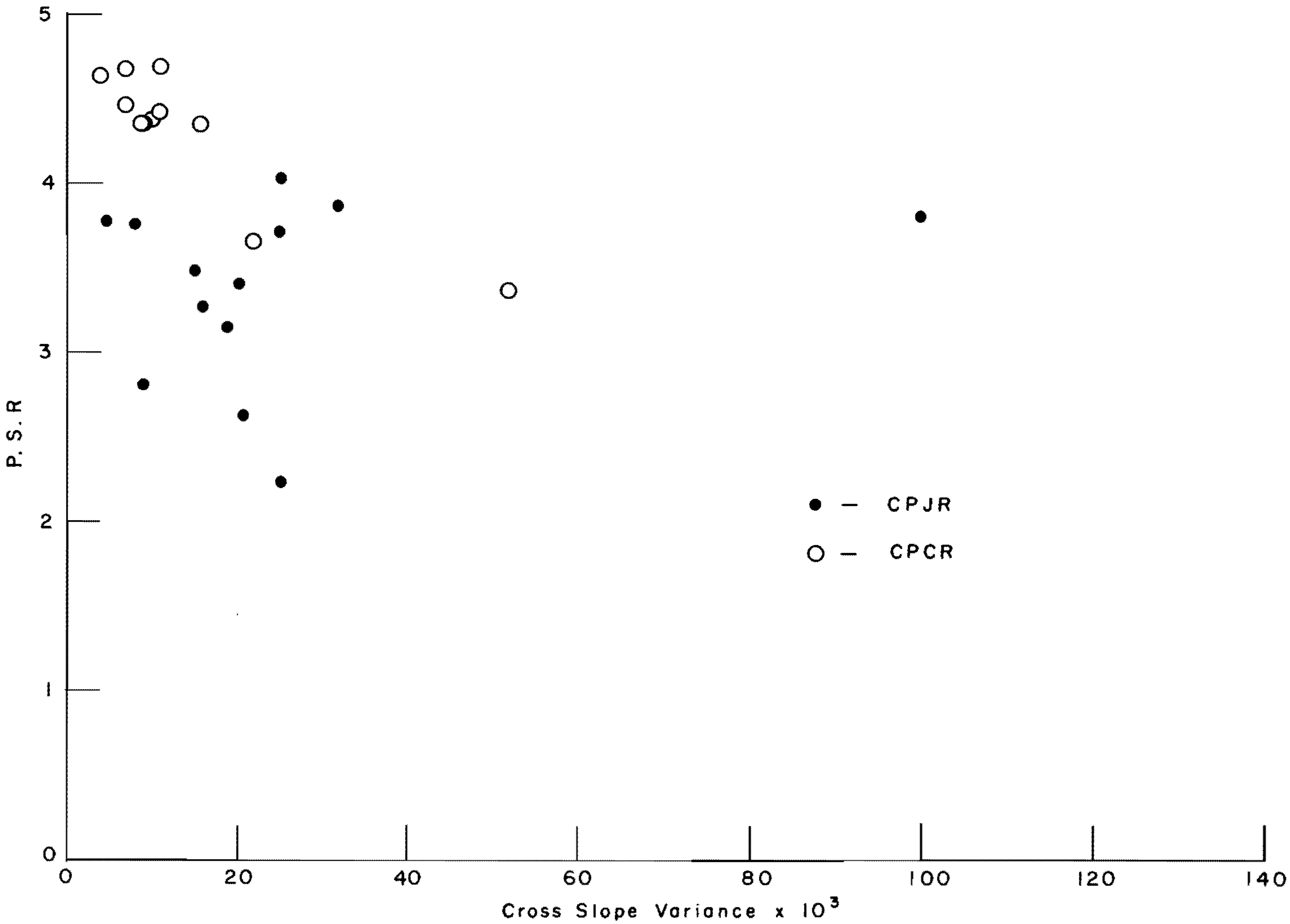


Fig A6.10. PSR versus cross slope variance for 25 rigid pavements at 20 miles per hour.

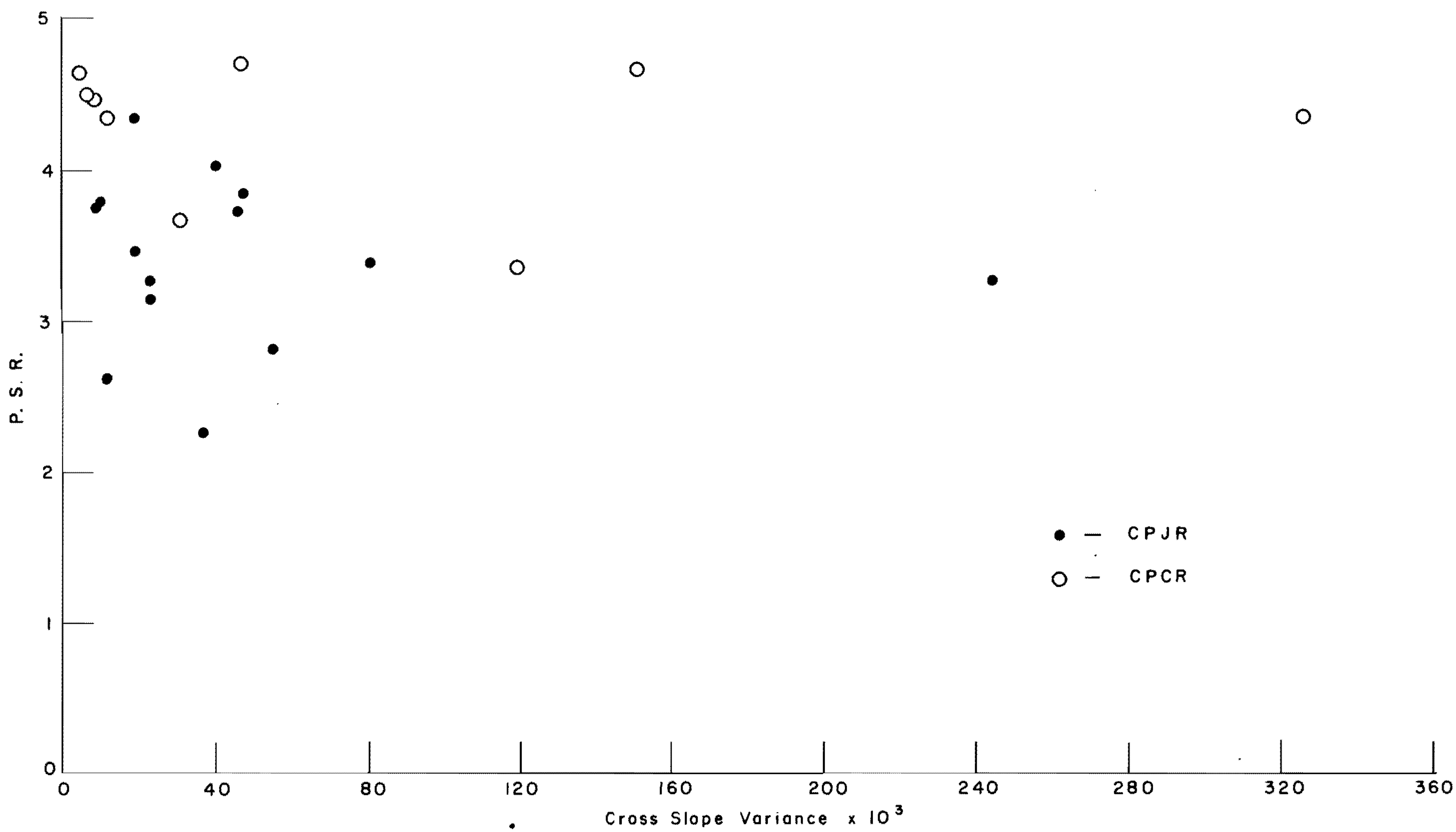


Fig A6.11. PSR versus cross slope variance for 25 rigid pavements at 34 miles per hour.

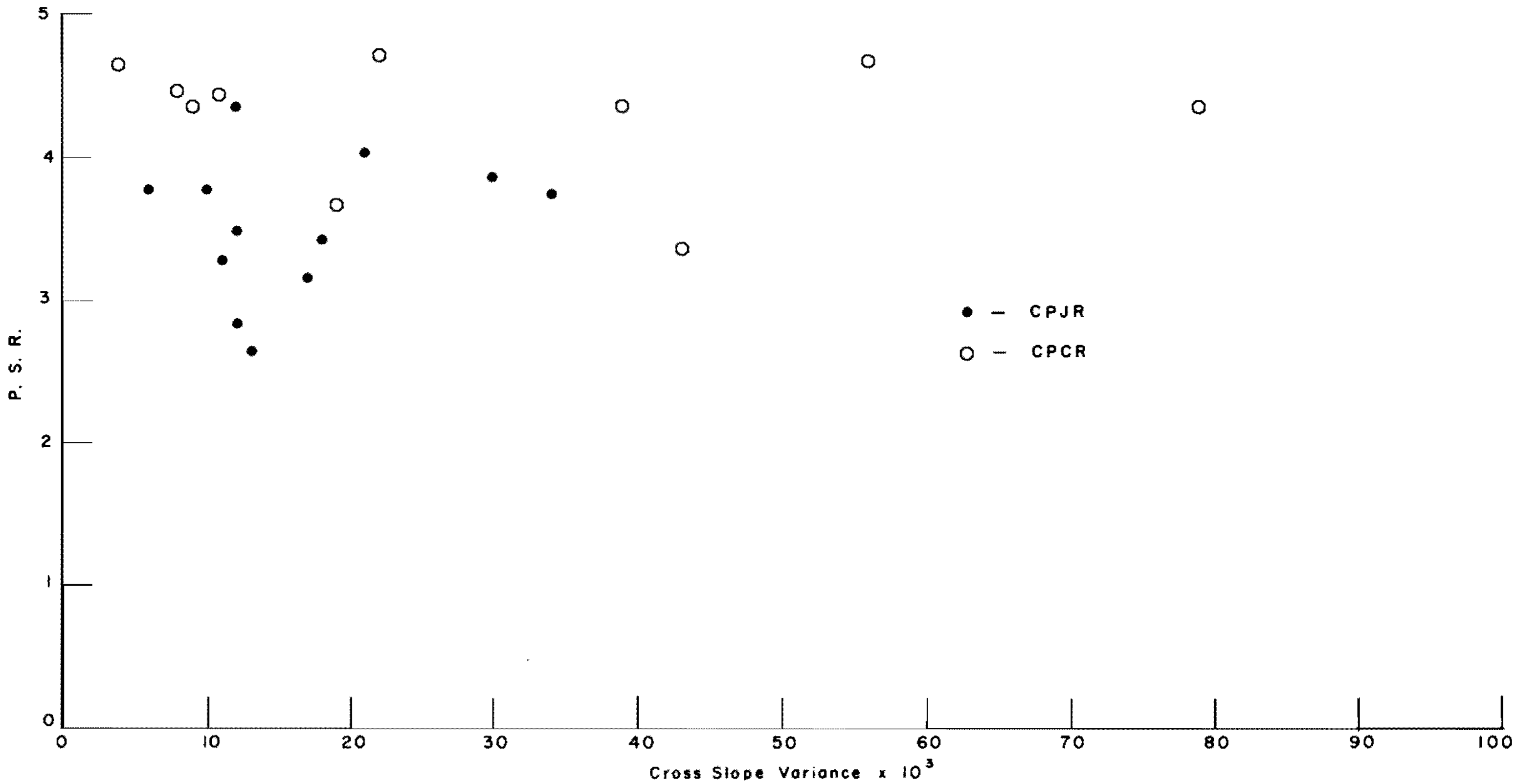


Fig A6.12. PSR versus cross slope variance for 23 rigid pavements at 50 miles per hour.

APPENDIX 7

LIST OF DISCARDED TEST SECTIONS

TABLE A7.1. FLEXIBLE PAVEMENT RUNS WHICH WERE REMOVED FROM FURTHER ANALYSIS WITH REASONS

Section No.	Vehicle Speed 20 mph	34 mph	50 mph	Reason for Deleting Data from Analysis
12	R1*, R2, L1**, L2	R1, R2, L1, L2	R1, R2, L1, L2	Outlier
13	R1, R2, L1, L2	R1, R2, L1, L2	R1, R2, L1, L2	Outlier no runs considered
14	R1, R2, L1, L2	R1, R2, L1, L2	R1, R2, L1, L2	Outlier
16	R1, R2, L1, L2	R1, R2, L1, L2	R1, R2, L1, L2	Photocell crosstalk into data channel
81			R2	Photocell crosstalk into data channel
82	R1			Photocell crosstalk into data channel
86		R1, R2, L1, L2	R1, R2	Photocell crosstalk into data channel
93		R1, L1		Photocell crosstalk into data channel
100	R1	R1	R1, R2	Photocell crosstalk into data channel
103			R1, R2	Photocell crosstalk into data channel
104			L1, L2	Photocell crosstalk into data channel
109	R1, R2, L1, L2	R1, R2, L1, L2	R1, R2, L1, L2	Photocell crosstalk into data channel

* Right profile data, run 1.

** Left profile data, run 1.

TABLE A7.2. RIGID PAVEMENT RUNS WHICH WERE REMOVED FROM FURTHER ANALYSIS WITH REASONS

Section No.	Vehicle Speed			Reason for Deleting Data from Analysis
	20 mph	34 mph	50 mph	
8	R1*, R2	R1, R2	R1, R2	Gravel and mud in right wheel path (Road still under construction)
26	R1, R2, L1**, L2	R1, R2, L1, L2	R1, R2, L1, L2	Photocell crosstalk into data channel
29	R1, R2, L1, L2	R1, R2, L1, L2	R1, R2, L1, L2	Photocell crosstalk into data channel
45		R1, R2	R1, R2	Photocell crosstalk into data channel
96	R1, R2, L1, L2	R1, R2, L1, L2	R1, R2, L1, L2	Photocell crosstalk into data channel
107			R1, R2	Photocell crosstalk into data channel

* Right profile data, run 1.

** Left profile data, run 1.

APPENDIX 8

PROGRAM PROF

APPENDIX 8. PROGRAM PROF

Purpose

The purpose of this program is to convert a data tape generated on the SDS 930 computer, which has points from the left and right profiles alternately and has the identification record following the data records, into two tapes for use with the CDC 6600 computer, where one tape contains only data from one profile and the other tape contains the data from the other profile and the identification records precede the data records for each file. Also, the data are changed from 12-bit resolution to 8-bit resolution.

Method

The data records are read from the tape onto disc until an identification record is located. This record was written as five 24-bit words in 2's complement on the SDS machine. The subroutines PACKID and PACK are used to generate five 60-bit words in 1's complement as required for proper use in the CDC 6600. These five 60-bit words are then written on both the two right and left profile tapes being generated. The disc file into which the data were copied is now rewound, and each 1500 word data record (12-bit words) is read. This time, however, only the subroutine PACK is needed to generate the required 1's complement 12-bit resolution data words. To reduce this to 8-bit resolution, for nonnegative numbers, 8 is added to the number and this sum is divided by 16; and for negative numbers 8 is subtracted from the number and this result is divided by 16. The resulting 1500 words of 8-bit resolution are divided into two 750-word records, each consisting of only right and left profile data, respectively. These records are then written on the proper right and left profile tapes. The procedure is continued until all the records in the original data file are processed, after each data file a end-of-file mark is written.

Input

The first data card contains

(1) Columns 1 through 5: if M is greater than zero, then the first M files of the input tape will be processed. If M = 0 , then files will be processed until a double EOF is encountered. M is read in I5 format.

(2) Columns 6 through 10: if N is greater than zero, then the number of records of each file which are converted and written on the output tapes is not greater than N , with either the first N records converted and written or all records if there are no more than N . If N = 0 , then either the first 21 records are converted and written, or the entire group of records, if there are no more than 21. N is read in I5 format.

Following this card are seven cards which list in order the files not to be converted and written. These are read from the cards in 20I4 format. These are not the numbers that appear in the first identification word but refer to the files position on the input tape.

(1) The input tape is assigned to tape unit 3.

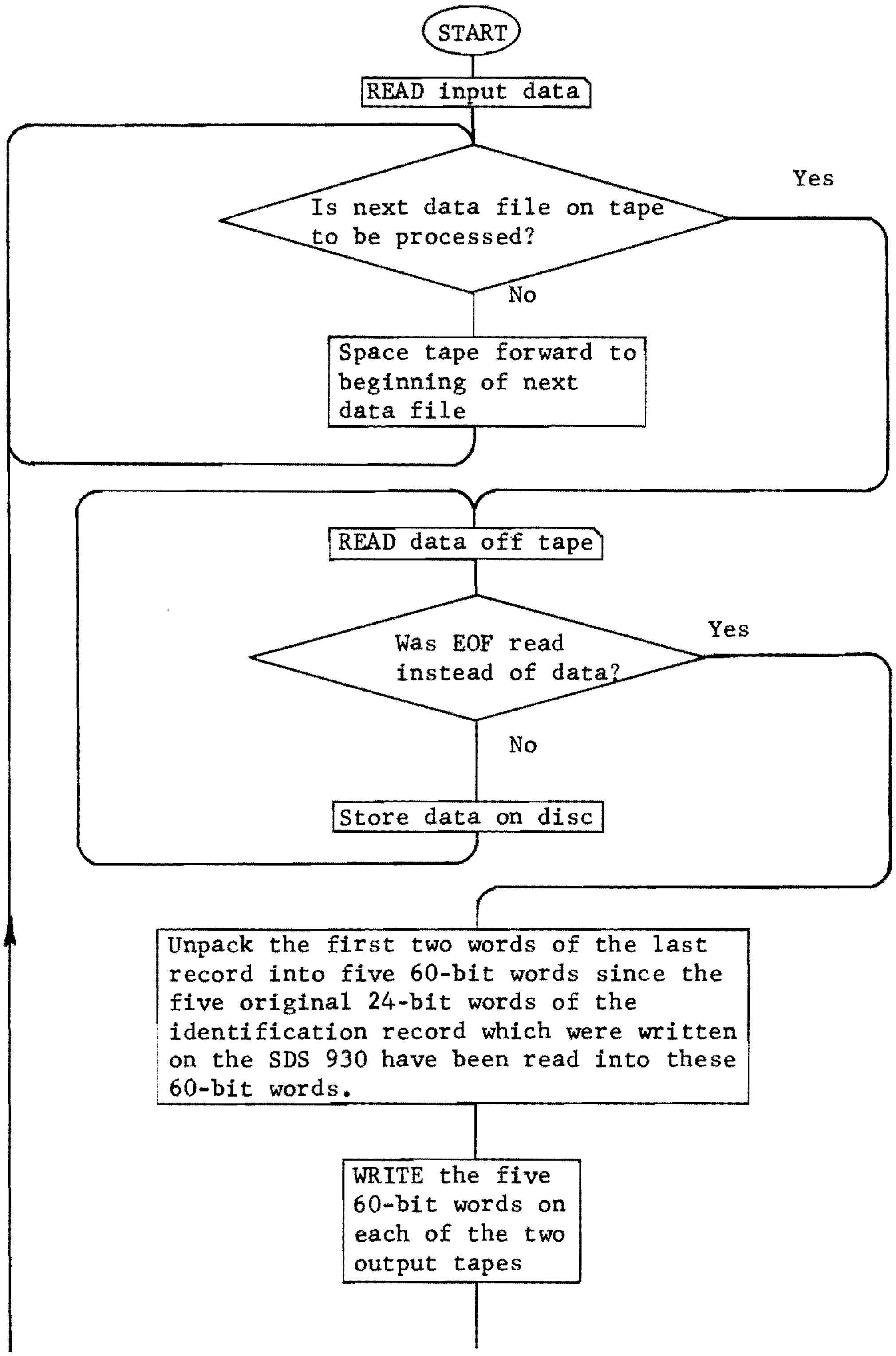
(2) The output tape consisting of data points 1, 3, 5, ... from the input tape is usually the right profile and is assigned to tape unit 1.

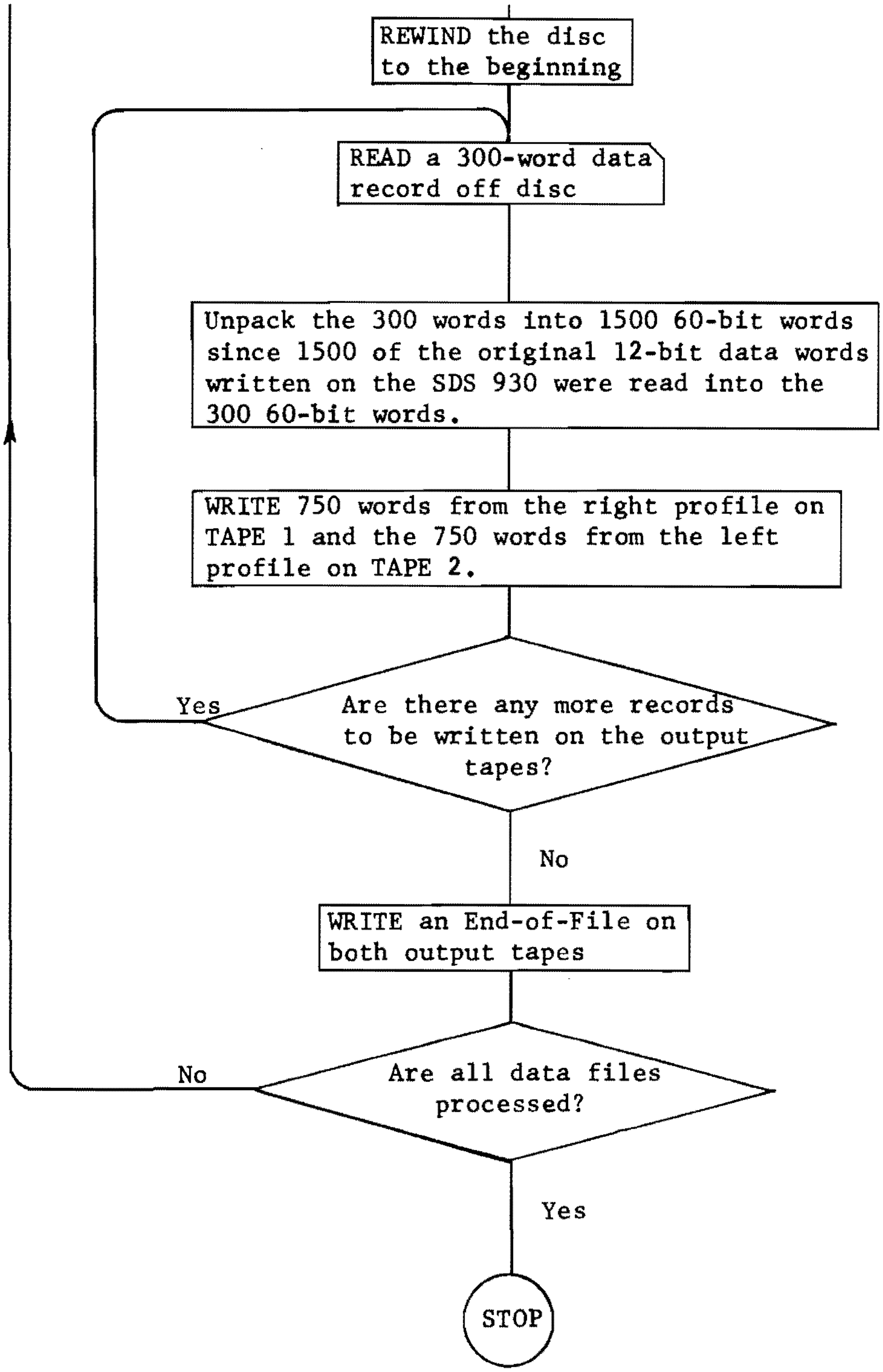
(3) The output tape for the other profile is assigned to tape unit 4.

Output

The identification records for each file which is converted and written on the output tape is printed.

SUMMARY FLOW CHART FOR PROGRAM PROF




REWIND the disc to the beginning
READ a 300-word data record off disc
Unpack the 300 words into 1500 60-bit words since 1500 of the original 12-bit data words written on the SDS 930 were read into the 300 60-bit words.
WRITE 750 words from the right profile on TAPE 1 and the 750 words from the left profile on TAPE 2.
Are there any more records to be written on the output tapes?
Yes
No
WRITE an End-of-File on both output tapes
Are all data files processed?
No
Yes
STOP

THE AUTHORS

Freddy L. Roberts is currently an Associate Professor of Civil Engineering at Clemson University. He was formerly a Research Engineer Associate with the Center for Highway Research at The University of Texas at Austin, where his research area of primary interest was the development of a measuring system for pavement serviceability using the Surface Dynamics Profilometer.

W. Ronald Hudson is an Associate Professor of Civil Engineering and Associate Dean of the College of Engineering at The University of Texas at Austin. He has had a wide variety of experience as a research engineer with the Texas Highway Department and the Center for Highway Research at The University of Texas at Austin and was Assistant Chief of the Rigid Pavement Research Branch of the AASHO Road Test. He is the author of numerous publications and was the recipient of the 1967 ASCE J. James R. Croes Medal. He is presently concerned with research in the areas of (1) analysis and design of pavement management systems, (2) measurement of pavement roughness performance, (3) slab analysis and design, and (4) tensile strength of stabilized subbase materials.