DEVELOPMENT OF A SYSTEM FOR HIGH-SPEED MEASUREMENT OF PAVEMENT ROUGHNESS, FINAL REPORT

by

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

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PREFACE

This is the fifth and final report in a series of reports presenting results from Research Project No. 3-8-63-73, "Development of a System for High-Speed Measurement of Pavement Roughness."

The project was initiated to evaluate roadway roughness and to provide a better measurement of present serviceability index (PSI) and roughness factors which affect vehicle dynamics. During this project a profile measuring system was developed around a General Motors Surface Dynamics Profilometer and a set of PSI prediction equations useful for ascertaining roughness measurement objectives was obtained. Details on project research activities are provided in the reports listed on the following page. This final report summarizes project research efforts and discusses in detail recent research investigations not covered in previous reports.

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LIST OF PROJECT REPORTS AND COMMENTS

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.

Report No. 73-5F, "Development of a System for High-Speed Measurement of Pavement Roughness, Final Report," by Roger S. Walker, W. Ronald Hudson, and Freddy L. Roberts, provides a summary of project research effort and detailed discussions of research during the last year of the project.

ABSTRACT

This report concludes work performed on Research Project 3-8-63-73, "Development of a System for High-Speed Measurement of Pavement Roughness." A brief background of project research efforts is given referencing pertinent project reports. Detailed discussions of research activities during this past year, not covered in past reports, are provided. These discussions include wheel replacement investigations, research activities in construction control, spectral analysis methods, Mays Road Meter correlation studies, and PSI model investigations. Special emphasis is placed on new methods for using spectral analysis for identification of various road profile characteristics. Extension of these new methods may provide the best approach yet available to development of adequate road profile specifications and construction control.

KEY WORDS: Surface Dynamics (SD) Profilometer, Mays Road Meter, analog-to-digital, present serviceability index (PSI), slope variance, roughness index, road profile, spectral analysis, power spectrum, coherence.

SUMMARY

This report concludes project activities on Research Project 3-8-63-73, "Development of a System for High-Speed Measurement of Pavement Roughness." This project was initiated to evaluate roadway roughness and to provide a better measurement of present serviceability index (PSI) and roughness factors which affect vehicle dynamics. At current design speeds of 80 miles per hour, roadway roughness is an increasingly important factor in vehicle and highway safety. In order to establish design criteria for an adequate, safe, and comfortable ride, reliable information is needed on pavement and bridge surface roughness. During this project a profile measuring system was developed which included both the SD Profilometer and a Hewlett-Packard Analog-to-Digital (A-D) System. By providing an accurate road profile measurement it was hoped that these design objectives could be more readily attained. The following is a summary description of the research performed during this project.

The SD Profilometer was purchased by the Texas Highway Department in February of 1967. The purchase of this unit for measuring road roughness was recommended after a thorough investigation of existing road roughness measuring equipment. The results of this study are reported in Research Report No. 73-1, "High-Speed Road Profile Equipment Evaluation." Following delivery of the SD Road Profilometer, there was a shakedown phase in which various operating problems were found and eliminated. A road profile measuring system was then developed which involved both the SD Profilometer for obtaining the data and an A-D computer facility for converting the data to digital form for computer analysis. Research Report No. 73-2, "A Profile Measuring, Recording, and Processing System," describes the details of this system. This original system included an XDS 930 A-D facility for the A-D requirements, owned and operated by The University of Texas at Austin. To provide continuing A-D capability for this and other research projects and for use by the Texas Highway Department, a Hewlett-Packard A-D facility was purchased for the system. Research Report No. 73-4, "Analog-to-Digital

System," provides a detailed description of this general-purpose facility and its use in the road profile measuring system.

In order to use data obtained from the road profile measuring system for predicting pavement serviceability indexes, two large-scale sessions were held during the summer of 1968 in which representative test sections were rated and their profiles measured. Various summary statistics computed from the measured profiles were then correlated with the PSR ratings obtained from the rating panel. From these correlations several PSI prediction equations were developed. Research Report No. 73-3, "Pavement Serviceability Equations Using the Surface Dynamics Profilometer," provides a detailed discussion of these two rating sessions. The discussions include a statistical analysis of the results of the ratings from these sessions and a description of the resulting PSI or pavement serviceability equations obtained by correlating these ratings with various summary statistics obtained with the profilometer.

During the past year, project personnel have made considerable use of the road profile measuring system using the SD Profilometer and the new H-P A-D system. Specific areas of concentration have been

(1) validating the PSI prediction equations,

(2) decreasing the system throughput time requirement,

(3) providing profile measurements for other research projects (for example, "Dynamics of Highway Loading," Project No. 3-8-67-108),

(4) obtaining a degree of confidence for running the profilometer for other field uses,

(5) investigation of methods for using spectral analysis as a tool for road profile analysis,

(6) investigations for finding an inexpensive replacement wheel,

(7) the use of spectral analysis methods for identifying differences in pavement construction techniques, and

(8) initial correlation studies of the SD Profilometer and the Mays Road Meter.

IMPLEMENTATION STATEMENT

The following useful results have been revealed by Project 73 research efforts:

(1) Two large-scale rating sessions were conducted and used to develop PSI prediction equations. These equations can be used for evaluating PSI on Texas pavements.

(2) Several hundred miles of pavements have been evaluated with the SD Profilometer.

(3) The SD Profilometer can and has been successfully used to provide roughness measurements related to vehicle dynamic studies (Research Project 3-8-67-108).

(4) Harmonic analysis techniques on road profile data have been developed and are useful in such areas as construction control. These techniques have been successfully used on I-45 near Bryan for detecting differences in asphalt pavement laying devices.

(5) The profile measuring system can be used to provide input for the flexible and rigid pavement system design programs in Project 1-8-69-123. It can also be used to provide roughness data for other research projects such as Project 3-8-68-118.

(6) The profile measuring system can be used to provide a calibration standard for other roughness measuring devices such as the Mays Road Meter.

(7) The profile measuring system is useful for evaluating initial serviceability and riding quality for new construction for the various equipment and pavement types.

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CHAPTER 1. INTRODUCTION

This report concludes research on Project 3-8-63-73, "Development of a System for High-Speed Measurement of Pavement Roughness."

The project was begun in 1963 to evaluate existing and proposed roughness measuring devices which could be altered or used for high-speed measurement of road roughness. Investigation revealed that the General Motors Surface Dynamics Profilometer (herein referred to as the SD Profilometer) provided reasonable road profiles at high speeds (Refs 1 and 2), and this device was purchased by the project. Plans were made to use it, and once the road profile information was available, the primary research interest became the problem of how to process the data and how to relate them to road roughness.

In rating sessions conducted in the Austin, Houston, and Dallas-Fort Worth areas, pavement sections were rated by a panel of "average" drivers (Ref 3). The means of the ratings made by the panel members were correlated with the summary statistics of the measured profiles of the same sections and various models were developed.

The last part of the project was devoted to evaluating the equations, investigating for better and more economical methods of using the profilometer, and determining new and better methods of analyzing road profile information. In the last area, recent success has resulted in a great deal of optimism concerning use of spectral analysis for analyzing profile data. Spectral analysis techniques not only permit a method for correlating road roughness but also provide a means for identifying different construction methods.

Project work has also included development of an analog-to-digital processing system and data processing procedures for computing the various summary statistics of road profile data obtained with the SD Profilometer (Ref 4). An error analysis of the complete measuring process, i.e., data measurements, analog-to-digital operations, and digital data processing, has also been made.

The five reports prepared by the project are

73-1, "High-Speed Road Profile Equipment Evaluation,"

73-2, "A Profile Measuring, Recording, and Processing System,"

73-3, "Pavement Serviceability Equations Using the Surface Dynamics Profilometer,"

73-4, "Analog-to-Digital System," and

73-5F, "Development of a System for High-Speed Measurement of Pavement Roughness, Final Report."

This report is divided into two principal areas: (1) a brief summary of all project research efforts and (2) detailed discussions of recent research activities not included in past reports. Chapters 1 and 2 provide the project summary information and Chapters 3 through 8 provide the detailed discussions on recent research activities. The reader should refer to the first four reports for technical details on the former project activities; no attempt has been made to include them herein.

CHAPTER 2. SUMMARY OF RESEARCH EFFORTS

Research efforts for this project may be categorized into the following areas:

(1) investigations of existing and proposed roughness measuring devices;

(2) purchase of the General Motors SD Profilometer, initial evaluations of this device, and improvements to this device (the SD Profilometer);

(3) development of the Road Profile Measuring System;

(4) development of pavement serviceability equations from data obtained by the Road Profile Measuring System (PSI prediction models); and

(5) other uses of the Road Profile Measuring System.

These five areas are discussed below.

Initial Project Investigations

This project was initiated in 1963 to evaluate existing and proposed roughness measuring devices which could be altered or used for high-speed measurement of road roughness. A thorough investigation of existing equipment was described in Report 73-1, which recommended that the sponsors purchase the General Motors (GM) Profilometer.

After overcoming the complexities of purchasing the device, an order was placed for a profilometer with K. J. Law Engineering Company in August 1966.

The SD Profilometer

In an effort to expedite delivery of the Surface Dynamics (SD) Profilometer (trade name for the General Motors Profilometer), the project supervisor visited Detroit on November 4 and 5, 1966, and discussed the SD Profilometer with personnel of the Michigan State Highway Department and the General Motors Proving Grounds and Messrs. K. J. Law and Elson Spangler. As a result of this visit, several improvements were incorporated into the final design, including additional data-recording capabilities, calibration, calibration checks, cruise control to maintain speed with an accurate indicator for easy visibility to the driver, internal control for raising the sensing wheels, and modification of interior furniture to enhance operation and safety.

The SD Profilometer (Fig 1) was received in Texas on February 6, 1967, and the initial evaluation began immediately. The initial evaluation was conducted over four test sections in the Austin area on which precision level surveys had been run by a Texas Highway Department survey party.

Any prototype device can be expected to have problems, but the number encountered with this device was larger than expected.

In November 1967, several major engineering improvements in the analog computing unit of the Surface Dynamics Profilometer were made by Law Engineering. These improvements were principally in the overload and gain circuitry, and a photocell amplifier module was added. Since these improvements were being incorporated in all future profilometer systems, Law Engineering agreed to incorporate these improvements in the analog computing unit of the profilometer equipment without cost. The computer was sent to Law Engineering for these modifications.

Road Profile Measuring System

Since the SD Profilometer alone is incapable of providing the type of data required for this research project, a road profile measuring system was developed. Figure 2 depicts a general block diagram of this system. Three major subsystems are indicated in this figure, the SD Profilometer, and the analog-to-digital (A-D) and digital processing subsystems. Data processing for the system can be pursued in several ways, including analog or digital processing. The analog processing has advantages when a digital computer is unavailable and only processing techniques such as harmonic analyses and power spectral density are desired. However, other techniques, such as slope variance or roughness indices, are more difficult to obtain in analog data form and lend themselves to digital processing. Because of the availability of a digital computer and the resulting increased flexibility, digital processing was chosen for this system.

Fig 1. Surface Dynamics Profilometer.

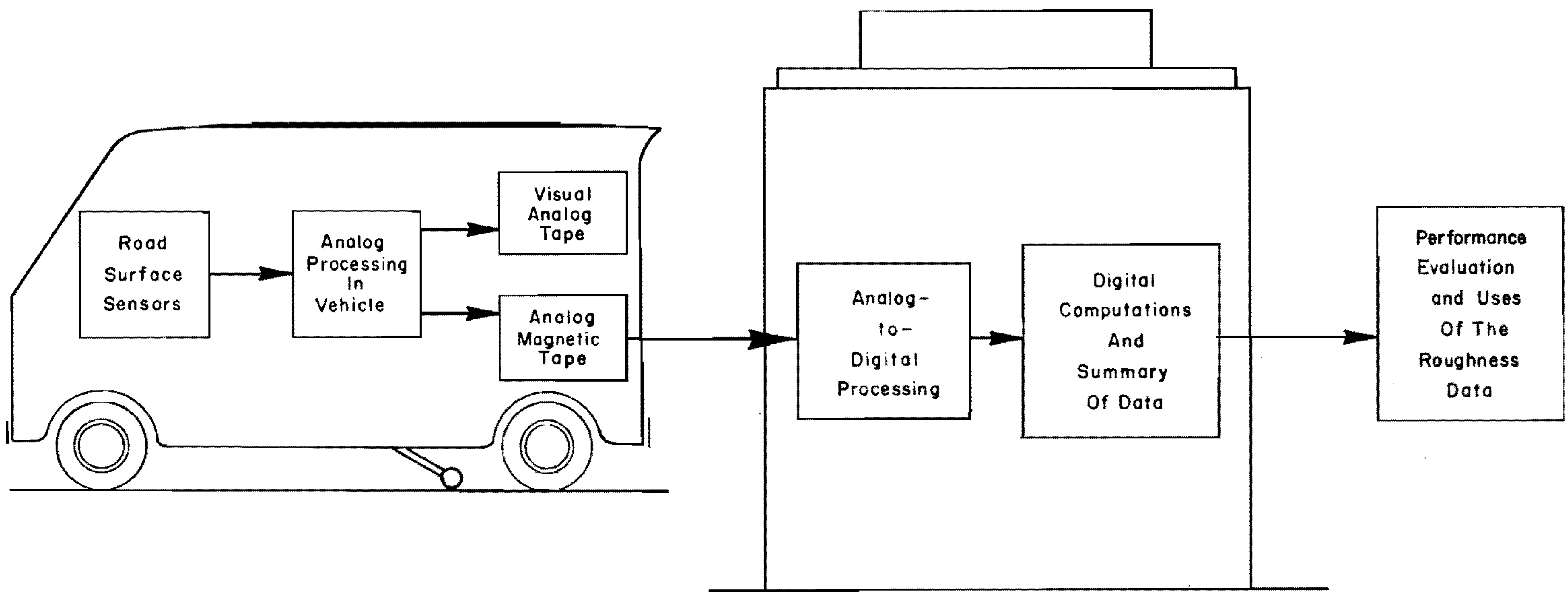

Fig 2. Profilometer measurement system.

The SD Profilometer subsystem obtains an analog voltage proportional to the road profile. It is this output in which analog processing is employed. For digital processing, however, this signal is sent to the A-D subsystem where it is converted to digital form. The A-D subsystem initially consisted of an XDS 930 general-purpose computer with an A-D peripheral unit owned by The University of Texas. Subsequently, a Hewlett-Packard 2115A computer was purchased and installed at the Texas Highway Department especially for this A-D requirement.

A detailed description of the road profile measuring system is provided in Report 73-2. Report 73-4 provides a complete description of the Hewlett-Packard A-D subsystem.

PSR Prediction Models

A pavement rating session was conducted to correlate the opinion of the traveling public on 125 specific sections of road with the objective measures of pavement roughness and deterioration as reported in Report 73-3 (Ref 3). A panel of 15 typical road users riding in typical American automobiles rated the pavements in accordance with methods developed by Carey and Irick (Ref 5) which serve as a basis for most current pavement rating systems. The panel's opinion of the riding quality of road sections was represented by a present serviceability rating (PSR) value. A preliminary rating session was first held during the period of February 5 through 7, 1968. This session was conducted to allow project personnel an opportunity to instruct the raters as to their purpose, to see how the SD Profilometer would function under routine working conditions, and to provide some meaningful data to test the analysis programs and to establish preliminary present serviceability models. The two large-scale rating sessions were conducted during the summer of 1968. The sites for the two full-scale rating periods were selected to cover two different topographical areas of Texas. The first rating period was conducted in the Houston-Gulf Coast area and the second in the Dallas-Fort Worth area. These diverse regions were selected to allow a large inference space for use in development of useful PSR prediction models. Models were then developed which expressed these ratings as a function of various road profile statistics. The primary statistics used in these prediction models were slope variance and roughness index of the digitized road profile data. Research Report 73-3 provides detailed discussions on the rating sessions and development of these models.

Other Uses of the Road Profile Measuring System

Other uses of the road profile system have included providing road profile data for Project No. 3-8-67-108, "Dynamics of Highway Loading;" correlations of PSI values obtained by the system with the Mays Road Meter; evaluations of the PSI models; system analysis methods on the measuring system; and the use of the system in construction control. The use of the system to correlate roughness with dynamic load is described in Research Report 108-1F. The other research areas are discussed in the following chapters.

CHAPTER 3. MAYS ROAD METER CORRELATIONS

Because of the amount of time required to obtain PSI values, about three to five days, the project staff has always sought some type of in-vehicle summary device. The quarter-car simulator manufactured by Law Engineering is one such device. Because of the unavailability of this device at the time, however, and also because of some initial problems with this device as indicated by the Pennsylvania Highway Department, it was decided to install a Mays Road Meter (MRM) to provide an estimate of pavement roughness for immediate field use. Complete roughness statistics would be available once the SD Profilometer data were processed. The installation of the MRM in the SD Profilometer would also permit correlation studies of the MRM with the profilometer as well as checks on each instrument.

Installation Attempts of Mays Road Meter in SD Profilometer

An MRM was obtained from the Texas Highway Department, and several improvements suggested by Mr. Ivan Mays were incorporated. After the MRM was installed, it was soon determined that reliable data could not be obtained because of the stiffness in the profilometer vehicle's suspension system. Several sessions were held with Mr. Mays in attempts to solve this problem. Using a smaller operating pulley and working with different tensions on the measuring cable proved futile. A trip was made to the Texas Transportation Institute, Texas A&M University, in order to discuss the problem with Mr. Brad Phillips, who had considerable experience with the device (Ref 7). Apparently the leaf springs in the truck were too stiff for the MRM. After reviewing the data accuracies obtained with the MRM in a coil spring suspension system, it was decided that the Mays Road Meter could not successfully be used in the profilometer vehicle and it was removed.

Mays Road Meter-SD Profilometer Correlations

Because of the simplicity and low cost of the MRM, it was decided to try and correlate this device with the SD Profilometer. A 1969 Ford was obtained from the Texas Highway Department and the MRM installed in it. A preliminary experiment was then conducted where two sets of repeat runs over 15 test sections in the Austin area were made with the MRM. The MRM average distance measurements were correlated with PSI computed from a 20-mph prediction equation* which uses principally log slope variance as its independent variable. Table 1 provides the PSI values and MRM distance measurements.

The plots of PSI versus MRM distance measures are depicted in Fig 3. The prediction equation relating PSI to the MRM distance measures is given below.

$$PSI = 2.77 - 1.99 (\log_{10} M - 1.87) \qquad (3.1)$$

where

M = Mays Meter distance reading,

R^2 = 0.876,

Standard error = 0.345.

It should be noted that this experiment was simply a pilot study and is by no means complete. Thus, the above equation should be used only as an estimate of PSI. Also, as discussed in Chapter 6, some inconclusive comparisons were obtained with the MRM and SD Profilometer on tests in the Bryan area. A more complete investigation and correlation between these two instruments will be conducted under Project 3-8-71-156, "Surface Dynamics Road Profilometer Application."

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* The 20-mph equation used is similar to the 20-mph equation reported in Report 73-3. It differs in that the variables were centered about their means before running the regression analysis. See Chapter 7 herein.

TABLE 1. PSI-MRM VALUES

Section	PSI	MRM Distance	
		Run 1	Run 2
1	2.476	86.9	
2	1.555	165.5	169.7
3	2.517	87.4	84.3
4	2.491	229.0	217.3
5	2.939	59.3	46.2
6	1.503	243.3	235.0
7	3.491	22.9	18.1
8	2.567	62.9	64.1
9	3.654	43.4	41.6
10	3.674	35.7	33.1
11	2.657	48.5	43.7
12	2.565	114.1	107.7
13	2.597	100.8	100.3
14	3.589	38.9	45.9
15	3.384	68.9	64.3

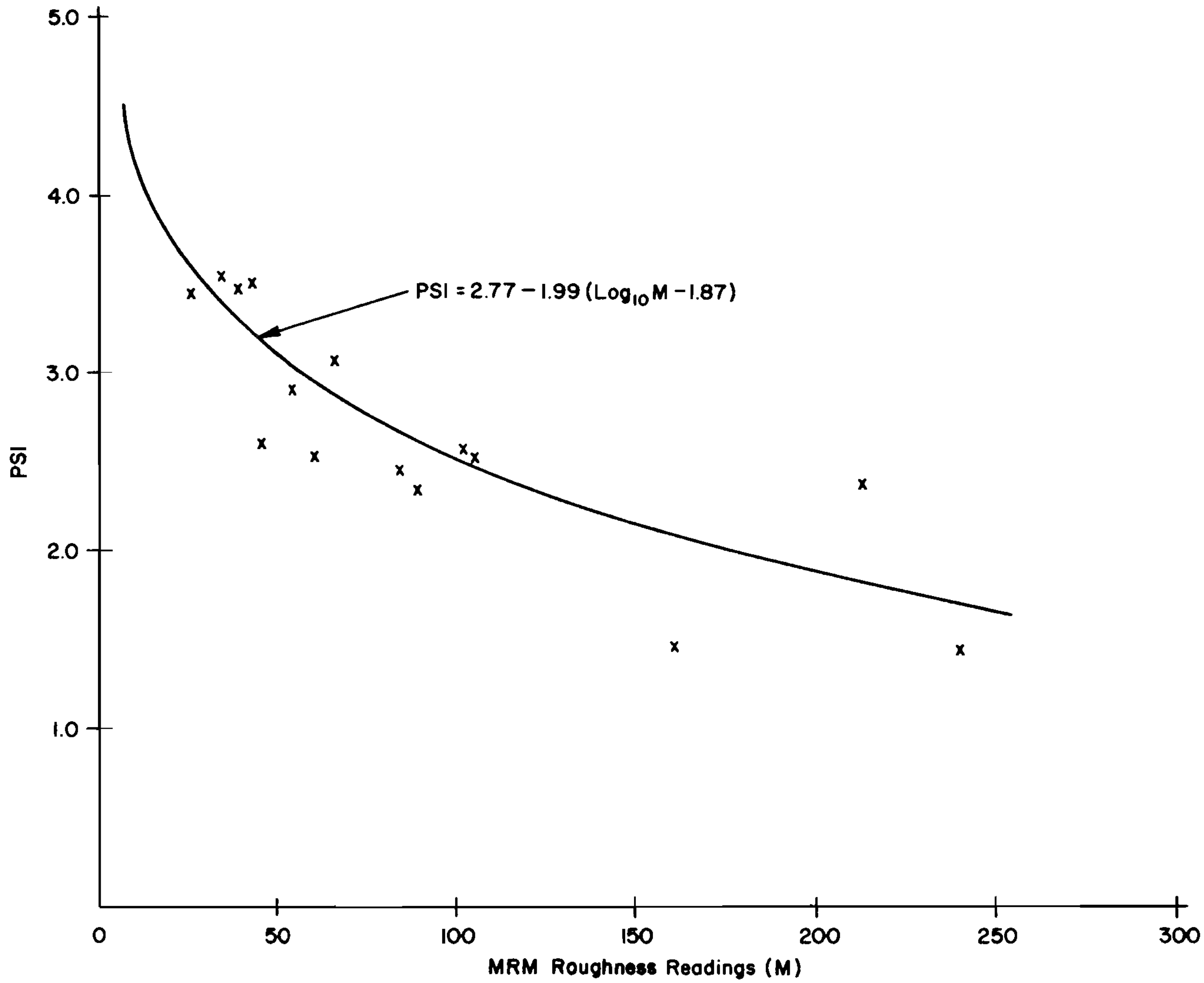

Fig 3. Surface Dynamics Profilometer PSI versus MRM roughness.

CHAPTER 4. SPECTRAL ANALYSIS AND THE SD PROFILOMETER

Introduction

Development of the General Motors Surface Dynamics Profilometer has made it possible to rapidly obtain road profile data. In addition, the SD Profilometer provides better data than other profilometers, in that long wavelength information is included in the data (Refs 2 and 8). With this new device, however, came the many problems of how to process and use the large quantities of data obtained. Research efforts at the Center for Highway Research at The University of Texas at Austin were primarily directed toward computing various summary statistics such as slope variance and roughness index values from the digitized road profile data. These statistics were used for correlations with a rating panel to develop Pavement Serviceability Index (PSI) prediction equations (Refs 3 and 9). Recent work has been expanded to include the use of spectral analysis for analyzing these data.

Spectral analysis, which separates road profile data into the various frequencies contained in the data, has been discussed by Quinn and Hagen using rod and level measurements for obtaining profile data (Ref 10) and briefly by General Motors using the SD Profilometer as the measuring device (Ref 11). In the studies by Quinn, problems in obtaining a standardized method for computing power spectra were discussed. Some of these problems described by Quinn still exist, although the profile data obtained by Quinn for his studies were not obtained with the profilometer and the fast Fourier transform (FFT)* was not used to compute the power spectral estimates.

The General Motors report included several power spectral plots of road profile data obtained with the profilometer. In the study, however, the investigators towed the profilometer behind a test truck at 3 mph so that usable data could be obtained for their investigations. Wheel bounce at the

*The fast Fourier transform is an algorithm which provides Fourier coefficients directly. Use of this method is much faster for computing power spectral estimates than the mean-lagged product method which was most commonly used until the last ten years.

higher speeds of the road-following wheel was said to be detrimental to their studies. (The profilometer was towed so that approximately the same wheel path used by the towing or test truck would be measured as required by the experiment.)

Consideration of this brief background would seem to suggest rejection of the use of power spectrum or spectral analysis as an analysis tool for examining road profile data obtained with the SD Profilometer. In this report, however, a way to avoid many of the problems mentioned in the above reports is discussed, and some practical methods of using spectral analysis on data obtained with the SD Profilometer are given.

Appendix 1 provides a brief discussion of spectral analysis and Appendix 2 discusses some problems which should be avoided when computing power spectrum and coherence estimates.

Accurate power spectral estimates require certain statistical assumptions about the data to be analyzed. The following is a discussion of the conditions imposed on road profile data in order to satisfy these assumptions.

Statistical Assumptions for Spectral Analysis Methods of Road Profile Data

Accurate power spectral estimates of road profile data should be from a stationary Gaussian random process. An ensemble of random time functions (or random process) is stationary if any translation of the time (or distance) origin leaves its statistical properties unchanged. Since power spectrum may be thought of as a second-moment spectrum (see Appendix 1), its first and second moments fall under this category. The profilometer filters out all low-frequency and dc components. Data characteristics of the first moment or mean approximately meet this definition (also see trend removal discussions in Appendix 2). However, the second moment or variance requirement is not so easily satisfied. Darlington (Ref 13) has found that road profile variance is reasonably constant on newer concrete and bituminous pavements. The total problem of nonstationarity, however, can be somewhat ignored by a change in viewpoint, from a local to an overall or averaging effect. That is, from the overall viewpoint, an averaging of several regions of rough and smooth pavements is of primary concern. For this viewpoint, if stationarity is not met, the variance values would be too high for the smooth regions and too low for the rough regions.

It should be noted that the stationary problems are not confined to spectral analysis, but also affect slope variance or other summary statistics and must always be watched for in any statistical analysis. In most such analyses, the overall viewpoint is usually assumed.

In Ref 13, Darlington provides a good discussion concerning the random characteristics of road profile data. These discussions lead to the assumption that typical highway profile data, as obtained with the SD Profilometer, are usually Gaussian or near-Gaussian since they are an ensemble of random time functions and have a mean approximately equal to zero.

These restrictions are not as serious as they might first appear, since it has been shown (Ref 12) that the power spectrum estimates are fairly robust to non-Gaussian signals. Furthermore, by using the combinations of (1) data from the profilometer, (2) spectral analysis from an overall viewpoint, and (3) trend removal techniques (Ref 12), the problems of stationarity are alleviated.

Coherence analysis (see Appendix 1) has been found quite useful for current road profile analysis because of its capacity to detect differences between two different road profiles on a frequency basis. In addition, it also has several other advantageous features which should be noted. First, Foster and Guinzy (Ref 17) found that coherence is also fairly insensitive to non-Gaussian signals. Second, by comparing run to run, or right wheel-path versus left wheel-path profiles for the same road section, profiles are stationary or nonstationary in the same manner. Since each coherence value is a statistic, confidence limits can be applied, and statistical tests on these coherence values can be made. It is in the uses of coherence analysis that most recent progress has been made at the Center for Highway Research.

Some of the problems which must be avoided in using spectral analysis are provided in Appendix 2. The next two chapters describe how a combination of coherence and statistics has been used in detecting road-following wheel characteristics of the profilometer and differences in construction methods for laying an asphalt base material.

CHAPTER 5. WHEEL REPLACEMENT INVESTIGATIONS

The SD Profilometer was developed so that road profile data could be obtained at high speeds without causing undue traffic interference. A potentiometer mounted to a road-following or sensor wheel is used to detect sensor-wheel and vehicle-body displacements (high-frequency roughness) (Ref 2). The weakest link in the overall system has been found to be this sensor, or road-following wheel, for the following reasons:

(1) the mechanical equipment causes most of the system troubles, at least more so than the electronics;

(2) the usable life of these wheels is too short considering their high cost; and

(3) wheel bounce is not uncommon; e.g., it has been noted at speeds as low as 10 mph on relatively good roads with a PSI > 4.0.

Many of the mechanical problems mentioned can probably be solved only by use of a noncontact probe, which should also greatly enhance operation of the SD Profilometer.

The limited usable life of the sensor wheel, its susceptibility to cutting, and its high cost (about $500), prompted investigations for an inexpensive substitute. Law Engineering is now selling a less expensive wheel for about $300, and recent but incomplete investigations have proven it thus far acceptable in terms of its measurement capabilities. Indications on its usable life have yet to be obtained.

Several inexpensive wheels were acquired but, after careful examinations and testing (e.g., in terms of balancing, construction, visual measuring quality, etc.), all but one were eliminated as a potential replacement wheel candidate. A test was then conducted to determine if any differences could be discerned between the standard $500 wheel delivered with the system (from now on referred to as the control wheel) and this replacement wheel candidate.

To conduct this experiment, the various measurement characteristics which could be used to discern possible differences were first defined. Since a set of PSI prediction equations was developed (Refs 3 and 9), it was decided to use the independent variables in this set of equations as one group of characteristics, i.e., log slope variance and roughness index. Significant differences in these statistics would then indicate significant differences in PSI measurements. As indicated earlier, these two variables, however, provide only one index for the total profile waveform. Thus, it was also decided to use coherence values between repeat runs for each frequency range as a further check on possible wheel differences. The following experiment was then designed (see Fig 4).

Wheel Type	two levels (control wheel and replacement wheel)
Roughness	three levels (PSI values of 4.0, 2.5, and 1.7)
Speed	two levels (50 mph and 20 mph)
Replication	six replications

The analyses of variance for the log slope variance and roughness index statistics are given in Tables 2 and 4, respectively. As noted in these tables, there is no significant difference between wheel type or speed, but only in roughness type, as expected.

From these findings, it can be concluded that the inexpensive wheel could replace the control wheel for computing PSI. Examination of the marginal means (Tables 3 and 5) seems to provide further evidence to support using the replacement wheel, since the marginal mean of the replacement wheel is less than that of the control wheel in the log slope variance analysis; however, just the reverse is true in the roughness index analysis. Thus, it might be suspected, particularly with the large number of of degrees of freedom, that there are no significant differences between the replacement wheel and the control wheel. However, an examination using spectral analysis reveals certain significant differences in characteristics of the two wheels.

For the spectral analysis, coherences between repeat runs were used as the dependent variable. Table 6 provides the general analysis of variance which was then run on all spectral frequencies. For this experiment, the frequency spectrum was divided into 128 frequency bands; hence, there were 128 analysis of variance runs. As noted from this table, the third-order interaction term is used as the experimental error with only two degrees of freedom. To get a better test, the other interaction terms were tested and pooled if not found significant at the 75 percent confidence level. This

				Wheel Type	
				Control Wheel	Replacement Wheel
Roughness	Rough (PSI=1.7)	Speed	50		
			20		
	Medium (PSI =2.5)	Speed	50		
			20		
	Smooth (PSI =4.0)	Speed	50		
			20		

6 Replications per Cell

Fig 4. Experiment design for replacement wheel experiment.

TABLE 2. ANALYSIS OF VARIANCE FOR LOG SLOPE VARIANCE

Source	Degrees of Freedom	Sums of Squares	Mean Squares
Wheel type (1)	1	.04289	.04289
Roughness (2)	2	20.74885	10.37443*
Speed (3)	1	.04714	.04714
12	2	.87306	.43653
13	1	.11598	.11598
23	2	.61547	.30773
123	2	.00036	.00018
Experimental error	60	8.55918	.14265
Total	71	31.00293	

* Significant at 99 percent confidence level.

TABLE 3. MARGINAL MEANS FOR LOG SLOPE VARIANCE

Factors	Categories	Means
1	1 - Replacement wheel	1.96151
	2 - Control wheel	2.01032
2	1 - Smooth	1.22690
	2 - Medium	2.35175
	3 - Rough	2.37909
3	1 - 50 mph	2.01150
	2 - 20 mph	1.96033

TABLE 4. ANALYSIS OF VARIANCE FOR ROUGHNESS INDEX

Source	Degrees of Freedom	Sums of Squares	Mean Squares
Wheel type (1)	1	3870.11278	3870.11278
Roughness (2)	2	2997657.24426	1498828.62213*
Speed (3)	1	11002.62726	11002.62726
12	2	43553.67089	21776.83545
13	1	359.85474	359.85474
23	2	9182.44606	4591.22303
123	2	745.69207	372.84603
Experimental Error	60	114013.74619	1900.22910
Total	71	3180385.39424	

* Significant at 99 percent confidence level.

TABLE 5. MARGINAL MEANS FOR ROUGHNESS INDEX

Factors	Categories	Means
1	1 - Replacement wheel	417.04149
	2 - Control wheel	402.37841
2	1 - Smooth	136.82475
	2 - Medium	464.90328
	3 - Rough	627.40182
3	1 - 50 mph	422.07176
	2 - 20 mph	397.34814

TABLE 6. ANALYSIS OF VARIANCE FOR COHERENCE

Source	Degrees of Freedom	
Wheel type (1)	1	
Roughness (2)	2	
Speed (3)	1	
12	2	Pool when possible
13	1	Pool when possible
23	2	Pool when possible
Error (123)	2	Pool when possible

yields a possible maximum of seven degrees of freedom, as noted. In all cases, at least some terms were pooled.

A few comments should be made in regard to the assumptions of normality necessary for the AOV tests. The coherence samples do not come from a normal distribution, as may be noted in Ref 31. However, for coherence of above about 0.25 and a little less than 1.0, and for 10 or more degrees of freedom, these curves are near normal or at least fairly symmetrical. In addition, the F test in the AOV has been found fairly robust for some symmetrical distributions. The restriction of normality, however, is a stringent restriction in many cases and should be considered when drawing conclusions about the AOV results.

From the results of the coherence AOV test, roughness was found significant as expected at the 99 percent confidence level in most cases down to wavelengths of about 4.5 feet. Speed was found significant at the 97.5 percent level at the 83 and 43-foot wavelengths. This is logical since these frequencies are affected by the filtering action of the analog computer due to the 20-mph and 50-mph speed differences. Most important, the wheel type was found significant at the 99 percent confidence level at wavelength bands corresponding to one-half, twice, and three times the sensor wheel circumference. There was a small mean-square error term corresponding to the sensor wheel circumference, but it was not found to be significant at the 90 percent confidence level. Finally, speed, roughness, and wheel type were all significant at the 99 percent confidence level at the third harmonic of the wheel circumference. From these results, it can be concluded that both wheels bounce (as was noted from the power spectral plots), but that the bounce of the replacement wheel significantly affects the variance amplitudes at harmonics of the wheel circumference, and furthermore, this bounce is a function of roughness type and speed. These conclusions appear quite reasonable, yielding more confidence to the AOV assumptions.

From this experiment it is tempting to use the replacement wheel when computing PSI, particularly where many runs are required over rough sections, which might result in more rapid wear of the sensor wheel. On the other hand, the experiment may indicate the robustness of the log slope variance and roughness index statistics and that the control wheel should be employed for accurate profile measurements.

Repeat runs on many different road sections reveal that at 20 mph and greater speeds, wavelengths less than 4.5 feet (which correspond to the third harmonic of the wheel circumference) are difficult to measure twice unless perhaps exactly the same wheel path is rerun. That is, these coherence values (including their respective confidence limits) tend to drop below 0.5. This result can be accounted for by considering first the wheel bounce problems at these speeds and second the failure to drive the vehicle over exactly the same wheel path. On roads, the longer wavelengths are usually more uniform, whereas the short wavelengths tend to be more localized. In addition, the ability of the vehicle to measure the very small amplitude roughness, particularly on smooth roads, becomes a problem and in most roads cannot be detected.

An example of wheel bounce with the control wheels on a smooth section run at 10 mph is shown in Figs 5 and 6 for both left and right sensor wheels. The PSI computed for the section was 3.7. The section is located on I-45 near Buffalo, Texas. As may be noted, the spectral peaks at 0.645 cycles per foot which is in the same frequency band as the wheel circumference. A more pronounced effect of this bounce exists for the left wheel; however, further plots indicate that this is simply a function of the road traveled.

Coherence between repeat runs seldom yields high coherence values less than about 4.5-foot wavelengths which are much greater than 9 inches, or 0.75 foot (the base length used in computing slope variance). Since wheel bounce peaks up to 0.645 foot, slope variance is clearly biased by both wheel bounce and the inability of the vehicle to travel exactly the same wheel path (i.e., without concerted effort of driving exactly the same wheel path). Furthermore, it should be noted that much of the right-hand portion of the spectrum is nearly horizontal, or that the energies in these frequencies are all about equal. This characteristic can be considered system noise (coherence is one measure of its randomness) and is similar to white noise, i.e., an ensemble whose spectral density is sensibly constant through the frequencies of interest.* Slope variance is thus lower bounded by the system or random noise and probably neasures roughness indirectly through wheel bounce in many cases of smooth sections at high speeds.

These general observations seem to further support the use of the cheaper wheel, particularly for PSI measurements and when the high speeds and longer-wavelength results are desired. For precise road profile measurements and

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*System noise will include not only electronic noise but the failure of the system to obtain exactly the same profile twice. This may be due to electronic noise, the measuring limits of the profilometer, or simply because the exact wheel path was not repeated.

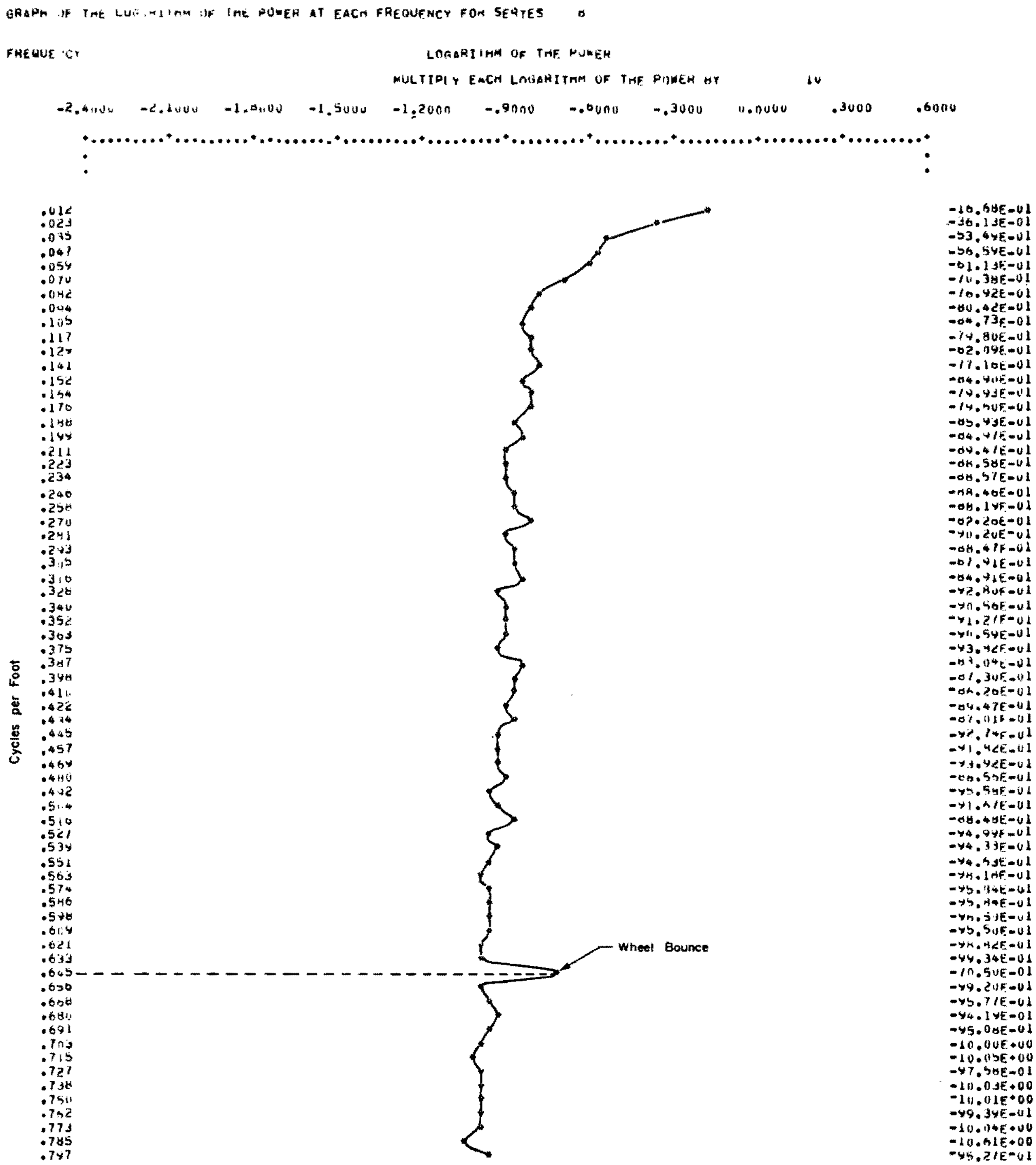

Fig 5. Power spectral plot for left wheel path.

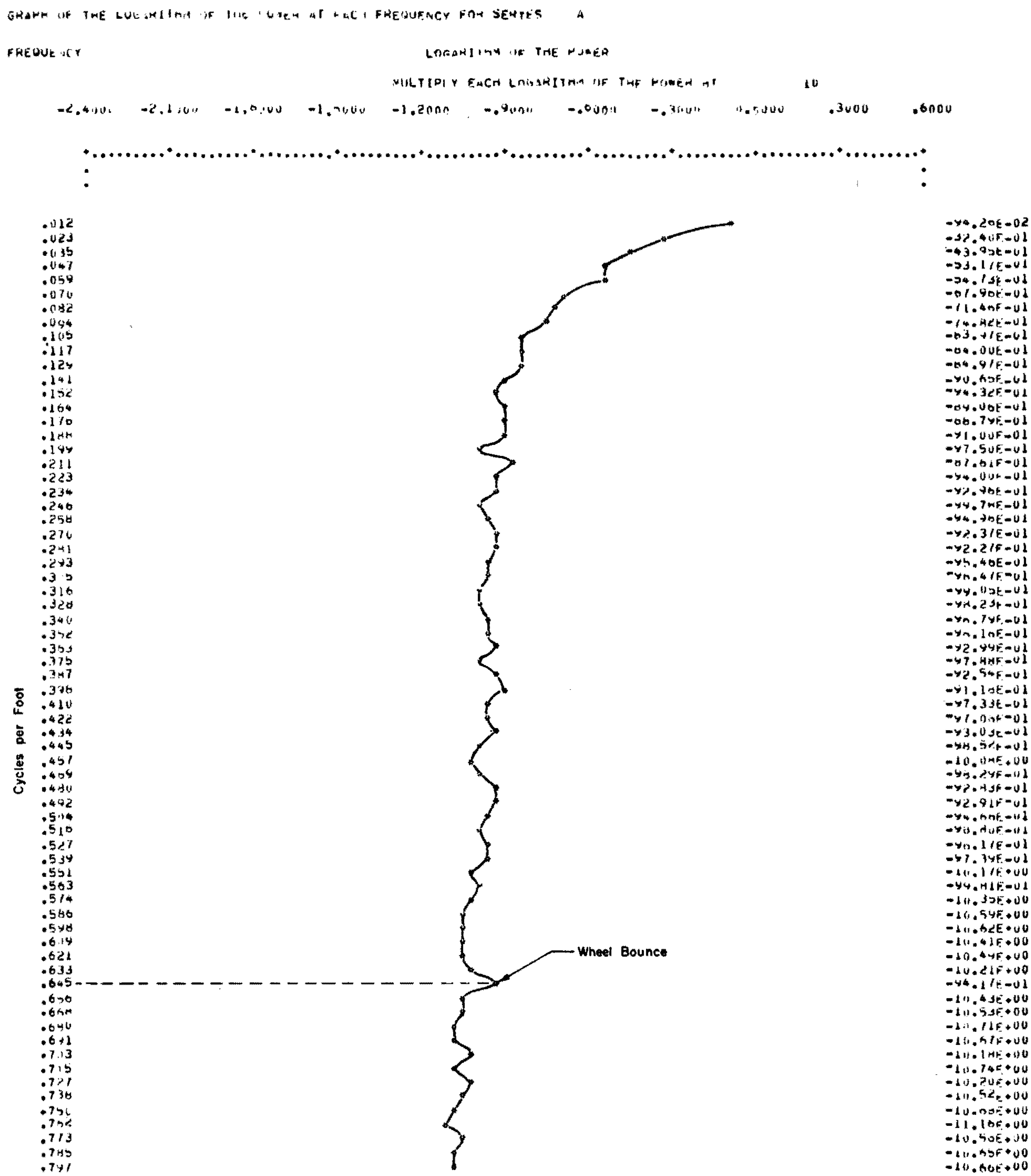

Fig 6. Power spectral plot for right wheel path.

short wavelengths, it would seem, though, that the control wheels should be used and then at a very low speed. This is consistent with the earlier comments on the General Motors use of the profilometer in Ref 11.

With spectral analysis, measuring characteristics of the system for particular road types can be investigated by studying the coherence of repeat runs. Additional use of spectral analysis for determining differences between construction methods is discussed in the next chapter.

CHAPTER 6. CONSTRUCTION CONTROL

In the preceding chapter, the use of spectral analysis for replacement wheel investigations for the SD Profilometer was discussed. This chapter describes some recent results of investigating differences between two methods of laying an asphalt base material on an interstate road (I-45) in Texas. The two are the "traveling straightedge" and the "stretched wire" methods. The stretched wire method had been employed in this particular area, but because of its greater cost over the traveling straightedge method, there was interest in determining if any differences between the methods could be found and, if so, what conclusions could be drawn from these differences. In the following discussions, it will be shown that differences between these methods were found. However, what effects these differences may yield are yet to be determined.

For the experiment, the SD Profilometer was driven over two sample sets: one set was taken in July and one in August for each construction method and where the sample sets or sections in July were geographically different from the set run in August. Each sample set consisted of four 1200-foot randomly selected sections of about 2 miles of road in the July runs and about 1 mile of road in the August runs for each method. The two methods were employed side by side on the northbound and southbound lanes, respectively.

From the road profiles measured with the SD Profilometer, slope variance, cross-slope variance, roughness index, PSI, and spectral analysis were all computed.

The slope variance, cross-slope, roughness index, and PSI values all revealed that the traveling straightedge method yielded a less rough road and, in many of the cases, this statistic was found significant at the 95 percent level. These findings would all seem to indicate that the traveling straightedge should be used, not only because of cost, but also because it actually yielded a less rough road. A few facts, however, should be noted. The material being laid is only the base material; portland cement concrete will be used on top of this base and will thus change the short wavelength roughness. Also, the base length used for computing slope variance (9 inches) is very sensitive to the very small amplitude short wavelengths.

Since these small amplitude bumps are probably taken out or at least changed by the final concrete top layer, the use of slope variance and roughness index as a basis for deciding one method is better than the second for laying an asphaltic base material is not too useful. However, as far as indicating the small roughness differences, they do provide some measure which might be useful for other problems. Table 7 provides the average PSI values for the four sets of runs. For smooth roads such as these, the PSI is almost completely determined from the log slope variance.

To discern possible differences in uniform wavelengths which one method might consistently introduce over the other, coherence between right and left wheel paths or profiles was computed. "T" tests were then made on these values for each frequency range to see if one method had higher coherence for a particular frequency than the second. These tests indicated that there were differences at the 99 percent confidence level for wavelengths in the 24 to 34-foot range and at 95 percent confidence for wavelengths in the 55 to 100-foot range. Tests on the two common sets to insure that their frequencies were not significantly different were made to provide further validation. These yielded the proper indications. Furthermore, the 10-mph runs yielded the same set of results for the 24 to 34-foot results. The 55 to 100-foot band could not be called significantly different at the 95 percent confidence level; however, this band has begun to be affected by the analog computer filtering in the profilometer. The coherence means were a little higher for the 10-mph runs, as expected. Table 8 gives the results of these runs.

These findings, of course, are dependent on how representative the two sets of runs are of all such sections in which these two construction methods were used. The consistency in the two run sets as well as between the 10 and 20-mph runs, however, lends strong support to the measurement accuracies.

In regard to the statistical characteristics of coherence, the coherence values were obtained at about 30 degrees of freedom from a population that is fairly symmetrical. The normality assumption of this population, however, is not as important because of the central limit theorem, particularly with the peaks in these distributions and the number of degrees of freedom used (14 for the 20-mph runs) in the "T" tests.

TABLE 7. AVERAGE PSI VALUES* (BASE MATERIALS)

Run Set	Traveling Straightedge	Stretched Wire
July sets 1 and 2	3.7	3.4
August sets 3 and 4	3.6	3.4

* Computed from 20-mph equation.

TABLE 8. WAVELENGTH ANALYSIS

	Mean Coherence at 20 mph		
Wavelength Bands (feet)	Traveling Straightedge	Stretched Wire	Notes
24 to 34, 20 mph	0.751 (0.851 at 10 mph)	0.524 (0.610 at 10 mph)	Significant with 99% confidence
55 to 100, 20 mph	0.960 (0.877 at 10 mph)	0.815 (0.806 at 10 mph)	Significant with 95% confidence

Further investigation of the physical characteristics of the longitudinal grade reference ski used in the northbound lane where the frequency band, 24 to 34 feet, was found to be significant revealed a definite relationship with the ski dimensions and this band. Figure 7, a schematic of the ski dimensions, shows that, although the 40-foot frame is rigid, spring-loaded metal shoes are used for roadway contact. Without these shoes, the ski would tend to generate 40-foot wavelengths, as shown in Fig 8. With these spring-loaded shoes, however, the ski frame deflected only when the spring for the contacting shoe had reached its maximum contraction. This tends to reduce the width of these bumps to values between 20 to 40 feet, which most likely tend to be distributed around 30 feet, or in the 24 to 32-foot wavelength bands. The other band found significant is in the vicinity of the second harmonic.

By using spectral analysis, differences between roads constructed by the two methods were discerned. Determining such differences is one problem; relating these differences to pavement rideability or deterioration is another. For example, even though the traveling straightedge method might have introduced these wavelength differences, its effect on riding quality might be negligible. The latter part of Chapter 7 discusses a method of relating PSI to wavelengths in a road with the use of coherence.

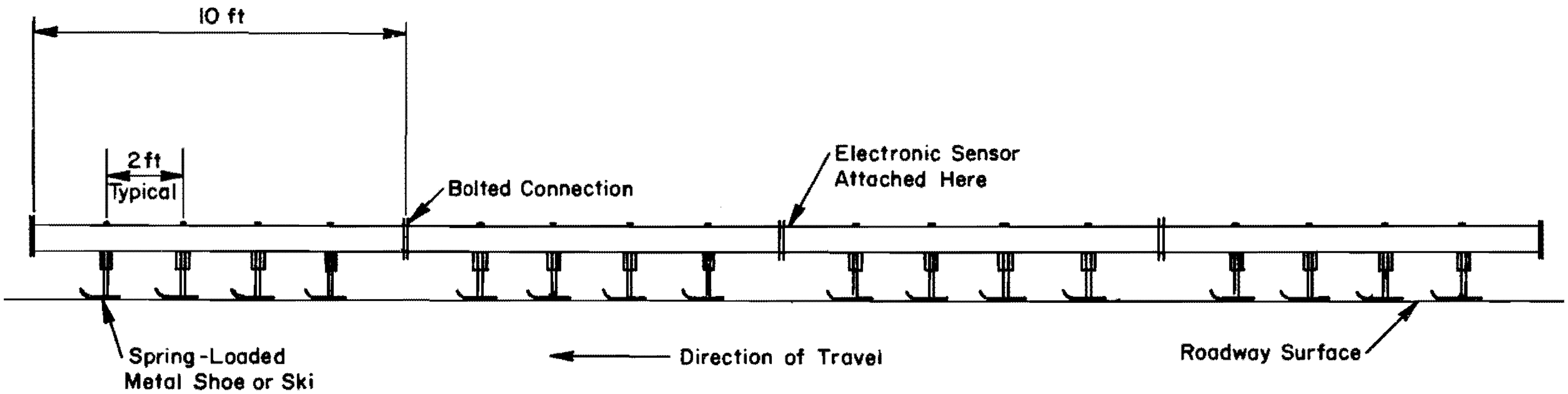

Fig 7. Longitudinal grade reference ski.

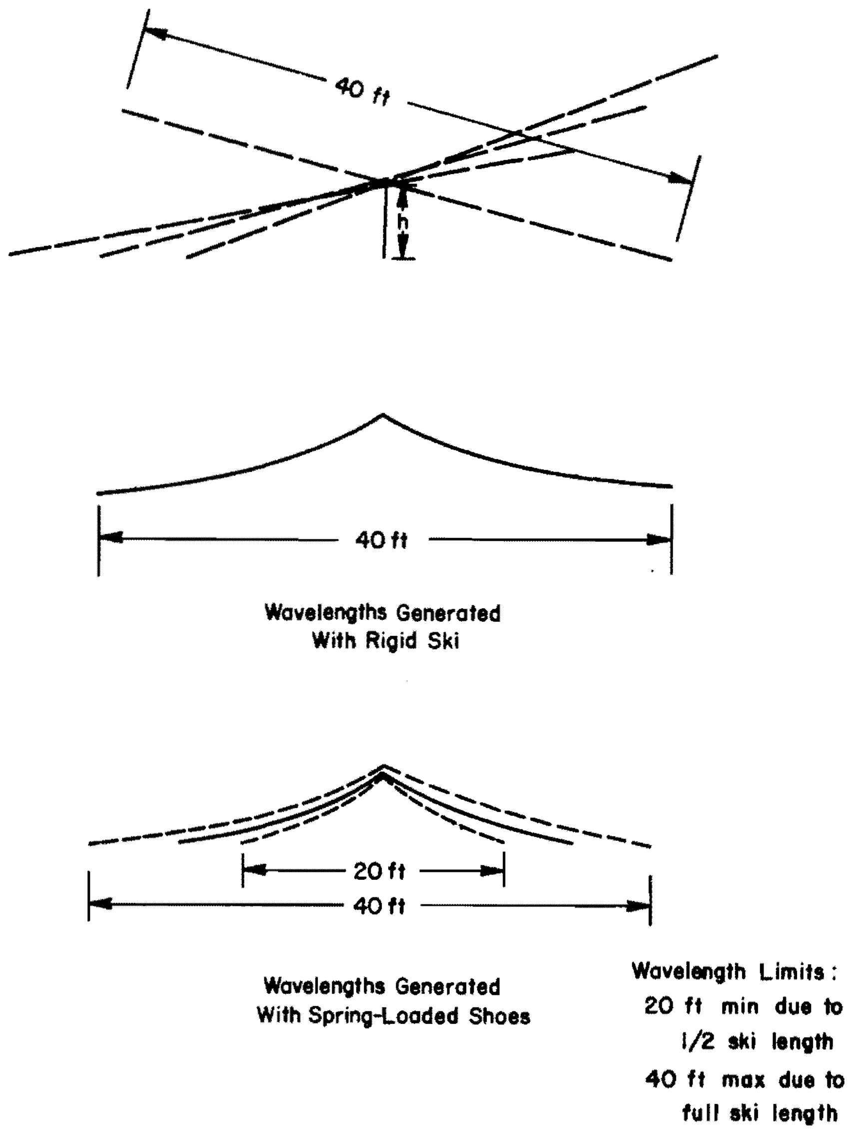

Fig 8. Wavelengths generated by longitudinal grade reference ski transversing abrupt bump.

CHAPTER 7. ADDITIONAL SYSTEM INVESTIGATIONS

This chapter discusses miscellaneous investigations to discern system variations. First, differences between A-D processing systems are investigated. Results from this investigation also provide some indication of the variations of slope variance and roughness index. Next, past runs over fifteen test sections, as well as some other sections, are used to evaluate the usefulness of the PSI prediction models. A new 20-mph equation is provided, along with a shortened version of this equation. Finally, some comments on the use of spectral analysis for generating additional PSI equations are discussed.

System Processing Variations

As mentioned in Chapter 2, the profile measuring system initially used an XDS 930 computer for A-D operations. Later, an HP 2115 computer system was purchased for this purpose. Since the new HP system is not set up to provide simultaneous sampling of right and left profile signals, only alternate channels are sampled for each distance pulse (see Ref 2), resulting in only half as many data points. An initial experiment revealed variations in slope variance because of this alternative sampling. Hence, an experiment was conducted to determine the significance of these variations. Figure 9 illustrates the experiment design used. As noted, three levels of roughness (smooth, medium rough, and rough) were used, two speeds (50 and 20 mph), three repeat runs, and three repeat samplings were run for each system type. For the XDS 930 system, both simultaneous sampling and alternative sampling were used, thus yielding the three levels of processing computer types. The analyses of variance and the marginal means for both log slope variance and roughness index for each wheel type are provided in Appendix 3. As may be noted from these tables, only roughness is significant, as expected.

From the results of this experiment, it can be concluded that there are no differences between using alternate sampling from the HP 2115 system and using simultaneous sampling (or every sample) from the XDS 930 system.

				Processing Computer Type								
				XDS (Simultaneous)			XDS (Alternate)			HP		
				Runs			Runs			Runs		
				1	2	3	1	2	3	1	2	3
Roughness	Rough (PSI=1.7)	Speed	50									
			20									
	Medium (PSI=2.5)	Speed	50									
			20									
	Smooth (PSI=4.0)	Speed	50									
			20									

3 Replications per Cell

Fig 9. Experiment design for investigating A-D sensitivity.

PSI Model Evaluations

Evaluations of some of the various PSI models reported on in Refs 3 and 9 were obtained by repeat runs primarily over 15 test sections in the Austin area and several sections on I-45 near Buffalo. The purpose in making most runs was to investigate and obtain confidence in the operating characteristics of the measuring system. The runs near Buffalo were for the construction control studies discussed in Chapter 6. However, these runs did provide some indication of the stability of the models used, and also helped to establish two additional models. It has generally been found that in most cases, PSI variations between repeat runs are small, at least within the standard error of the model, and for the most part yield reasonable PSI readings. There have been a few sections found, however, in which one or more of the equations reported in Ref 3 will yield a bad PSI reading. A new equation was generated from the old 20-3 or 20-mph slope variance equation by running the regression analysis program on centered data (see Ref 3, page 109). This centering of the data, although not significantly increasing the correlation coefficient, tends to give good results in almost all cases. This new equation is given in Table 9.

For cases of roads above about 2 PSR with normal texture and negligible patching and cracking, a shortened form of the equation can be used which consists only of slope variance. This shortened equation is given as

$$PSI = 3.27 - 1.37(\log SV - 0.78) \quad (7.1)$$

The R^2 for this equation is 0.81 with a standard error of 0.45.

Use of Spectral Analysis for Computing PSI

Since spectral analysis can be used for characterizing the various wavelengths contained in a road, the correlation of the characteristics bands with pavement rideability should be possible. For example, successful correlation of coherence values between repeat runs of right and left wheel for each frequency band with the PSR ratings would yield a new method for computing PSI as a function of wavelengths in the road. It would also provide a measure of which wavelengths are most undesirable to a rider and, hence, could be used as a scale for specifications in construction control.

TABLE 9. CENTERED PSI EQUATION

(R^2 = 0.94)

(Standard Error = 0.341)

Variable	Coefficient	x(Variable - Mean)
Constant	2.79390	
Log Slope Variance	-0.77413	(ALGSV - 0.78201)
Cracking	0.00404	(CRACK - 49.98911)
Cross Slope x Road Variance	.31788	(XSV x RV - 4.25945)
Rut Depth Variance	- .27446	(RDVAR - 1.89518)
Texture	- .03684	(AVG TEX - 6.42750)
Cracking and Patching	- .00593	(C + P - 80.95696)
Cross Slope x Texture	- .06803	(XSV x TEX - 11.18080)
Crack x Rut Depth	- .00040	(C x RDV - 153.56028)
Patch x Rut Depth	.00243	(P x RD - 21.22633)
Patch x Texture	- .00103	(P x TEX - 82.91263)
Rut Depth x Texture	.01544	(RDV x TEX - 15.79056)

$$PSI = Constant + C_1(V_1 - M_1) + C_2(V_2 - M_2) + \ldots C_m(V_m - M_m)$$

where

Constant = constant term above,

C_i = coefficient term above,

V_i = variable term above,

M_i = mean term above.

It would be much more meaningful than slope variance, since various wavelength bands are physically more easily accounted for than a single statistic such as slope variance or roughness index measurements.

CHAPTER 8. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This report concludes work done on Project 3-8-63-73, "Development of a System for High-Speed Measurement of Pavement Roughness." The report includes a summary of work done on this project and references the appropriate reports which described this work. In addition, the report also includes new research conducted during the past year on the topics of replacement wheel analysis, construction control investigations, Mays Road Meter correlation analysis, PSI validation investigations, and power spectral usage investigations.

Spectral analysis techniques and their use in most of the above mentioned topics are discussed in detail. These discussions include a brief summary of the various terms and definitions common in spectral analysis, followed by the use of spectral analysis in identifying a suitable inexpensive replacement wheel, its use in construction control, and some general comments on current investigations of its use in obtaining a new PSI prediction equation. An appendix is included which briefly describes some of the common pitfalls which must be avoided in using spectral analysis.

Some of the more important conclusions drawn from this report are

(1) The SD Profilometer is a very useful device for providing road profile data but it must be included in a total system involving A-D and digital processing operations.

(2) The set of PSI equations developed during the project and reported on in Research Report 73-3 and in this report have been found to provide good results in most cases.

(3) Spectral analysis has been found to be a very useful tool for analyzing road profile data obtained with the SD Profilometer.

(4) Through the combined use of spectral analysis and slope variance, conditions under which an inexpensive sensor wheel can be satisfactorily used in place of the much more expensive wheel delivered with the system are defined.

(5) Spectral analysis is useful for establishing measurement accuracies of the SD Profilometer for the various operating speeds.

(6) Spectral analysis can be successfully used for discerning differences in various construction techniques not discernable with other common statistics such as slope variance.

(7) It may be possible to use spectral analysis for obtaining a measurement of which wavelengths are most bothersome to the rider and for determining how the various wavelengths change as a pavement ages.

It is recommended that further studies be continued in

(1) the use of the SD Profilometer for research purposes, including its use for making data runs for Project 118, "Study of Expansive Clays in Roadway Structural Systems," Project 123, "A System Analysis of Pavement Design and Research Implementation," and other such projects;

(2) further investigations of the sensitivity of the PSI prediction models;

(3) comparison runs for the purpose of calibration of less sophisticated devices used by the sponsor, such as the Mays Road Meter; and

(4) use of spectral analysis in construction control, development of a new set of PSI prediction models, and determining how various wavelengths change as a pavement deteriorates.

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APPENDIX 1

A BRIEF DISCUSSION OF SPECTRAL ANALYSIS

APPENDIX 1. A BRIEF DISCUSSION OF SPECTRAL ANALYSIS

The term spectral analysis as it is employed in this report includes all techniques for summarizing time series functions by separating these functions into their frequency components. A detailed discussion of spectral analysis techniques such as Fourier transformations, power spectrum, and coherence will not be provided, but information on these analysis tools can be found in the listed references. A brief description of these terms is given in order to supplement the text.

In 1807, Fourier discovered that an "arbitrary" function could be expressed as a linear combination of sine and cosine terms. The mathematical transformation which performs this operation on a function to transform data from the time domain to the frequency domain was appropriately named a Fourier transformation.

The following equation provides the formula for this transformation for a smooth function:

$$G(t) = \frac{a_o}{2} + \sum_{n=1}^{\infty} (a_n \cos nt + b_n \sin nt) \qquad \text{(A1.1)}$$

where

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(t) \cos nt \, dt \quad \text{, and}$$

$$b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(t) \sin nt \, dt \; - \pi \le t \le \pi$$

Figure 10 depicts a very simple waveform, composed of only two sine waves, which illustrates a simple example of this transformation. The more

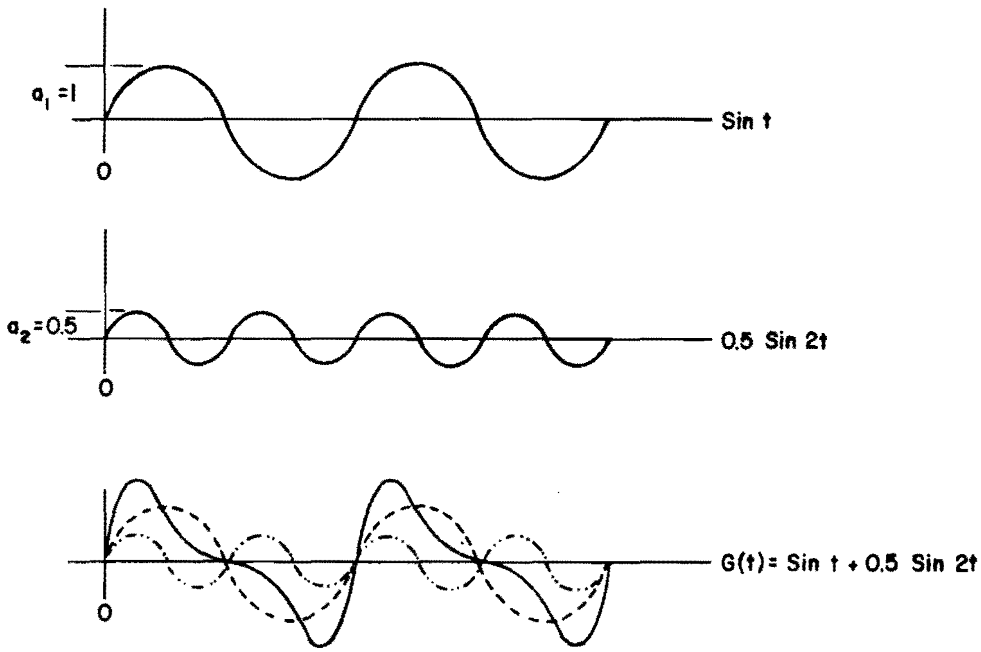

Fig 10. Complex wave consisting of first and second sine terms of its Fourier coefficients.

complicated waveforms can, of course, consist of an infinite number of these terms.

Equation A1.1 is one of several formulations of the Fourier transformation. Another formulation is given by the formula

$$S(f) = \int_{-\infty}^{\infty} G(t) \cdot e^{-2\pi ft} \, dt \qquad (A1.2)$$

$$G(t) = \int_{-\infty}^{\infty} S(f) \cdot e^{i2\pi ft} \, df \qquad (A1.3)$$

The exponential terms can easily be derived using trigonometric identities. For road profile analysis, the function $G(t)$ is the road profile as measured with the SD Profilometer, where t is the time or distance variable.

Transforming profile data from the time or distance domain to the frequency domain is one form of spectral analysis. However, although this form may have certain uses, it is of limited value because of its dependence on time or distance. That is, a profile waveform of constant shape will have the same energy or variance at any one frequency, but how this energy or variance is distributed between the sine and cosine terms depends on the phase shift or time position of the profile waveform. To obtain only the energy or variance of the profile waveform at each frequency, the amplitude of each sine and cosine term for each frequency is squared, with the phase angle being obtained from the arctangent of the ratio of the amplitudes. This spectrum, consisting only of amplitude and phase angles, is referred to as the power spectrum.

The autocovariance of a function, $x(t)$, at lag λ may be given as

$$C(\lambda) = \lim_{T \to \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t) \cdot x(t + \lambda) dt \qquad (A1.4)$$

It can be shown that the power spectrum is also the Fourier transform of the autovariance function, or

$$P(f) = \int_{-\infty}^{\infty} C(\lambda)e^{-i2\pi f\lambda}\, d\lambda \qquad (A1.5)$$

These equations have been discussed because power spectrum is relatively unfamiliar to some readers as a means of analyzing road profile data. From the above interpretation, we now see that power spectrum, so commonly used in communication engineering, geophysics, and other sciences, can also be referred to as a covariance spectrum (Ref 12). Thus, $P(f)df$ represents the contribution to the variance of the road profile waveform from frequencies f and $(f + df)$. Power spectrum, therefore, is another statistic, like slope variance, except that it provides a set of spectral values or variance densities for a road profile section, whereas slope variance or simple variance yields only one such value. It is this fact which prompted an interest in the investigation of spectral analysis as a means of providing some measure of roadway roughness.

Information on energy differences between two or more time series can be obtained with cross-spectrum analysis. Whereas power spectrum is the Fourier transform of the autocovariance, the cross-power spectrum is the Fourier transform of the crossvariance function between two separate time signals. Coherence can be thought of as a kind of normalized cross-power spectrum where its values range from zero to one. The coherence function is defined by the following equation:

$$\gamma xy = \begin{cases} \dfrac{\left|P_{xy}(w)\right|}{\sqrt{P_{xx}(w)P_{yy}(w)}} \text{ when } P_{xx}(w) \text{ and } P_{yy}(w) > 0 \\ 0 \text{ when } P_{xx}(w) \text{ and } P_{yy}(w) = 0 \end{cases} \qquad (A1.6)$$

where

$P_{xy}(w)$ = the cross-power spectrum between $x(t)$ and $y(t)$,

$P_{xx}(w)$ = the power spectrum of $x(t)$,

$P_{yy}(w)$ = the power spectrum of $y(t)$.

Also associated with coherence is a phase lag between $x(t)$ and $y(t)$.

Multiple coherence is analogous to the multiple-correlation matrix in statistics, and just as significance levels are used in correlation analysis, confidence levels may be used in cross-spectrum analysis. Goodman (Ref 14) discusses the theory and practices of cross-spectrum analysis. References 15 and 16 provide a good discussion of some of the relations and uses of cross-spectrum analysis.

APPENDIX 2

COMPUTATIONAL PROBLEMS IN USING SPECTRAL ANALYSIS FOR ANALYZING ROAD PROFILE DATA

APPENDIX 2. COMPUTATIONAL PROBLEMS IN USING SPECTRAL ANALYSIS FOR ANALYZING ROAD PROFILE DATA

This appendix briefly discusses some of the common problems which must be avoided if accurate measurements in spectral analysis are to be obtained. Greater details of these problems may be found in Refs 10, 12, and 14 through 31.

Aliasing

The problem of aliasing is probably the best known of the pitfalls that will be discussed. This problem results from the fact that high-frequency components of a time function, such as a profile signal, can impersonate low frequencies if the sampling rate is too low. Figure 11 illustrates this effect in which both high-frequency and low-frequency signals are sharing the identical sample points. Once sampled, there is no way of filtering this high-frequency impersonation out of the data. The solution to the problem is to insure that the sampling rate is at least twice as high as the highest frequency present.

Leakage

The problem of leakage occurs because of the use of a road profile signal of finite length. This usage may be thought of as multiplying the actual road profile signal by a rectangular data window which limits the infinite profile to finite lengths, as illustrated in Fig 12. Since multiplication in the time domain is equivalent to convolution in the frequency domain, the Fourier transform of the finite profile signal results in the transformed profile signal being convolved with a $\frac{\sin x}{x}$ function. For example, had the profile signal been a pure cosine wave, its Fourier transform would have been limited to only one point on the frequency axis (Fig 13). However, because of its finite length caused by the rectangular data window, the actual result is as depicted in Fig 13. As a result, a loss of energy due to these side lobes, as shown in this figure, occurs. The problem may be alleviated by using a

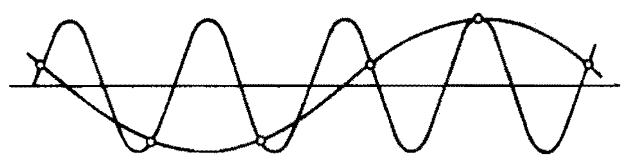

Fig 11. Aliasing effect of high-frequency wave (after Ref 18).

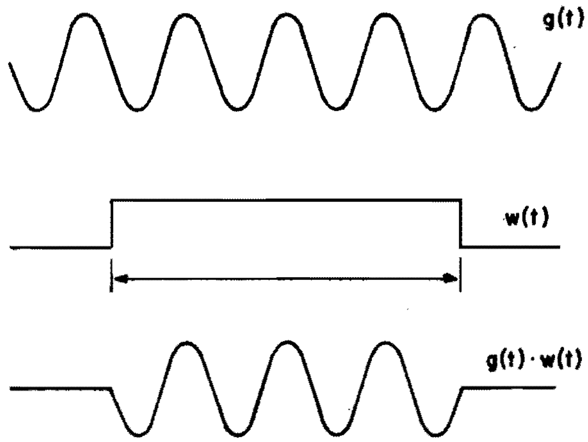

Fig 12. The rectangular data window result when using finite data record (after Ref 18).

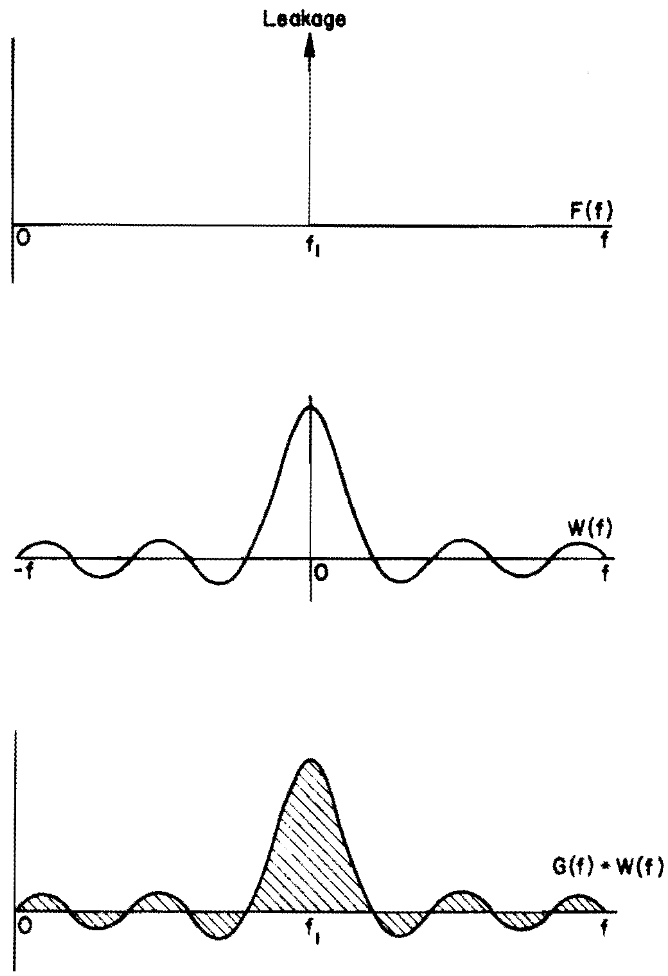

Fig 13. Results of convoluting rectangular data window with sine wave (after Ref 18).

different type of data window, one which, when transformed, appears more as a rectangular function (see Ref 12).

Picket-Fence Effect

Because of the multiplication of the profile signal by a finite-length data window, the effect of the FFT algorithm is similar to the use of a bank of bankpass filters, as indicated in Fig 14, which depicts the main lobes of the spectral window. The width of each main lobe is inversely proportional to the original profile length. To reduce this ripple distortion, the record length analyzed can be extended by a set of samples identically zero. This results in a redundant FFT algorithm by computing a set of Fourier coefficient terms lying between the original terms. This overlapping effect considerably reduces the amount of ripple, as shown in the figure.

Trend Removal

As discussed earlier, the filtering in the SD Profilometer attenuates the low-frequency and dc components from the profile signal, thus yielding a mean profile signal of approximately zero. It is the fact that this mean may not be identically zero which causes some distortion in the low-frequency spectral estimates. Blackman and Tukey (Ref 12) illustrate the effects on the spectral coefficients when this mean is only near zero and, as noted, the effects can be significant. This is the reason for their statement that it will almost never be wise to fail to use some type of trend removal function in the spectral analysis.

Degrees of Freedom

As in all statistical analysis, a reasonable number of degrees of freedom should be used when computing the spectral estimates. The power spectra estimate for a given frequency will vary about the population spectrum according to the chi-square distribution. The degrees of freedom, which are a function of the spectral window used, should then be large enough so that usable confidence limits can be obtained. In practice for road profile data, 20 or more degrees of freedom have been found desirable. Degrees of freedom are also

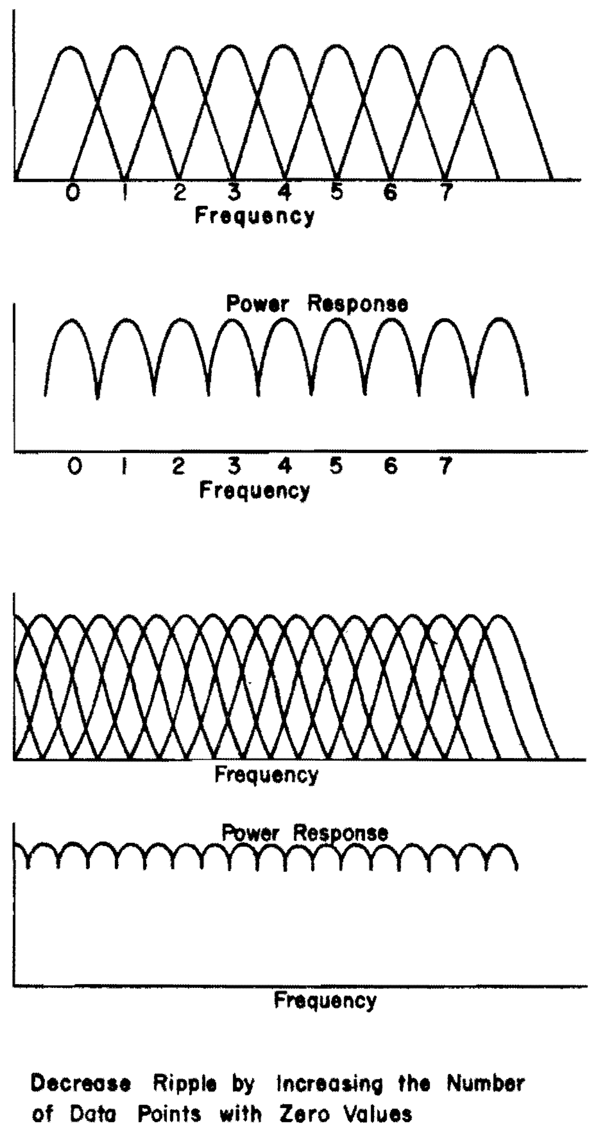

Fig 14. Picket-fence effect (after Ref 18).

extremely important in coherence analysis* (see Ref 13 for the distribution of coherence). Coherence quickly becomes unreliable if the degrees of freedom are insufficient and may even be unity if the degrees of freedom are too low. Too many degrees of freedom, however, can result in too-low coherence values if the spectral estimates are not constant within the spectral data interval (see Ref 10).

Prewhitening

Prewhitening, as defined by Blackman and Tukey, is the process of prefiltering the profile data so as to make the spectral density more nearly constant. This prefiltering, for example, can be used in the above section so that more degrees of freedom can be obtained for coherence computation. Prewhitening is discussed in detail by Blackman and Tukey and in many of the listed references.

* The establishment of confidence intervals on the coherence values can be made using the tables of Ref 29 for up to 21 degrees of freedom. Reference 16 provides additional graphs which can be used for obtaining 80 percent confidence limits on samples up to 200 degrees of freedom. Programs produced by Walker provide coherence distribution data for a large variety of population coherences, degrees of freedom, and confidence limit combinations (Ref 31).

APPENDIX 3

ANALYSIS OF VARIANCE AND MARGINAL MEAN TABLES

FOR A-D SENSITIVITY EXPERIMENT

TABLE 10. ANALYSIS OF VARIANCE FOR LOG SLOPE VARIANCE, RIGHT SIDE

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares
System (1)	2	.00511	.00256
Roughness (2)	2	31.72274	15.86137*
Speed (3)	1	1.50659	1.50659
Runs (4)	2	.25955	.12977
12	4	.00975	.00244
13	2	.02280	.01140
14	4	.00764	.00191
23	2	.09756	.04878
24	4	2.15458	.53864
34	2	.09318	.04659
123	4	.02623	.00656
124	8	.01951	.00244
134	4	.14630	.03657
234	4	.81795	.20449
1234	8	.16833	.02104
Experimental Error	108	11.07608	.10256
Total	161	48.13389	

* Significant as expected.

TABLE 11. ANALYSIS OF VARIANCE FOR LOG SLOPE VARIANCE, LEFT SIDE

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares
System (1)	2	.01572	0.00786
Roughness (2)	2	26.84688	13.42344
Speed (3)	1	.03917	0.03917
Runs (4)	2	1.15068	0.57534
12	4	.01483	.00371
13	2	.01824	.00912
14	4	.01756	.00439
23	2	.36300	.18150
24	4	2.40169	.60042
34	2	.46018	.23009
123	4	.02102	.00526
124	8	.04300	.00538
134	4	.01737	.00434
234	4	.89983	.22496
1234	8	.06953	.00869
Experimental Error	108	12.89168	.11937
Total	161	45.27039	

* Significant as expected.

TABLE 12. ANALYSIS OF VARIANCE FOR ROUGHNESS INDEX, RIGHT SIDE

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares
Processing type (1)	2	151.01538	75.50769
Roughness (2)	2	4044173.05266	2022086.52633*
Speed (3)	1	273.55452	273.55452
Runs (4)	2	44.08257	22.04128
12	4	51.64532	12.91133
13	2	90.99662	45.49831
14	4	200.31298	50.07824
23	2	9476.68158	4738.34079
24	4	4497.76645	1124.44161
34	2	955.68015	477.84007
123	4	71.04192	17.76048
124	8	779.48952	17.43619
134	4	162.19280	40.54820
234	4	2165.84543	541.46136
1234	8	959.53273	119.94159
Experimental Error	108	1576959.33680	14601.47534
Total	161	5641012.22742	

* Significant as expected.

TABLE 13. ANALYSIS OF VARIANCE FOR ROUGHNESS INDEX, LEFT SIDE

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares
System (1)	2	54.75315	27.37657
Roughness (2)	2	2012750.04026	1006375.02013*
Speed (3)	1	36.76066	36.76066
Runs (4)	2	5390.49261	2695.24630
12	4	181.11519	45.27880
13	2	95.22075	47.61038
14	4	194.28281	48.57070
23	2	2389.33898	1194.66949
24	4	10669.76007	2667.44002
34	2	4429.34127	2214.67064
123	4	128.93069	32.23267
124	8	290.96125	36.37016
134	4	86.03027	21.50757
234	4	10180.23751	2545.05938
1234	8	158.43703	19.80463
Experimental Error	108	1189722.13558	11015.94570
Total	161	3236757.83808	

*Significant as expected.

TABLE 14. MARGINAL MEANS FOR LOG SLOPE VARIANCE, RIGHT SIDE

Factors	Categories	Means
1	1 - HP	1.65899
	2 - XDS (Simultaneous)	1.65168
	3 - XDS (Alternate)	1.66543
2	1 - Smooth	1.04484
	2 - Medium	1.86022
	3 - Rough	2.07104
3	1 - 50 mph	1.56226
	2 - 20 mph	1.75514
4	1 - Run 1	1.61051
	2 - Run 2	1.65708
	3 - Run 3	1.70851

TABLE 15. MARGINAL MEANS FOR LOG SLOPE VARIANCE, LEFT SIDE

Factors	Categories	Means
1	1 - HP	1.45934
	2 - XDS (Simultaneous)	1.44766
	3 - XDS (Alternate)	1.43522
2	1 - Smooth	.87752
	2 - Medium	1.66162
	3 - Rough	1.80308
3	1 - 50 mph	1.43186
	2 - 20 mph	1.46296
4	1 - Run 1	1.36305
	2 - Run 2	1.41667
	3 - Run 3	1.56251

TABLE 16. MARGINAL MEANS FOR ROUGHNESS INDEX, RIGHT SIDE

Factors	Categories	Means
1	1 - HP	322.46764
	2 - XDS (Simultaneous)	320.75249
	3 - XDS (Alternate)	323.02023
2	1 - Smooth	118.11213
	2 - Medium	345.04612
	3 - Rough	503.08210
3	1 - 50 mph	320.78065
	2 - 20 mph	323.37958
4	1 - Run 1	322.45753
	2 - Run 2	322.44035
	3 - Run 3	321.34247

TABLE 17. MARGINAL MEANS FOR ROUGHNESS INDEX, LEFT SIDE

Factors	Categories	Means
1	1 - HP	266.27961
	2 - XDS (Simultaneous)	267.43064
	3 - XDS (Alternate)	266.12899
2	1 - Smooth	111.38435
	2 - Medium	320.46601
	3 - Rough	367.98887
3	1 - 50 mph	267.08944
	2 - 20 mph	266.13672
4	1 - Run 1	259.50444
	2 - Run 2	266.70151
	3 - Run 3	273.63329

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