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Development of Procedures for the Calibration of Profilographs

Research, Development, and Technology
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FOREWORD

Profilographs are widely used for measuring the smoothness of new pavements. All currently used profilographs are of similar configuration, established about 20 years ago. There are some minor variations, both in the construction and in the method of data analysis. The research reported here was motivated by the trend in many highway departments to improve the smoothness of new pavements. The research objective was to determine if the precision and sensitivity of profilographs can be improved through calibration or design changes. Since profilographs' response depends on the pavement roughness wavelength, the range of wavelengths of primary concern was first established. Based on considerations of rideability and pavement damage by heavy trucks, a range of wavelengths of 1.6 to 32 feet was selected. This is the critical roughness for speeds between 35 and 65 mph.

Several researchers have shown that none of these profilographs can produce accurate presentations of the pavement roughness profile. Amplitudes of some wavelengths in the pavement roughness spectrum are magnified while some are attenuated. Recommendations for a somewhat improved profilograph design are given, but the inherent limitations of profilographs makes the reliability of data on very smooth pavements questionable. In spite of these shortcomings, profilographs continue to be used since no inexpensive alternative is presently available.

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NOTICE

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16. Abstract

A review of current information concerning the methods and equipment for measuring the roughness of new pavements revealed that most States use rideability criteria to determine the quality of newly laid pavement, with the California profilograph as the dominant type of equipment employed. Bump specifications, which have been used throughout the highway construction industry for many years, are useful in controlling individual vertical deviations of pavement profile, but provide no information on the overall roughness over a longer distance. A full-scale testing program investigated the basic roughness characteristics of new pavements, represented by power spectral density functions which were then used to generate average-profile data. Road roughness measuring devices, including the California, Rainhart, and Ames profilographs, profilometer, and Mays meter, were evaluated on the basis of frequency response, precision, repeatability, reliability, and ease of operation. Researchers sought to determine whether correlations can be established between the profilographs and other roughness measuring devices. Computer simulation of a profilograph, in which the effect of varied design parameters on profilograph performance was investigated, yielded the formulation of an optimal profilograph design as a general optimization problem.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

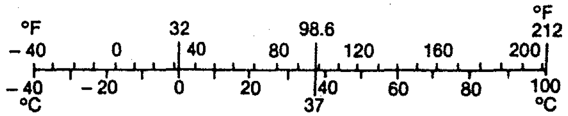
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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1. INTRODUCTION

OBJECTIVES

The main objectives of this study were:

- To develop calibration procedures for various types of profilographs and to determine if correlations can be established between the profilographs and with other roughness measuring devices.
- To conduct full-scale tests to evaluate equipment for measuring the roughness of new or newly surfaced pavement.
- To develop computer simulations for supporting the analysis of the field test data.

CURRENT INFORMATION ON METHODS AND EQUIPMENT FOR MEASURING ROUGHNESS

Current information concerning the methods and equipment used for measuring roughness of new pavements was reviewed at the beginning of this study. The primary sources of information in the review were:

- Summary Results of the 1987 AASHTO Rideability Study.[1]
- Questionnaire to Pavement Construction Engineers. ASTM E-17 Committee on Traveled Surface Characteristics, 1986.[2]
- Questionnaire to State Departments of Transportation. ASTM E-17 Committee on Traveled Surface Characteristics, 1987.[3]

The results of the three surveys, in which 36 States are represented, are summarized in table 1. Roughness measuring equipment and acceptance criteria based on overall quality (rideability) as well as on individual defects (bumps) of pavements are presented. Of the States listed in table 1, 80 percent apply rideability criteria, and 98 percent (all except one State) have bump specifications. Within the States using rideability criteria, 75

Table 1. Summary of information on currently used methods and equipment in measuring roughness during construction.

	PCC Pavement					Asphalt Pavement				
	Rideability		Bumps			Rideability		Bumps		
State	Equip.	IPM	Equip.	Inches	Feet	Equip.	IPM	Equip.	Inches	Feet
Alabama	RAH	12	NA			NA		STE10	1/4	10
Alaska	NA		NA			NA		STE10	3/16	10
Arizona	CAL	7	NA			NA		STE10	1/8	10
Arkansas	RAH	12	RAH	3/10	10	NA				
California	CAL	7	CAL	3/16	25	CAL	7	CAL	3/16	25
Colorado	CAL	7	NA			NA		STE10	3/16	10
Connecticut	CAL	12	STE10	1/4	10	NA		STE10	1/4	10
Florida	CAL		NA			NA		STE15	3/16	15
Hawaii	CAL	7	STE10	1/8	10	NA		STE10	3/16	10
Idaho	CAL	7	STE			CAL	7	STE		
Illinois	CAL	15	STE10	1/8	10	NA		STE10	1/8	10
Indiana	CAL	12	STE16	1/4	16	CAL	12	STE16	1/4	16
Iowa	CAL	15	CAL	1/2	25	CAL	15	CAL	1/2	25
Kansas	CAL	12	CAL	1/10	25	NA		STE10	3/16	10
Kentucky	RAH	12	STE10	1/8	10	MAY	psi 3.6	STE10	1/8	10
Louisiana	NA		STE10	1/8	10	NA		STE10	1/8	10
Maine	NA		STE16	1/4	16	NA		STE16	1/4	16
Maryland	NA		STE10	1/8	10	NA		STE5	1/8	10
Michigan	PRF	55	STE10	1/8	10	NA		STE10	1/8	10
Minnesota	BPR	85	STE10	1/8	10	NA		STE10	1/8	10
Mississippi	CAL	7	STE10	3/10	25	NA		CAL	3/10	25
Missouri	NA		STE10	1/8	10	NA		STE10	1/8	10
Montana	CAL	10	NA			NA		STE10	3/16	10
Nebraska	CAL	12	STE10	1/8	10	NA				
Nevada	CAL	7	CAL	3/10	25	NA		STE12	1/8	12
New Jersey	NA		STE10	1/8	10	NA		STE10	1/8	10
N. Carolina	RAH	7	RAH	3/10	25	NA		STE10	1/8	10
Ohio	CAL	12	CAL	1/2	25	NA		STE10	1/8	10
Oregon	CAL	7	NA			NA		STE12	1/4	12
Pennsylvania	CAL	15	CAL	3/10	25	NA		STE10	3/16	10
S. Carolina	MAY	70 @50	STE10	1/8	10	MAY	IPM 40	STE10	1/8	10
S. Dakota	CAL	10	CAL	3/10	25	NA		STE10	1/4	10
Tennessee	MAY	40 @50	STE12	1/8	12	MAY	IPM 40	STE12	1/4	12
Utah	CAL	7	CAL	3/10	25	NA		CAL	3/10	25
Washington	CAL	7	CAL	3/10	25	NA		STE10	1/8	10
W. Virginia	PRF	100	NA			NA		STE10	3/16	10

CAL	California Profilograph; 2/10 blanking band for ride quality
RAH	Rainhart Profilograph; 1/10 blanking band for ride quality
MAY	Mays Meter; 70 @ 50 : 70 IPM at 50 mi/h speed
STE	Straightedge; STE12 : 12-ft straightedge
PRF	Profilometer
BPR	BPR Roughometer; using other roughness index
NA	Not applicable

percent use acceptance requirements specified for portland cement concrete (PCC) pavements only; 25 percent have rideability criteria specified for both PCC and asphalt pavements. As it was observed in the AASHTO study, the number of States using rideability specifications grew steadily between 1981 and 1987.

The distribution of the type of roughness measuring devices used to evaluate rideability is as follows:

- California Profilograph - 21 States (58 percent).
- Rainhart Profilograph - 3 States (8 percent).
- Profilometer - 2 States (5.5 percent).
- Mays Meter - 3 States (8 percent).
- BPR Roughometer - 1 State (3 percent).

The equipment and requirements used in rideability specifications are presented in graphical form in figures 1 and 2. Because the California profilograph is the dominating type of device employed in measuring roughness of new pavements, it was given special attention in this study.

Bump specifications have been used in the highway construction industry for many years. The following bump specifications were reported in the three surveys:

- Blanking 1/8 inch in 10 ft - 16 States (44 percent).
- Blanking 3/16 inch in 10 ft - 7 States (19 percent).
- Blanking 1/4 inch in 10 ft - 3 States (8 percent).
- Blanking 1/4 inch in 16 ft - 2 States (5.5 percent).
- Blanking 1/4 inch in 12 ft - 2 States (5.5 percent).
- Blanking 1/8 inch in 12 ft - 1 State (3 percent).
- Blanking 3/10 inch in 25 ft - 1 State (3 percent).

It can be seen that the most common bump specification is 1/8 inch in 10 ft. The distribution of the bump amplitude-in-length requirement data is presented in figure 3.

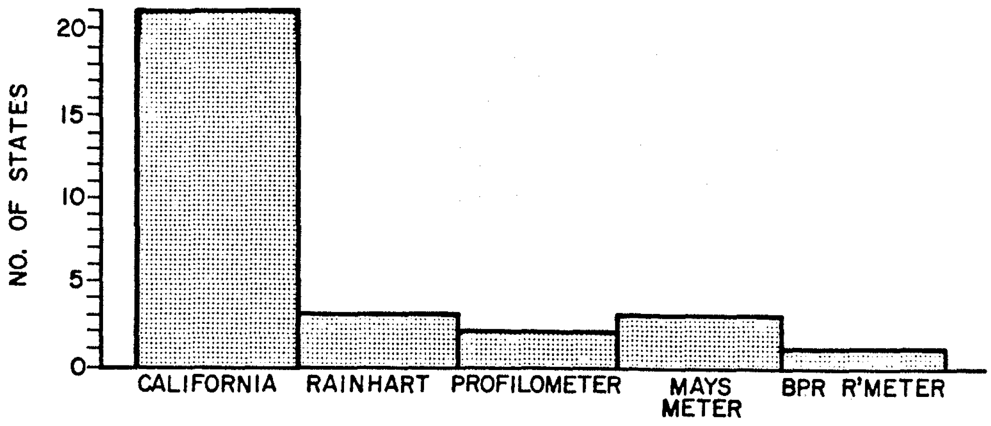

Figure 1. Distribution of type of devices used to measure rideability of new pavements.

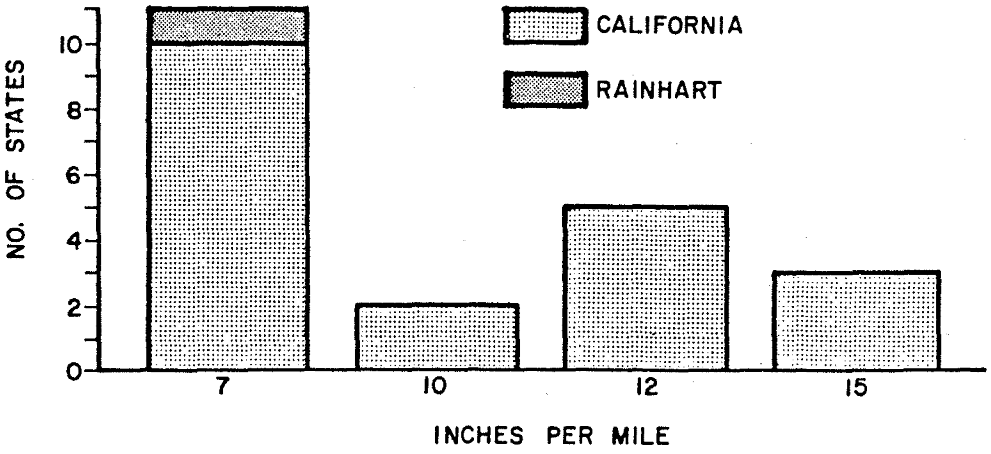

Figure 2. Distribution of rideability requirements, inches per mile.

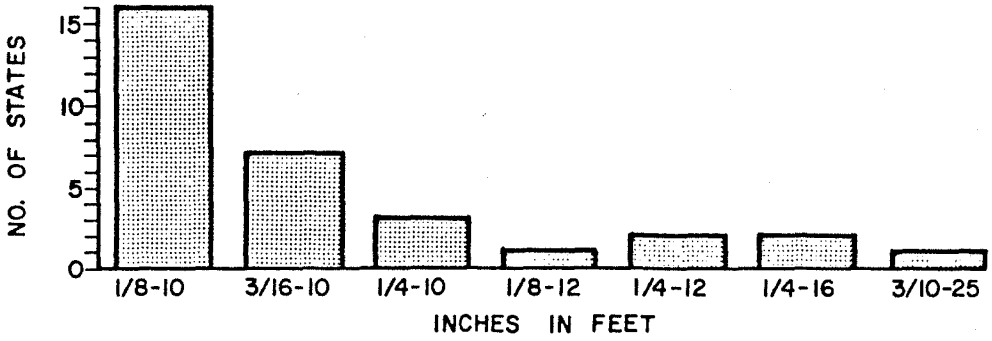

Figure 3. Distribution of bump amplitude-in-length requirements.

The straightedge is the dominating type of device used for bump measurements; it is used by 33, or 92 percent of, States. Two States, 5.5 percent, use the California profilograph, and one State, 3 percent, has no bump specifications.

Of the two specifications currently used by State highway agencies, the bump specification and the overall rideability, the latter provides a more representative measure of pavement quality. Although the bump specification may be useful in controlling individual vertical deviations of pavement profile (bumps or ridges), it provides no information about the overall roughness of a pavement section measured over a longer distance. The overall rideability was therefore chosen as the measure of pavement quality in this study. Specifically, the pavement roughness index, in inches per mile, calculated for a road section 0.1 mi in length, following the procedure used with the California profilograph, was employed to evaluate pavement characteristics in the remainder of this report. The selection of the California profilograph as the reference device was justified by the fact that it is, by far, the most popular device used to measure the roughness of new pavements. The length of the pavement section--0.1 mi--is long enough to be representative of overall pavement roughness. This length was also recommended in the AASHTO survey.[1]

The three surveys indicated also that a variety of devices are currently used in the evaluation of rideability of new pavements. The most common roughness measuring devices are generally classified in two groups--those directly measuring road profile (California, Rainhart, and Ames profilographs and the new profilometers) and those measuring vehicle response to roughness (Mays meter, BPR roughometer). In almost all cases, each of these devices produces a different measure of roughness, usually expressed in inches per mile. Despite the common measurement units, the roughness measures obtained with the different devices represent different measures of pavement roughness and cannot be compared directly. Several regression models were developed to represent the relationships between some of the devices in earlier studies.[4,5,6] None of these efforts could be considered successful, as the developed models either correlated poorly with actual data or were based on a wide range of roughness data, far exceeding the range of roughness typical for new pavements. In any case, the accuracy of the models was very poor when applied to new pavements with standard deviations of 5 in/mi or more, as measured with the California profilograph (5 IPM_{CA}).[1]

Developing accurate regression models relating different types of profilographs, and even to a greater extent, relating profilographs and other roughness measuring devices, presents an extremely difficult problem. The main difficulties stem from the nonlinear data processing procedures (blanking band) and from the relatively narrow range of roughness of new pavements. Initial efforts were recently undertaken by ASTM Committee E-17 on Pavement Management Technologies to develop uniform and adequate procedures for evaluating the roughness of new pavements from surface profile data. In this study, the procedure developed for the California profilograph was used mostly to provide uniformity of roughness data obtained with different devices. The selection of the California profilograph procedure was dictated by the fact that it is used with the most common device for measuring the roughness of new pavements. The authors of this report believe that the selection of the adequate data processing procedure for new pavements requires more research.

OUTLINE OF THE REPORT

Chapter 2 of this report presents the full-scale testing program. The equipment and the test road sites are described. A detailed description of the procedure followed in the field tests is also given.

Results of an investigation of the basic roughness characteristics of new pavements are reported in chapter 3. These characteristics are represented by power spectral density (PSD) functions. Individual PSD functions were computed for several PCC and bituminous pavements sections. The individual PSD functions were then averaged to give average PSD functions

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[1] *The symbol "IPM_{CA}" refers to roughness determined from profile data using the procedure developed for the California profilograph.*

for the two types of pavements, which were then used to generate average-profile data. Two computer programs, one using an iterative algorithm and the other using a direct method, were written to generate profile data of a desired power spectral density distribution.

Road roughness measuring equipment, used in the field tests, is evaluated in chapter 4. Roughness thresholds for new pavements are also proposed in this chapter. The following devices were evaluated: the California profilograph, Rainhart profilograph, profilometer, Mays meter, and Ames profilograph (partially). The main evaluation criteria included frequency response, precision, repeatability, reliability, and ease of operation.

The results of the correlation and regression analysis performed to establish relationships among the test devices are presented in chapter 5. The Ames profilograph was excluded from this analysis because only limited test data were obtained.

Computer simulation of a profilograph was used to investigate the effect of several design parameters on the profilograph performance. The design parameters that were varied in the simulation include the number of supporting wheels, spacing between the wheels, total length of the main truss, wear of the tire of the measuring wheel, and eccentricity of the measuring wheel. An optimal profilograph design is formulated as a general optimization problem.

The main findings from this study are summarized in chapter 7. The appendixes and the list of references used in the study complete the report. Appendix A contains the documentation of the computer programs that were developed.

2. FULL-SCALE TESTS

The devices used in the full-scale tests--a rolling beam straightedge, the profilometer, the Mays meter, the California profilograph, the Rainhart profilograph, and the Ames profilograph--represent three groups of roughness measuring equipment. These three groups are profilographs (California, Rainhart, Ames), profilometers and Response-Type Road Roughness Measuring systems (Mays meter). The rolling beam straightedge was used with the rod and level to provide the reference profile data.

DESCRIPTION OF TEST DEVICES

The devices for the testing program are listed in table 2.

Table 2. Equipment selected for full-scale tests.

Device
Rolling Beam Straightedge
Profilometer
Mays Meter
California Profilograph
Rainhart Profilograph
Ames Profilograph

A description of each device follows.

ROLLING BEAM STRAIGHTEDGE

The rolling beam straightedge utilizes a laser displacement transducer (see table 3 for specifications) attached to a trolley. A motorized cable drive system positions the trolley along a 25-ft rail. The rail is supported above the pavement by two adjustable legs mounted on 8-in wheels. The apparatus may be operated as a rolling straightedge or as a stationary, leveling straightedge. When the apparatus is used as a rolling straightedge, the trolley is centered between the supporting legs and the device is pulled along the pavement. The displacement transducer measures the height of the midpoint of the rail above the road surface. An optical encoder, mounted on one of the rolling wheels, provides pulses for the distance traveled.

Table 3. Selcom laser transducer specifications.

Measurement Range: 5.22448 in
Standoff Distance: 11.836 in
Accuracy: 0.00261 in
Resolution: 0.001306 in
Linearity: 0.00261 in

When the apparatus is used as a stationary, leveling straightedge, the device is positioned over the measurement section and the rolling wheels are locked. The rail is leveled by adjusting the height of the two legs. The cable drive system is activated, and the trolley is pulled along the length of the rail. The road profile is measured relative to the height of the rail. The drive system incorporates an optical encoder to provide distance pulses. Then with a rod and level, the height of each end of the beam is measured to establish a true level plane. The unit is then moved ahead 25 ft, and the measurements repeated. This procedure is repeated until the test length has been measured.

PROFILOMETER

The profilometer is a vehicle instrumented to measure and record longitudinal road profiles independent of variations in vehicle velocity. The measurement transducers include a laser displacement transducer (see table 3) and an accelerometer positioned over each wheel track. The displacement transducers measure the distance between the vehicle and the road surface; the accelerometers measure the acceleration of the vehicle normal to the road surface. Traveled distance is measured using an optical pulse encoder. The transducer signals are sampled spatially using a digital computer.

Profiles are computed by subtracting the vehicle's absolute altitude from the distance between the vehicle and the road surface. The vehicle's absolute altitude is computed by double-integrating the signal from each accelerometer. A spatial domain filter attenuates profile wavelength components in excess of a desired, preselected maximum wavelength.

MAYS METER

The Mays meter represents the group of response-type road roughness measuring systems (RTRRMs). Its measurement of roughness is an accumulated axle-body displacement in inches per mile of traveled distance. One of PennDOT's Mays meters was used for this study. The Mays meters were calibrated in January 1988 using the profilometer and a quarter car simulation. The Mays meter used in this study was recalibrated again in May 1988.

CALIFORNIA PROFILOGRAPH

A standard 12-wheel California profilograph was used in the full-scale tests. The pavement profile is measured by vertical displacement of the measuring wheel, mounted at the center of the main truss, with respect to the reference plane established by the 12 supporting wheels. Eight supporting wheels are mounted on the right-hand side of the main truss and four supporting wheels are mounted on the left-hand side.

To enhance data collection and processing, the profilograph was equipped with a computer data acquisition system. A simple potentiometer circuit provides an electrical dc signal representing the position of the recording pen in the profilograph. A Metrabyte Dash-8 interface board and a portable IBM personal computer are used to collect and store the profile signal from the potentiometer and the distance signal from the optical encoder. The data stored on floppy disks was further processed to calculate the roughness index and to develop regression models relating this profilograph to other devices. The listing of the computer data acquisition program is given in appendix A. The computer data acquisition system operates in parallel with the profilograph recording system; thus, there was no interference between the two systems. By using the computer program for the calculation of the profilograph roughness index, the entire process of data collection and processing was automated. The computer results were compared with roughness index values determined in the conventional manner, that is, hand-calculated from a profilograph strip chart.

RAINHART PROFILOGRAPH

The Rainhart profilograph operates on the same principle as the California profilograph. The 12 supporting wheels are mounted on tripods and are evenly distributed along the length of the profilograph. The computer data acquisition system was also installed to enhance data collection and processing.

AMES PROFILOGRAPH

The Ames profilograph was not included in the original test plan. However, because of its attractive technical and cost characteristics, this device was included in some full-scale tests. This profilograph was available for this study for a limited period of time. Nevertheless, a very intensive testing program was conducted during that short period, involving the Ames profilograph and the California profilograph. The data collected made it possible to establish correlation between the two profilographs directly. Using the results from the full-scale tests involving the California profilograph and other devices, correlations of the Ames profilograph with the other devices can be determined indirectly.

DESCRIPTION OF TEST SITES

Full-scale testing of both asphalt concrete and portland cement concrete pavement surfaces was conducted. The typical pavement test section was approximately 0.1 mi long. All of the pavements were either newly constructed or recently overlaid. In addition to the test pavements on the highway system, testing was done at the Pennsylvania Transportation Research Facilities (PTI test track). Tests were made at the following locations:

Asphalt Cement Concrete Pavement Surface

- Test track (resurface).
- Interstate 70 near Breezewood, PA, northbound lane (overlay).
- Interstate 83 near York, PA, northbound lane (overlay).

Portland Cement Concrete Pavement Surface

- Test track, large turn.
- U.S. Route 220 near Altoona, PA, westbound lane (new construction).
- U.S. Route 15 near Gettysburg, PA, northbound lanes (new construction).
- Interstate 80 near Clearfield, PA, west driving lane (reconstruction).

All of these locations, except for the test track, are four-lane facilities with 12-ft-wide lanes. Each site was divided to give a total of 30 test sections. Table 4 lists all test sections. All sites were chosen in coordination with PennDOT to allow measurements before the sections were open to traffic.

Table 4. Test sections.

Number	Location	Pavement Type	Section Length (mi)	Number	Location	Pavement Type	Section Length (mi)
1	Test Track	PCC	0.1	16	Rt. 15	PCC	0.1
2	Test Track	BCC	0.1	17	Rt. 15	PCC	0.1
3	Test Track	BCC	0.1	18	Rt. 15	PCC	0.1
4	Test Track	BCC	0.1	19	Rt. 15	PCC	0.1
5	Rt. 220	PCC	0.1	20	I 70	BCC	0.1
6	Rt. 220	PCC	0.1	21	I 70	BCC	0.1
7	Rt. 220	PCC	0.1	22	I 70	BCC	0.1
8	Rt. 220	PCC	0.1	23	I 70	BCC	0.1
9	Rt. 220	PCC	0.1	24	I 70	BCC	0.1
10	Rt. 80	PCC	0.1	25	I 70	BCC	0.1
11	Rt. 80	PCC	0.1	26	I 83	BCC	0.1
12	Rt. 80	PCC	0.1	27	I 83	BCC	0.1
13	Rt. 80	PCC	0.1	28	I 83	BCC	0.1
14	Rt. 80	PCC	0.1	29	I 83	BCC	0.1
15	Rt. 15	PCC	0.1	30	I 83	BCC	0.1

TESTING PROCEDURE

The testing procedure used is summarized in table 5.

Table 5. Testing procedure.

Testing Order	Device	No. of Tests
1	Laser Beam	1
2	California Profilograph	2
3	Mays Meter	2*
4	Rainhart Profilograph	2
5	Profilometer	2

* Each Mays meter test involved three runs, in accordance with ASTM E1082-85.

The order in which the devices were tested was established to minimize the time lost for equipment preparation. The same laser sensor was used by the laser beam and profilometer, and the same data acquisition system was shared by the California and the Rainhart profilographs. Each device was run twice on each test section.

In addition, the full-scale tests were preceded by repeatability tests that were conducted on the four test sections at the test track. Five measurements were obtained with each device on each test section to determine the repeatability of the measuring equipment.

TEST PLAN

The devices used in the full-scale tests were to be tested on at least 20 new or newly surfaced pavements, which were to include at least 10 rigid and 10 flexible pavements. The particular sites were selected during the summer construction season. A list of all new constructions to be completed during the period of spring through fall 1988 was obtained from PennDOT. From that list, 16 rigid and 14 flexible pavements were selected. Each test section was 0.1 mi long.

All devices were run on a given road test section during the same day. In most cases, it took less than 2 h to cover a 0.1-mi-long pavement with all of the devices tested except the laser beam, which required 6 h per site. The following measurements were taken at each site:

- Mays meter (all sites), plot of axle/body motion.
- Longitudinal profile with profilometer (all sites), body acceleration, and body/road height, and position on road.
- California profilograph (all sites), chart recording and digitized signals.
- Rainhart profilograph (all sites), chart recording and digitized signals.
- Ames profilograph (U.S. Rt. 220), chart recording.

- Laser beam (all sites), height from beam; (I 83, I 70, and U.S. Rt. 220), height from beam plus rod and level of each end of the beam.

The test report also contained general information on the type of pavement, date the pavement construction was completed, date of testing, and names of operators.

The following information, specific for each device, was also recorded: the time of testing, weather conditions (temperature, wind, and rainfall), and the roughness measured (if it was available immediately after the test run). All data were labeled and secured for further processing in the laboratory. Testing and recording met or exceeded the requirements of the ASTM standard under ballot by Committee E-17 on Traveled Surface Characteristics. Appendix B reprints this proposed standard, "Standard Test Method for Measuring Pavement Roughness Using a Profilograph."

3. ROUGHNESS CHARACTERISTICS OF NEW PAVEMENTS

Power Spectral Density Analysis of Field Data

To determine the wavelength content of new pavement profiles, power spectral density (PSD) functions were computed from the sets of data obtained with the laser beam.

A PSD function for a sequence of data points, x(i), i = 1,2,...,M, is defined by the following equation:[8]

$$S_{xx}(j) = 2\Delta\lambda \left\{ R(1) + \sum_{i=2}^{jmax} R(1)\cos[\eta(i-1)(j-1)/jmax] + (-1)^{j-1} R(jmax+1) \right\} \quad (1)$$

where

$\Delta\lambda$ = sampling interval
$R(j)$ = discrete autocorrelation function

The autocorrelation function for the profile data is calculated from:

$$R\,(j) = \frac{1}{M-j+1} \sum_{i=1}^{M-j+1} x(i)x(i+j-1),\ j=1,2,\ldots,jmax \quad (2)$$

where x(i) is the measured profile value at the distance $i\Delta\lambda$ from the beginning of the test site. Frequency is related to wavelength by:

$$f(j) = \frac{j-1}{2j_{max}\Delta\lambda}$$

The PSD function characterizes the manner in which power is distributed in the sequence x(i) as a function of frequency. It should also be noted that frequency is expressed here in feet^{-1}, i.e., spatial frequency.

In addition to representing a spectral power content of the profile, PSD can also be used to determine the power contained in the profile data over a specified wavelength range, $[\lambda_1, \lambda_2]$. The following equation describes the power content over the range $[\lambda_p, \lambda_q]$:

$$P_x(\lambda_p,\lambda_q) = (\lambda_q-\lambda_p) \sum_{j=p}^{q} S_{xx}(j) \tag{4}$$

The power content given by equation 4 can be considered to represent profile roughness in the specified range of wavelength. The power content can also be estimated by a coefficient of variance defined as:

$$\sigma_x{}^2 = \frac{1}{M} \sum_{i=1}^{M} [x(i)-\overline{x}]^2 \tag{5}$$

where $\overline{x}$ is the mean of the sequence x(i). The extent to which the measures defined by equations 4 and 5 correlate would depend on the selected range of wavelengths $[\lambda_p, \lambda_q]$.

The PSD functions were computed for seven sets of profile data measured with the laser beam. Five sets are from bituminous pavements, site numbers 1, 2, 4, and 5 on I-83 and site number 2 on I-70. Two data sets represent PCC pavements on site numbers 1 and 2 on U.S. Route 220. The listing of the FORTRAN computer program is given in appendix A. The plots of the computed PSD functions are shown in figures 4 through 10.

There are two curves on each figure. One curve represents a PSD function computed from raw data. These curves can be recognized by peaks that occur at the value of the horizontal coordinate, log (wave no./ft), equal to 1.1, which corresponds to the 12-ft wavelength. This peak indicates a presence of a dominant periodic component of frequency 1/12 ft^{-1} in the measured profile data and is caused by the deflection of the beam on which the laser height sensor moves above the pavement surface. The length of the beam is 12 ft.

The periodic signal component caused by the beam deflection was filtered out, and the PSD function of the modified signal was computed and plotted in figures 4 through 10. Figure 11 shows the PSD functions averaged over two PCC

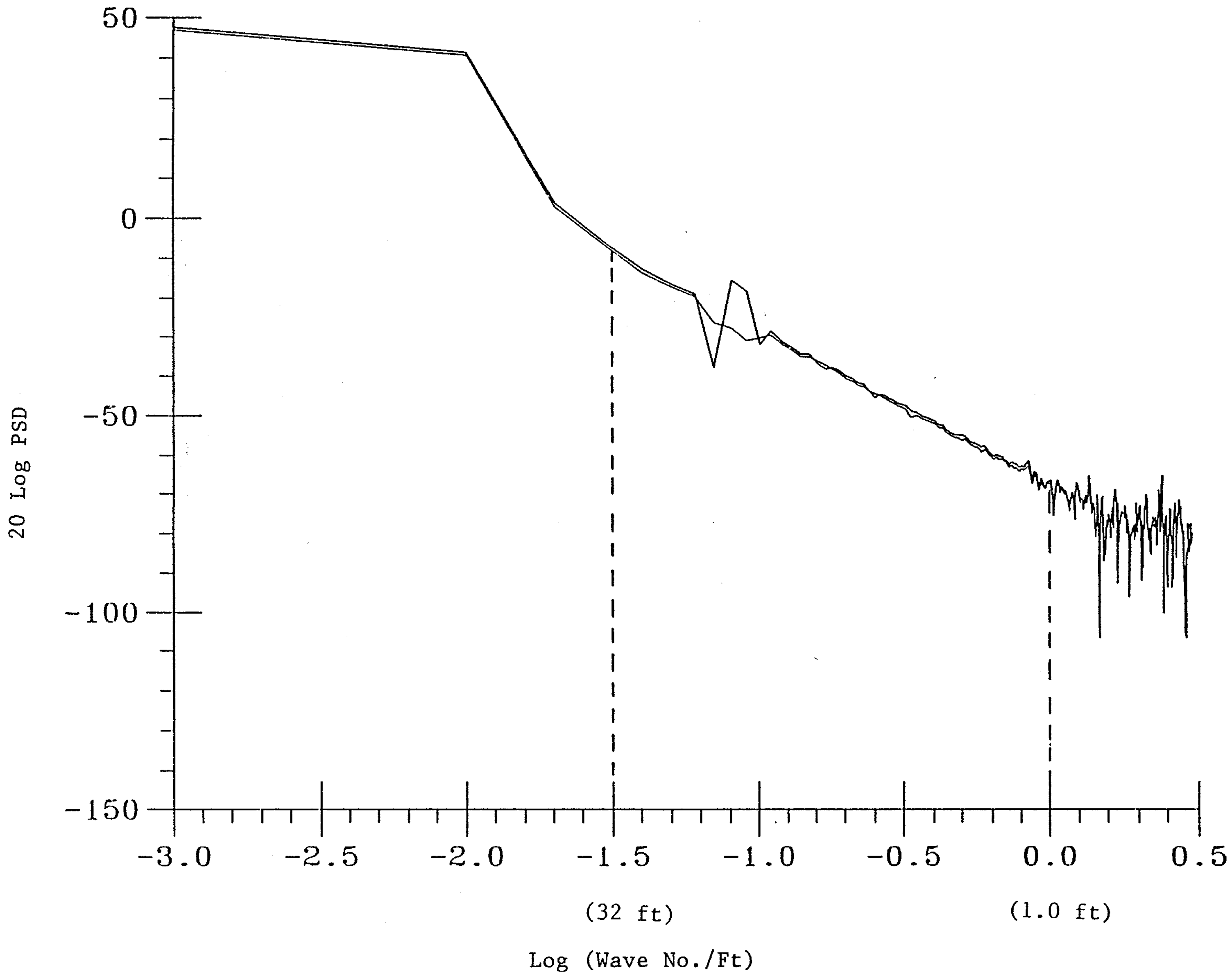


Figure 4. PSDs of the raw and modified profile data for site R221/1.

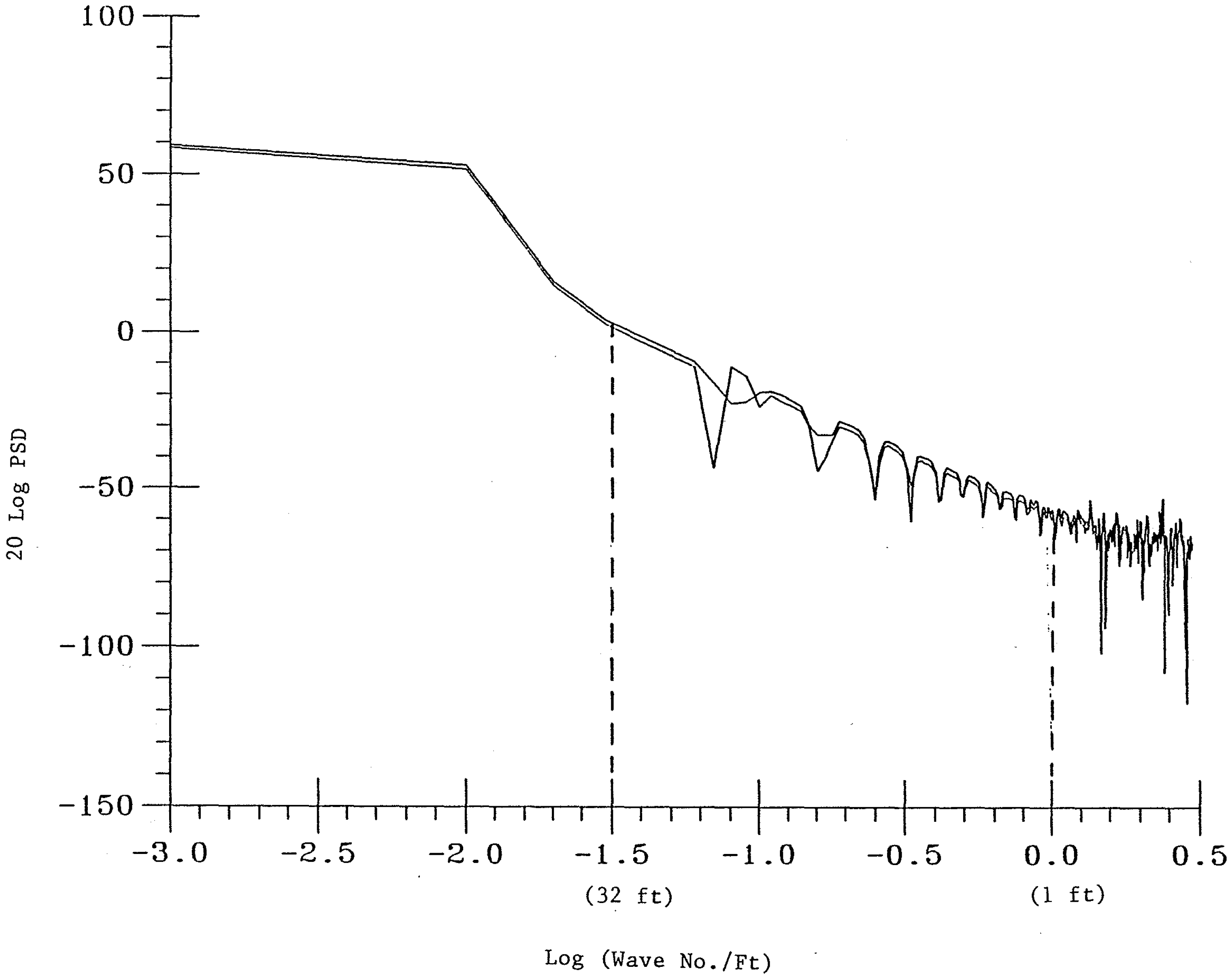


Figure 5. PSDs of the raw and modified profile data for site R221/2.

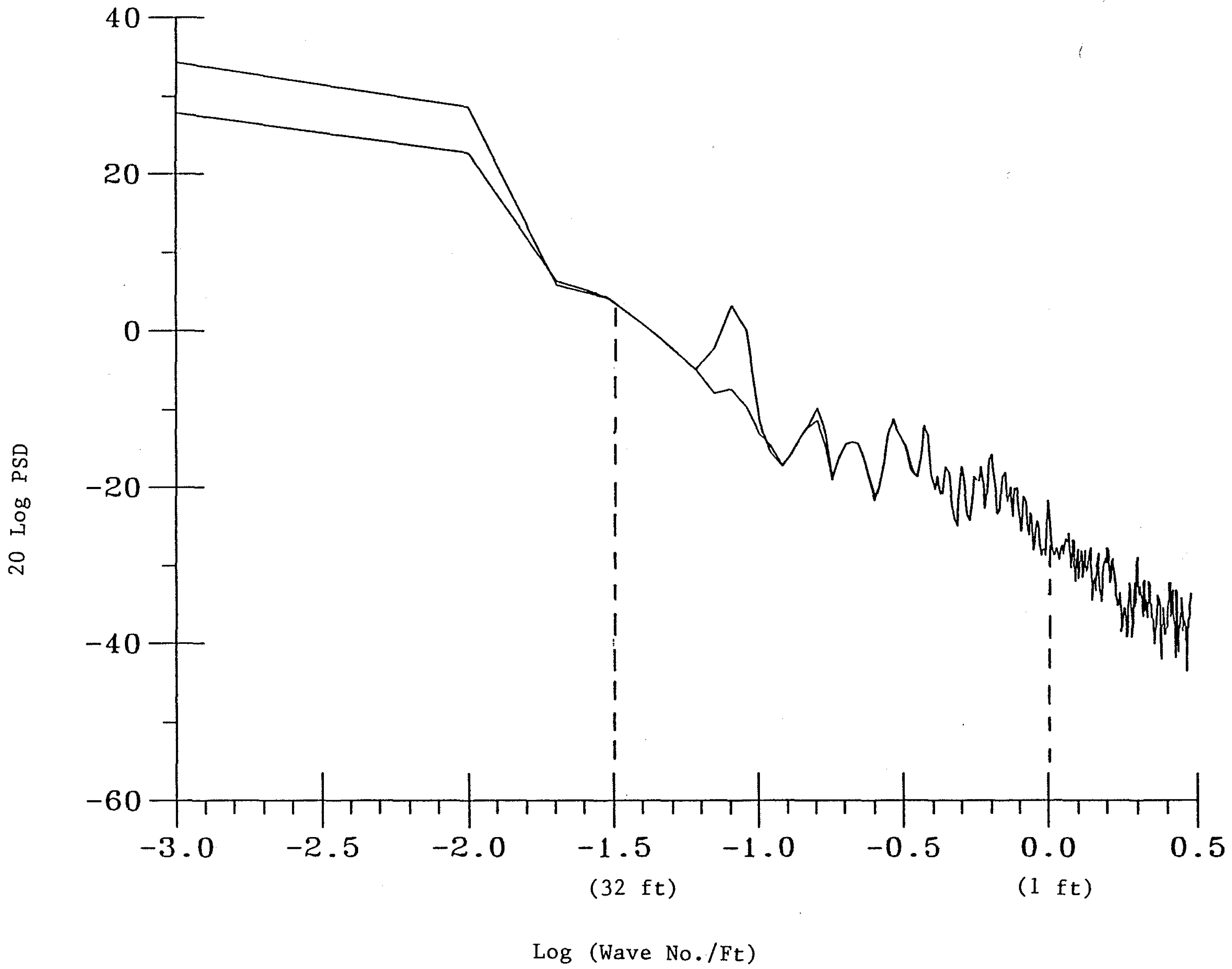


Figure 6. PSDs of the raw and modified profile data for site I70/2.

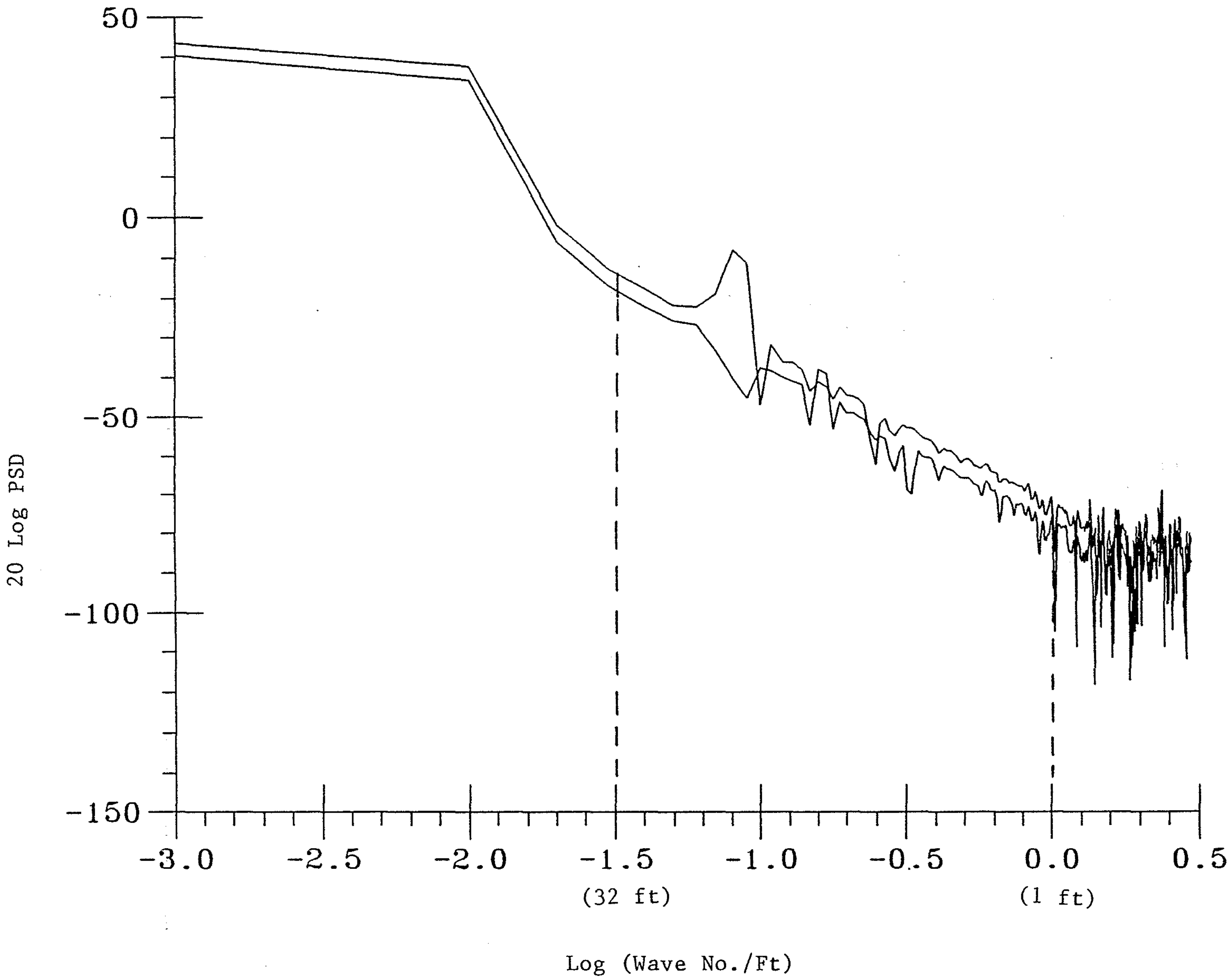


Figure 7. PSDs of the raw and modified profile data for site I83/1.

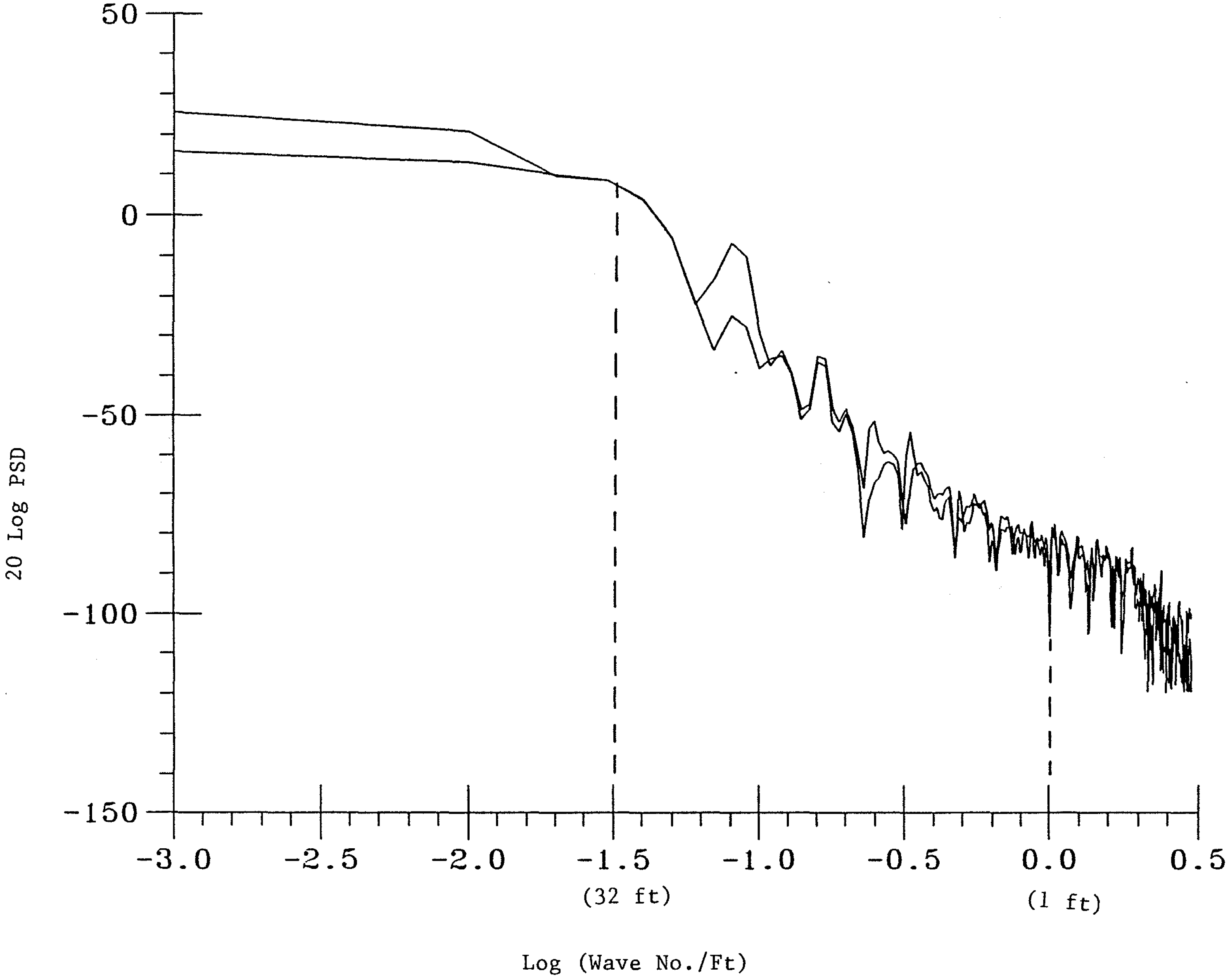


Figure 8. PSDs of the raw and modified profile data for site I83/2.

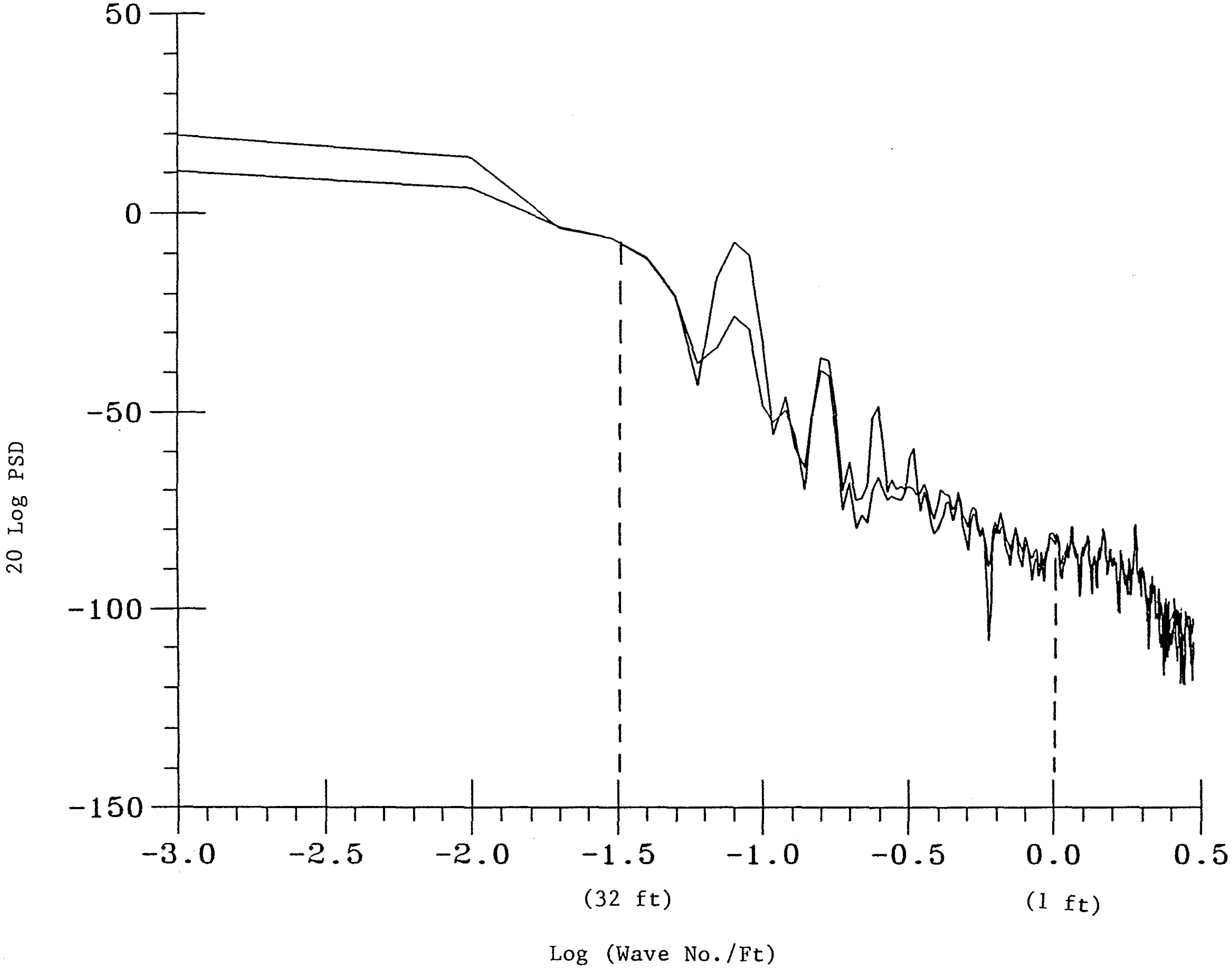


Figure 9. PSDs of the raw and modified profile data for site I83/4.

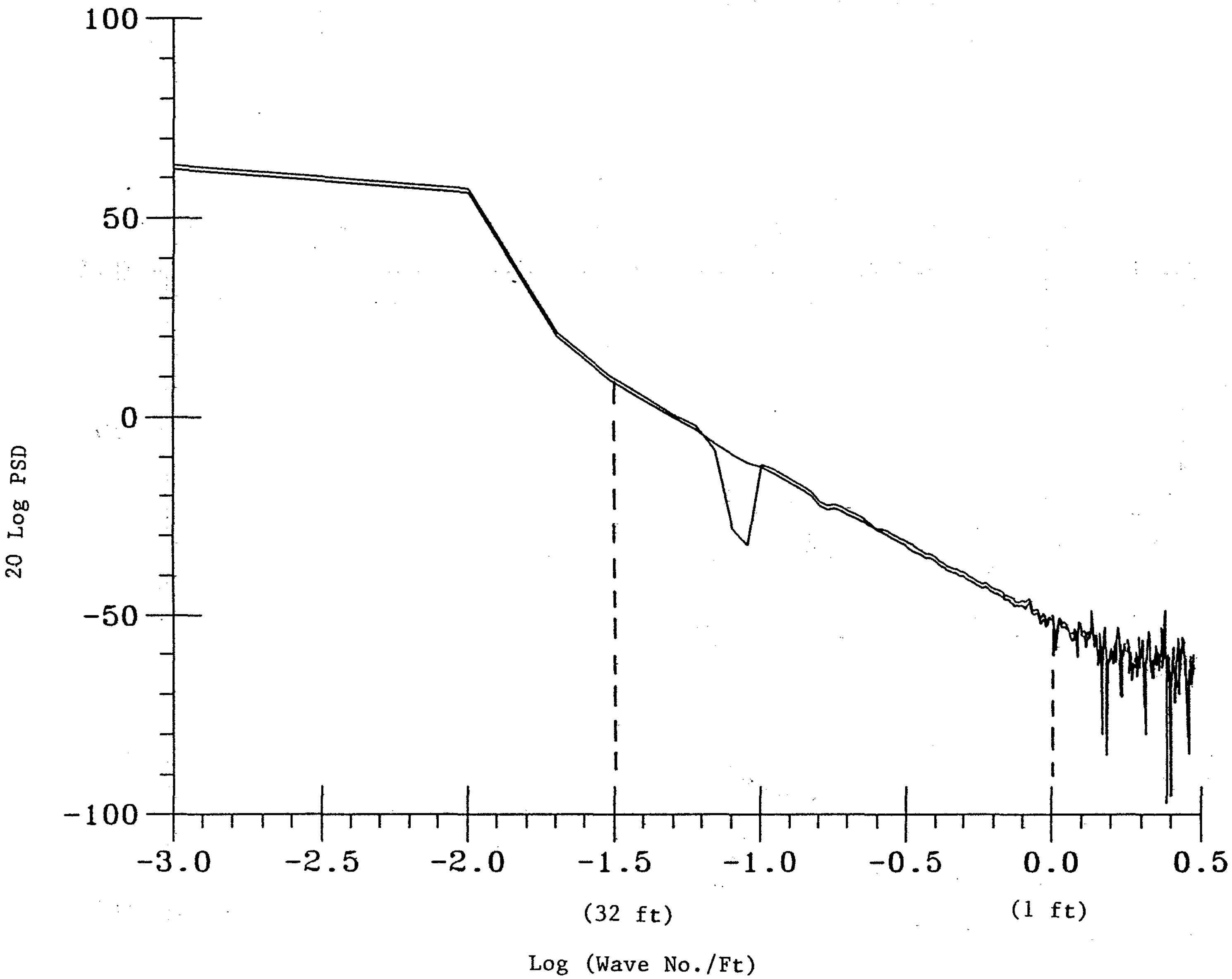


Figure 10. PSDs of the raw and modified profile data for site I83/5.

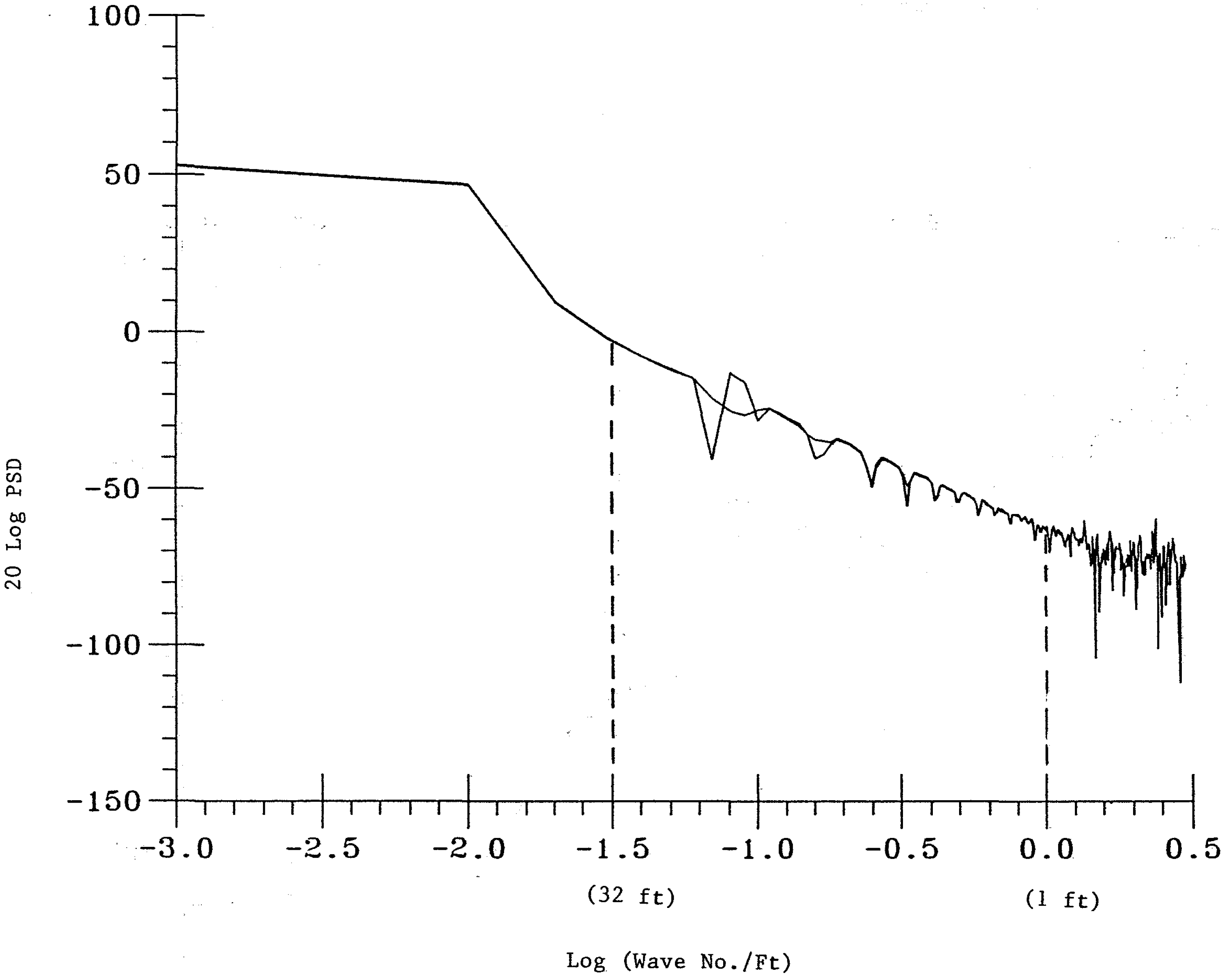


Figure 11. Comparison of average PSDs for the raw and modified PCC profile data.

pavement sites, and figure 12 displays the average PSD functions for five bituminous pavement sites. Curves for the raw and modified profile data are plotted in each figure.

In chapter 4 it will be shown that the range of wavelengths, which is most significant for the roughness of new pavements, extends approximately from 1 to 32 ft or, correspondingly, from -1.5 to 0 in terms of log (wave no./ft).

Figure 13 shows that there is very little difference between the PSD functions for PCC and bituminous pavements over this range of wavelengths. An approximate analytical formula was found to model the PSD function of new pavements versus the pavement wavelength, λ. The model equation for combined PCC and bituminous pavement data, plotted in figure 13, was developed using regression analysis in the following form:

$$\hat{S}_{xx} = 6.66 \times 10^{-4} \lambda^2 \tag{6}$$

where λ is the wavelength in feet and $\hat{S}_{xx}$ is the model PSD in square inch-feet per cycle. The model equation 6 is represented by the straight line in the logarithmic coordinate system in figure 14.

COMPUTER MODEL OF NEW PAVEMENT PROFILE

ITERATIVE PROCEDURE

This section presents an iterative algorithm for generating the road profile data sequence of a desired PSD function.

The literature provides several approximations of the power spectra of road surfaces for the practical range of vehicle velocities. Road or terrain irregularities can be described quantitatively by the autocorrelation function or power spectral density function. In the method proposed here, the power spectral density is modeled as a rational transfer function of reasonably low order. According to Hac,[7] for a variety of road and terrain inputs, a good

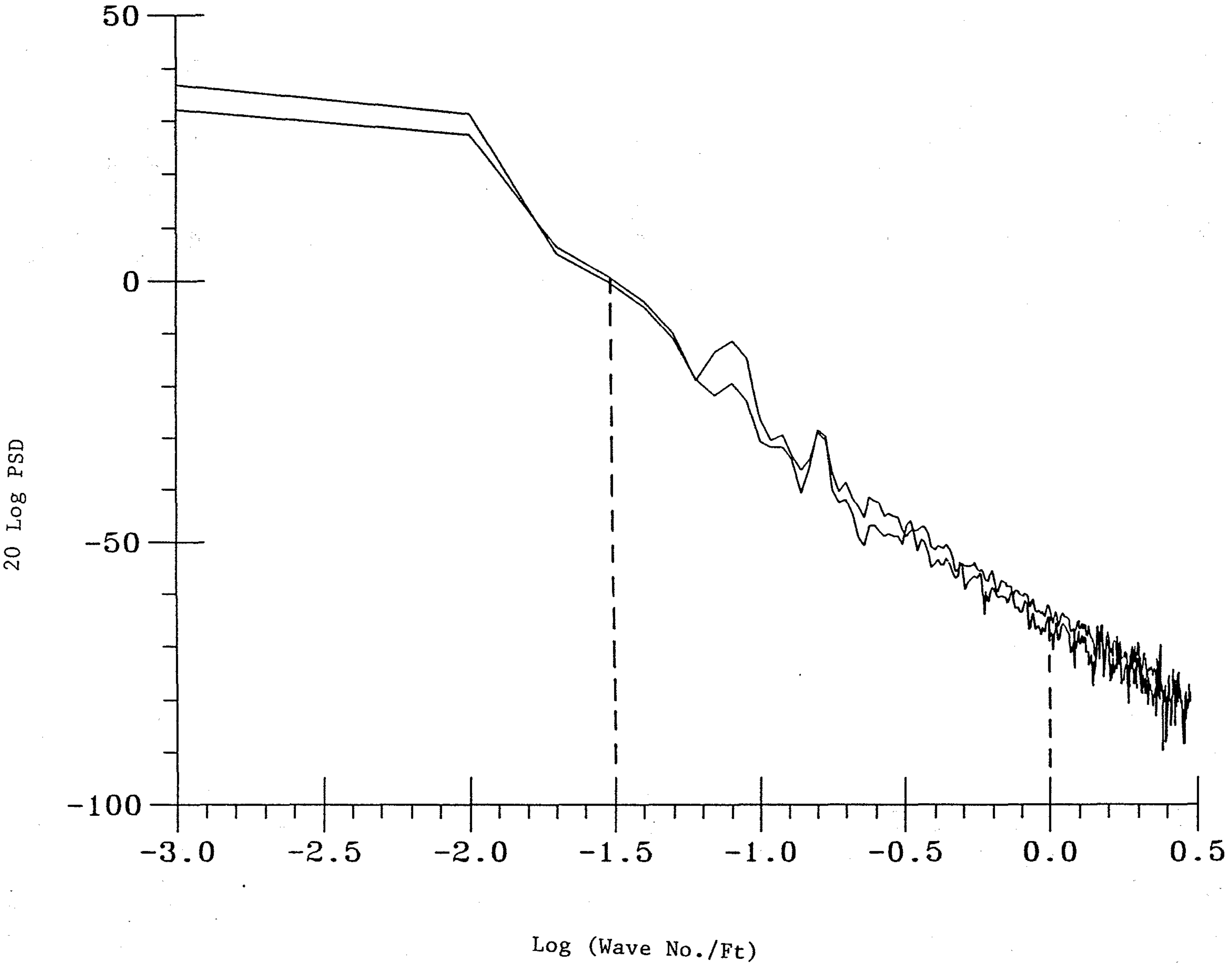


Figure 12. Comparison of average PSDs for the raw and modified bituminous profile data.

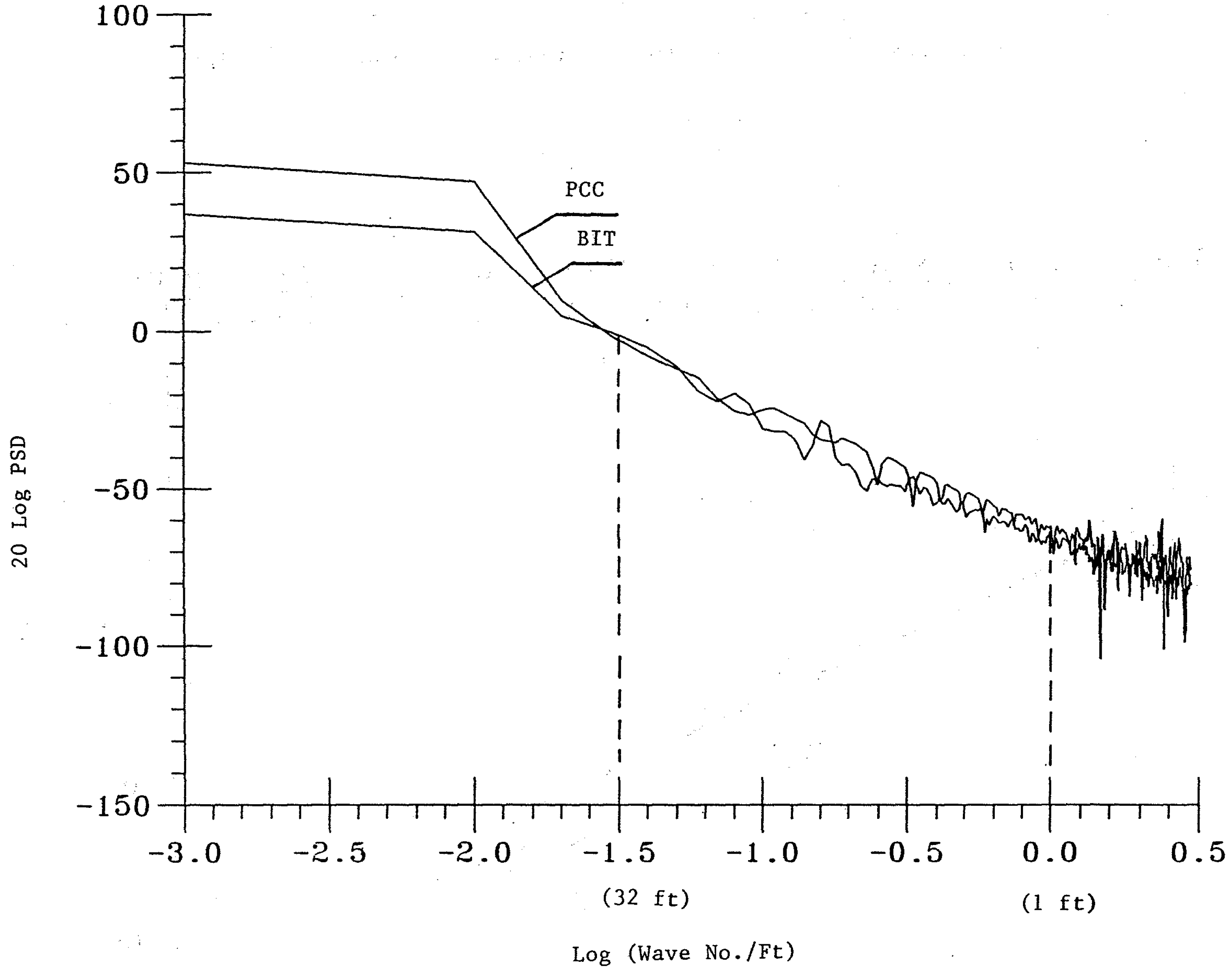


Figure 13. Average PSDs for (filtered) corrected PCC and bituminous pavement profile data.

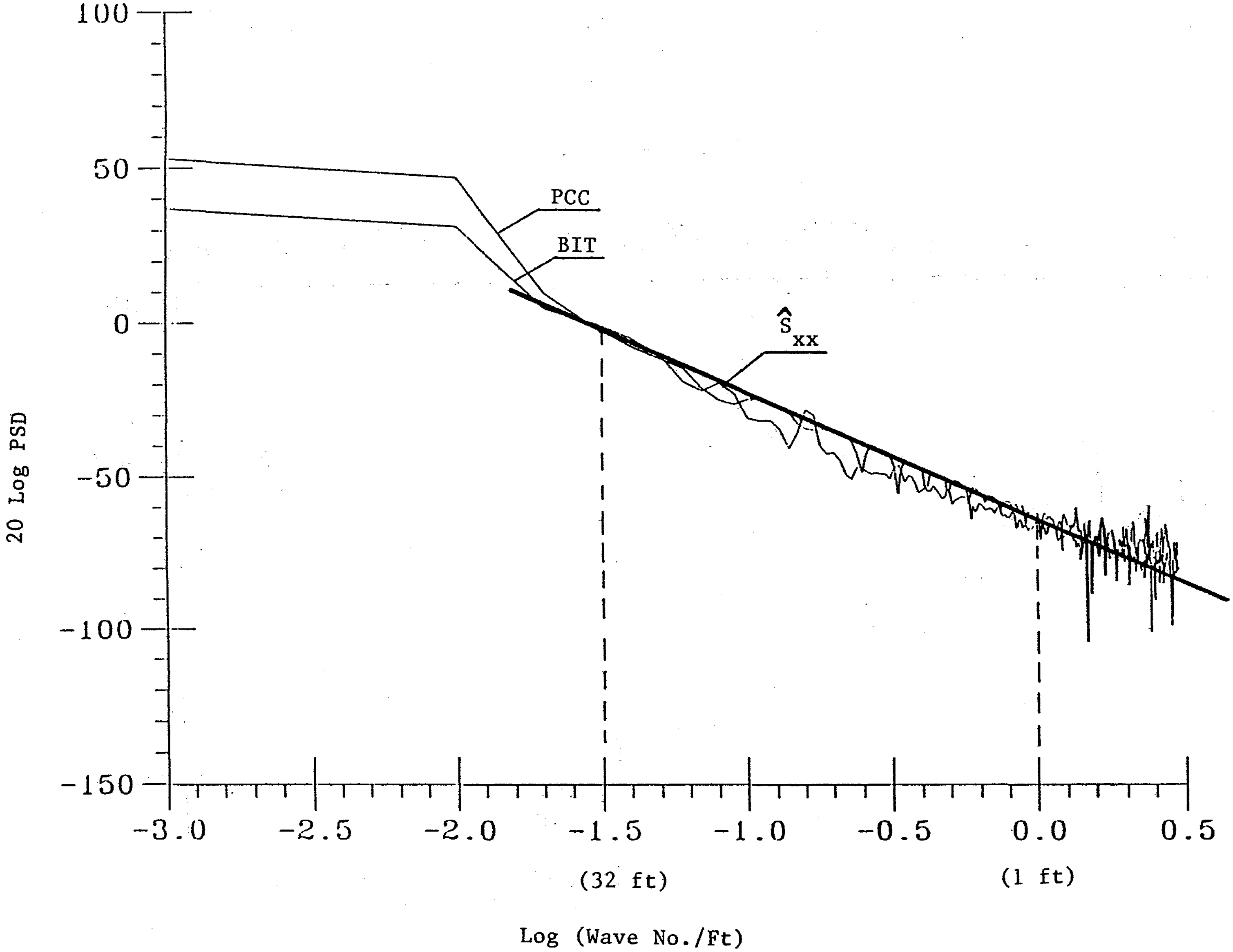


Figure 14. Model and actual PSD functions for new pavements.

approximation of the power spectral density is:

$$S(\omega) = (\sigma_1^2/\eta)[\alpha_1 v/(\omega^2 + \alpha_1^2 v^2)] +$$

$$(\sigma_2^2/\eta)[\alpha_2 v(\omega^2 + \alpha_2^2 v^2 + \beta^2 v^2)]/[(\omega^2 + \alpha_2^2 v^2 - \beta^2 v^2) + 4\alpha_2^2 \beta^2 v^4] \quad (7)$$

where

ω = angular frequency

v = vehicle velocity

α_1, α_2, β, σ_1^2, σ_2^2 = the coefficients, depending on type of road or terrain

The sum $\sigma_1^2 + \sigma_2^2$ represents the variance of road irregularities.[7] The process x(t) describing road irregularities with a spectral density as found using equation 7 can be treated as a stationary solution of the following linear differential equation:

$$\dddot{x}_1 + (a_1 + a_3)\ddot{x} + (a_0 + a_1 a_3)\dot{x}_1 + a_0 a_1 x_1 = d_1(\ddot{\delta} + b_3\dot{\delta} + b_0\delta) \quad (8)$$

where $\delta(t)$ is a white noise process of unitary intensity. The process of generating road profile data can be represented by a block of transfer functions given by equation 8 and subjected to white noise input as illustrated by figure 15.

Using State variable representation, the vector equations were numerically integrated. FORTRAN subroutines were used for the purpose. Another FORTRAN program was used to generate the white noise input. A complete listing of the FORTRAN computer program is given in appendix A.

To generate road profiles with a desired power spectral density, first, the effects of the model parameters on frequency characteristics of the generated profile had to be determined. The sensitivity of the PSD to the five model parameters α_1, α_2, β, σ_1^2, and σ_2^2 is illustrated in figures 16

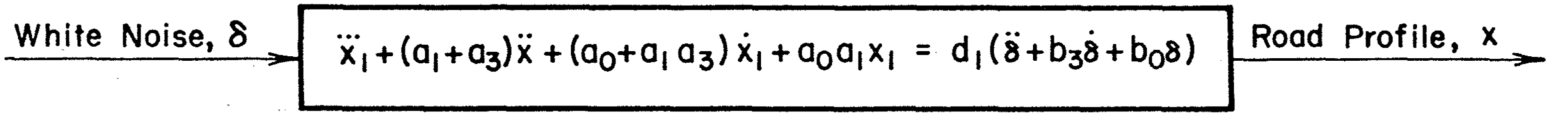


Figure 15. Block diagram of computer road profile generation using equation 8.

through 20. These figures illustrate that increasing σ_1^2 increases the power content in all frequencies; decreasing σ_2^2 increases the power content of the peak frequency. The effect of increasing ß is to shift the peak frequency to the right. The effect of decreasing α_1 is just to increase the power content in the very low frequency range (0 to 5 rad/s), with no appreciable effect on the rest of the frequencies. Parameter α_2 has a similar effect on the PSD as σ_2^2.

Once the effect of the five parameters on the power spectral density was studied, the next step was to write a computer program that would iteratively adjust these parameters until the desired spectrum of the generated road profile is obtained. This task is accomplished in the following manner: The desired power spectrum is drawn freehand on the graph. Another power spectrum for which the five parameters are known is drawn on the same plot. The problem at hand is to identify the five parameters for the freehand sketch. Three distances are identified between the two curves: d1--the distance between the curves along the $S(\omega)$ axis at zero frequency; d2--the distance between the peak frequencies along the frequency axis; and d3--the distance between PSDs at the peak frequencies. Subroutine PUL is used to calculate the PSD when the five parameters are input. Another subroutine, EST, estimates distances d1i, d2i, and d3i as the distances for the PSD curve generated in the i-th iteration. Depending on the distances calculated every time a curve is generated, three parameters, α_1, α_2, and ß, are changed until the distances are within the 2-percent range of the originally estimated values. Figure 21 shows a block diagram of the modus operandum. Once the parameters describing the freehand sketch of the PSD are identified, the filter transfer function can be assembled and the corresponding road profile generated.

The iterative method described here is very general and can be used in a variety of applications. It is, however, fairly complex and may require a large number of iterations before a desired profile sequence is generated. A much simpler method, developed specifically for generating road profile data, is described in the next section.

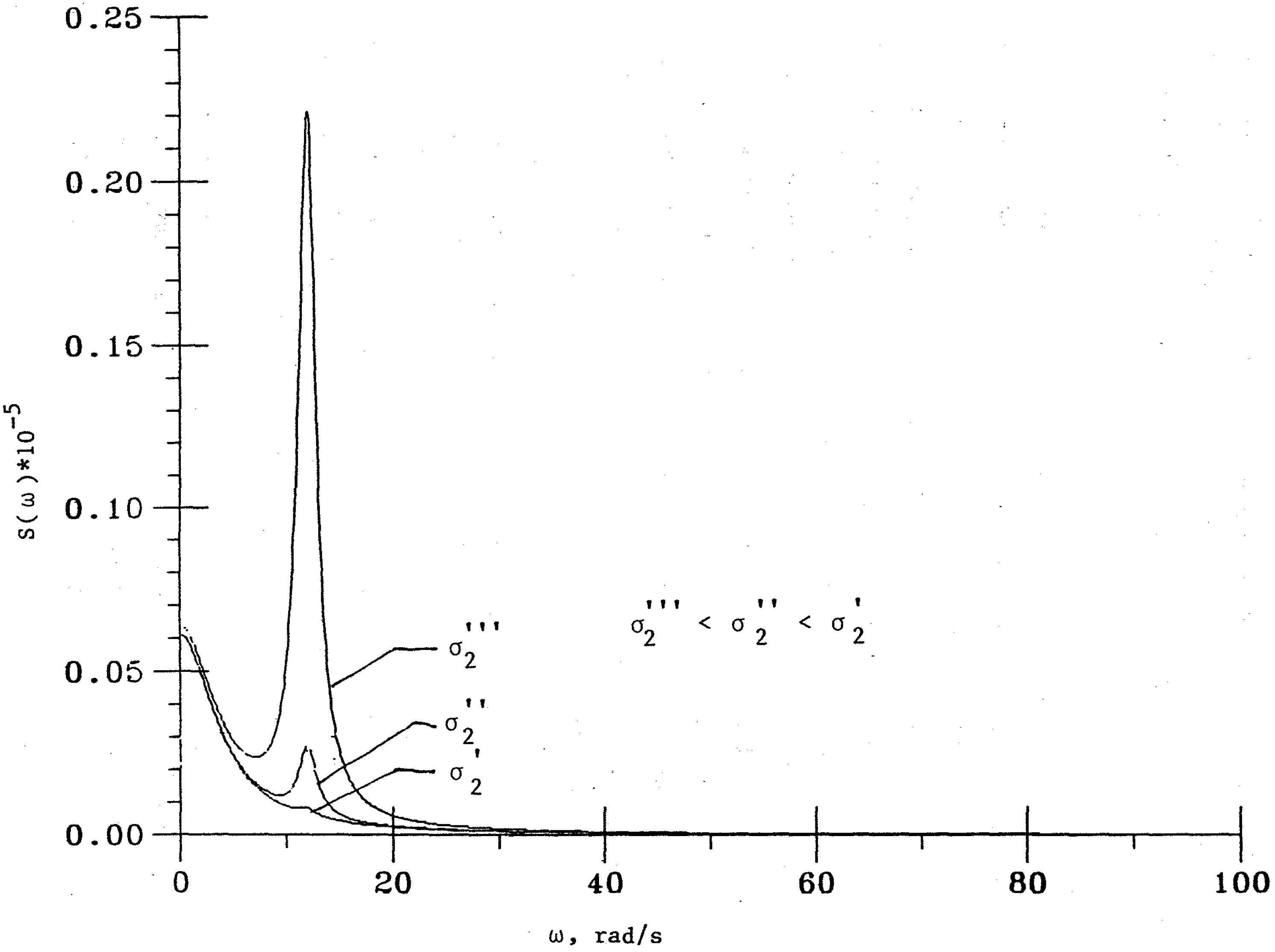


Figure 16. Effect of σ_2 on PSD function.

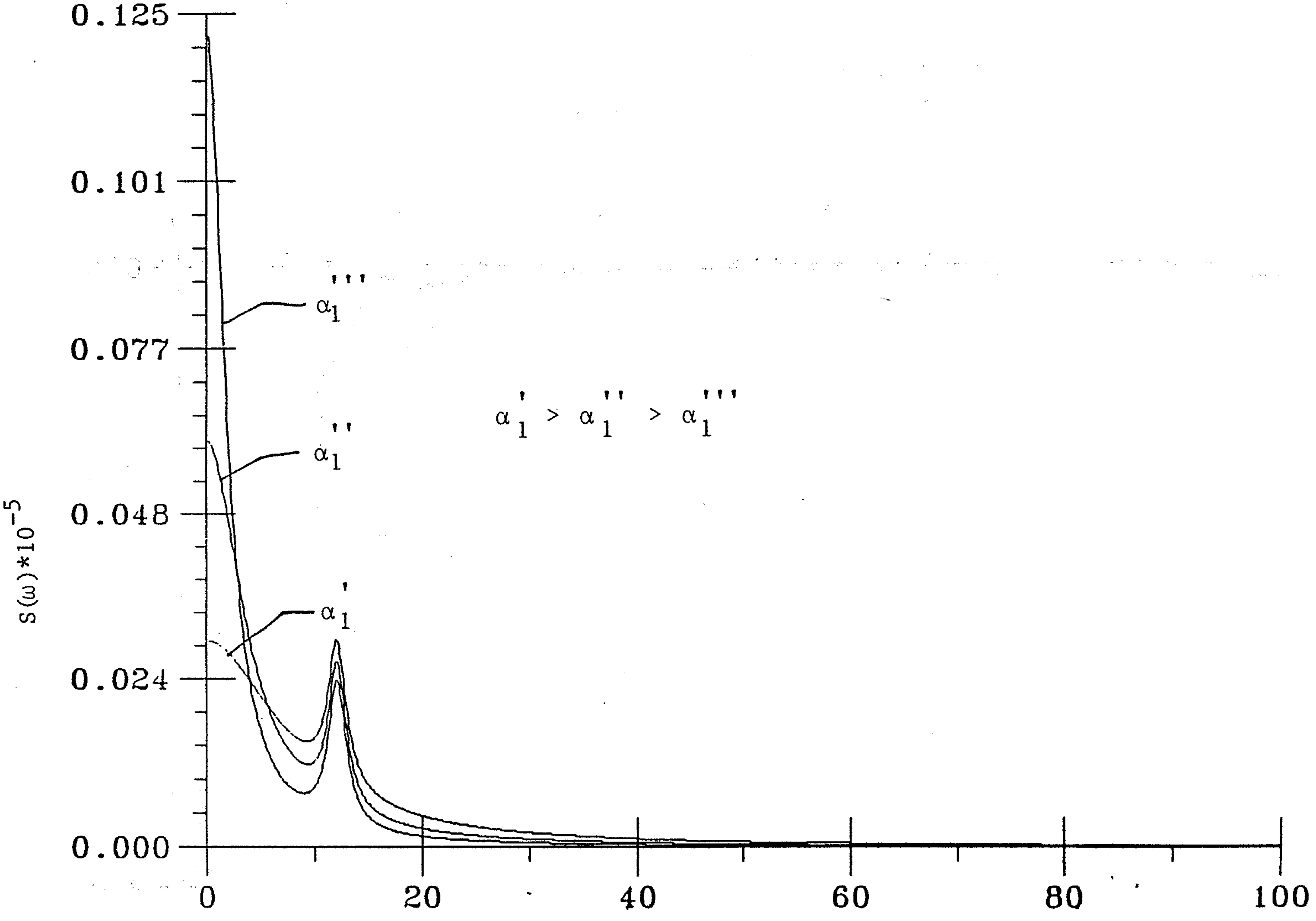


Figure 17. Effect of α_1 on PSD function.

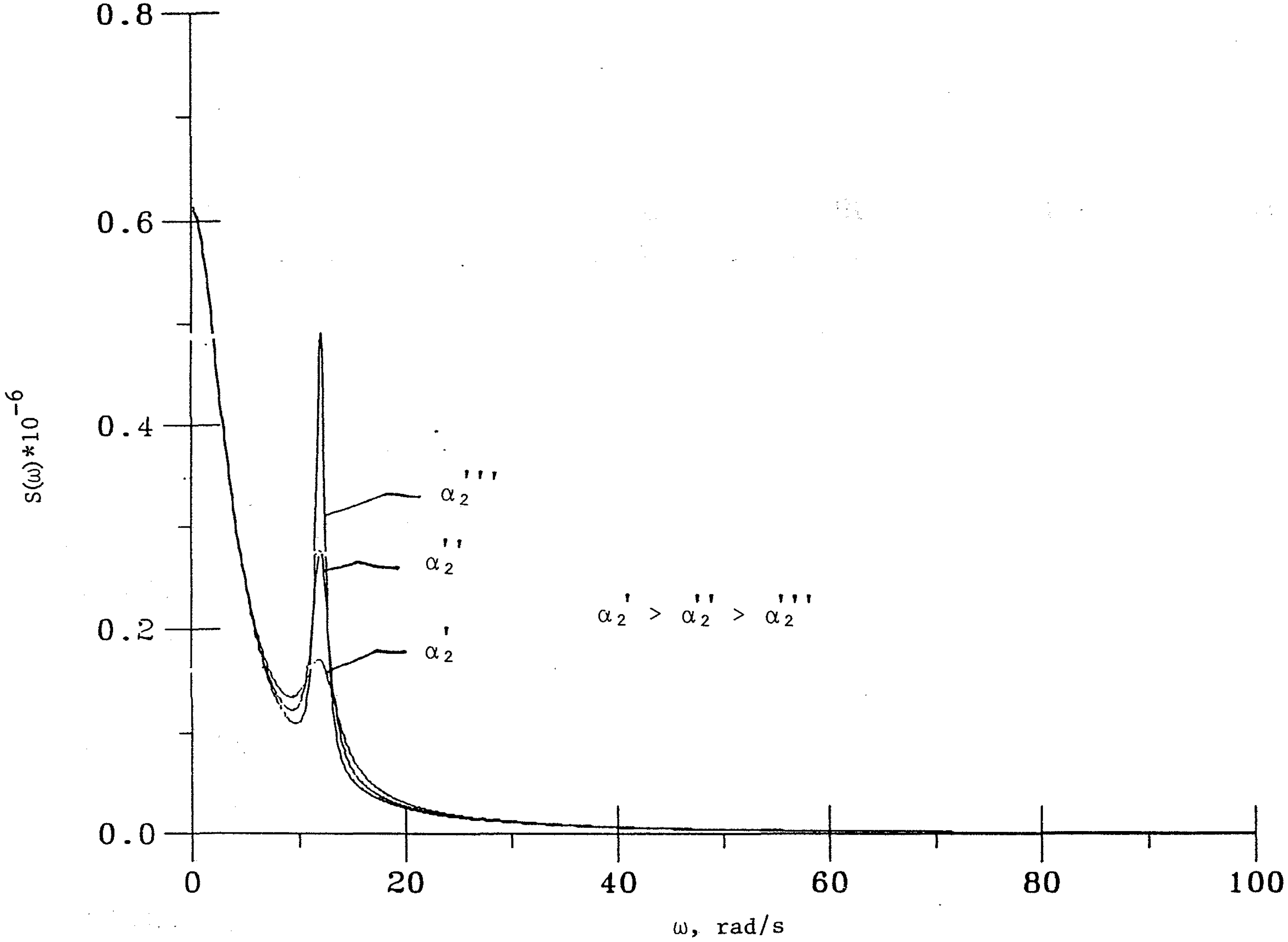


Figure 18. Effect of α_2 on PSD function.

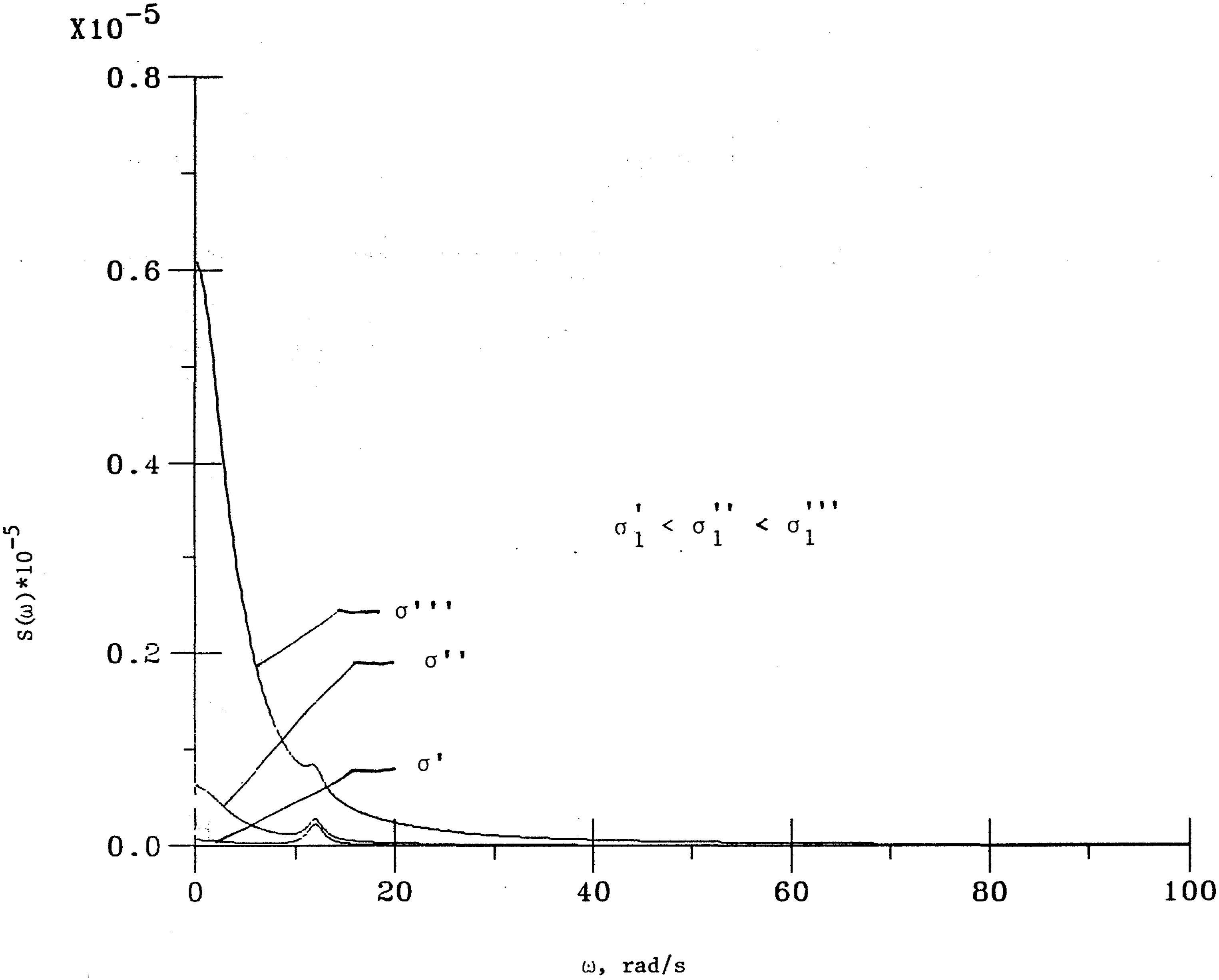


Figure 19. Effect of σ_1 on PSD function.

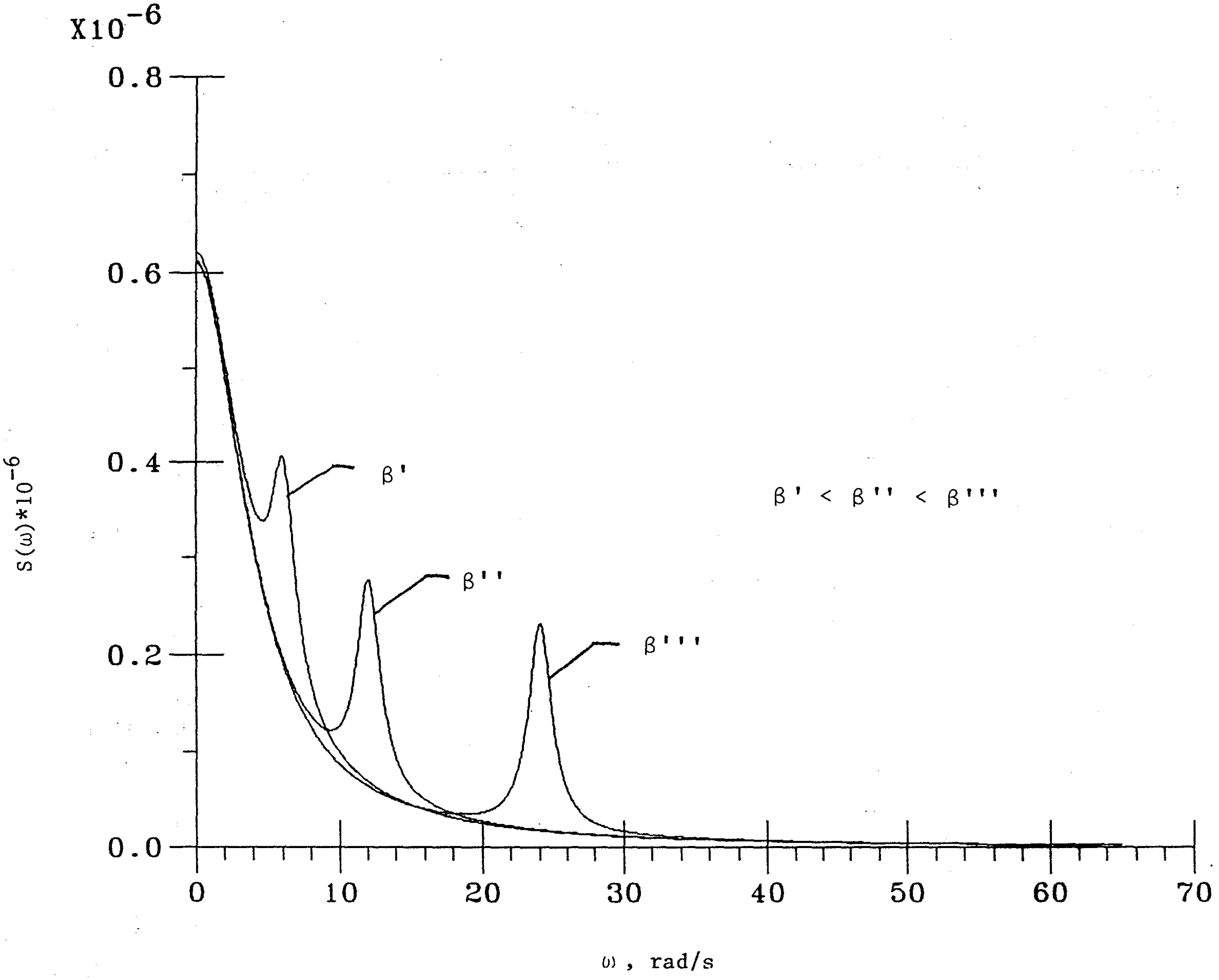


Figure 20. Effect of β on PSD function.

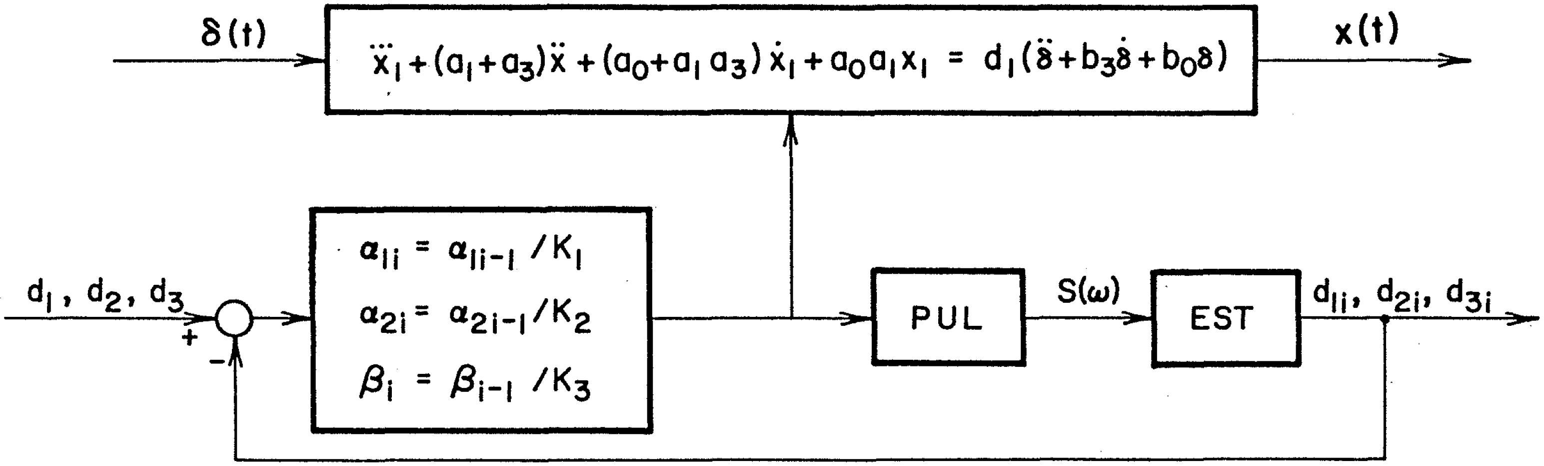


Figure 21. Block diagram of generating road profile of desired PSD using equation 8.

DIRECT PROCEDURE

In this method, the road profile data are calculated directly from the desired PSD function, S_{xx}, using the equation:

$$x_0(i) = \sum_{j=1}^{jmax} \left[\sqrt{\frac{2S_{xx}(j)}{jmax}} \quad \sin\,(2\eta f_j i\Delta\lambda + \phi_j) \right] \qquad (9)$$

where x_0 is the generated profile signal, and ϕ_j is a random phase angle between 0 and 2π. The other symbols used in equation 9 were defined earlier in this chapter. To obtain a desired roughness index, all profile data are multiplied by a constant gain factor. The value of the gain is chosen by a trial-and-error method until the desired roughness level is obtained. Figures 22 and 23 show samples of the generated profile data having the same PSD functions as those shown in figures 11 and 12. The roughness of the generated profile data was adjusted to 5 in/mi as measured with the California profilograph. The plotted profiles represent road sections 0.1 mi long. The PSD functions of the generated profiles were then computed and are shown in figure 24.

The problem of generating a sequence of data having a desired PSD function does not have a unique solution. In general, there is an infinite number of different sequences with the same PSD function, all of which can be considered to represent a typical profile of a new pavement. The profiles presented in figures 22 and 23 represent typical PCC and bituminous road profiles with a roughness index of 5 IPM_{CA}, but many other profile sequences may have the same PSD functions. A different sequence of profile data could, for example, be obtained by using a different random number generator for the phase angle in equation 9. All such profiles provide an equivalent test input for profilographs, and thus any one can be selected as the representative profile for new or newly surfaced pavements.

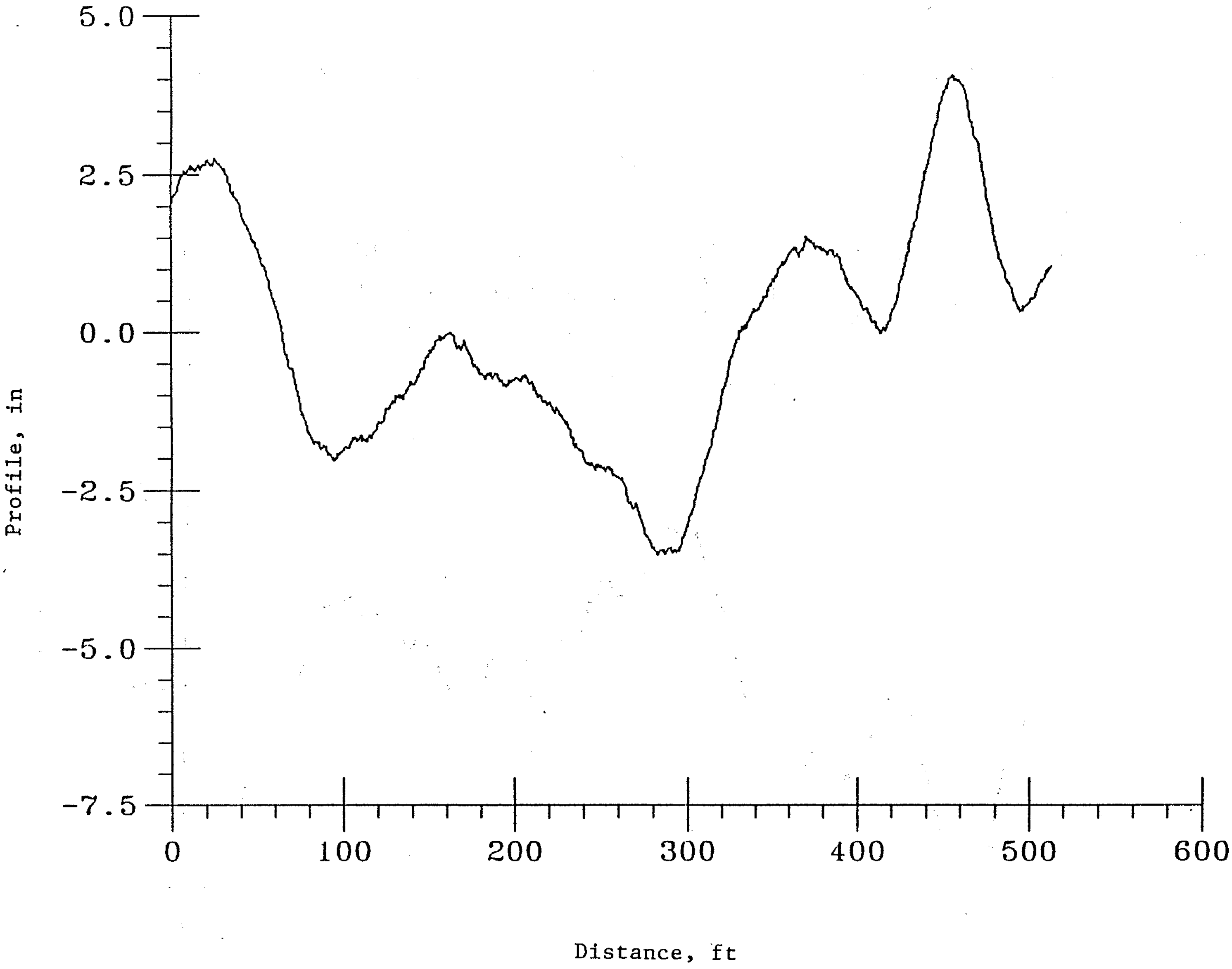


Figure 22. Computer-generated typical profile for PCC pavements, 5 IPM_{CA}.

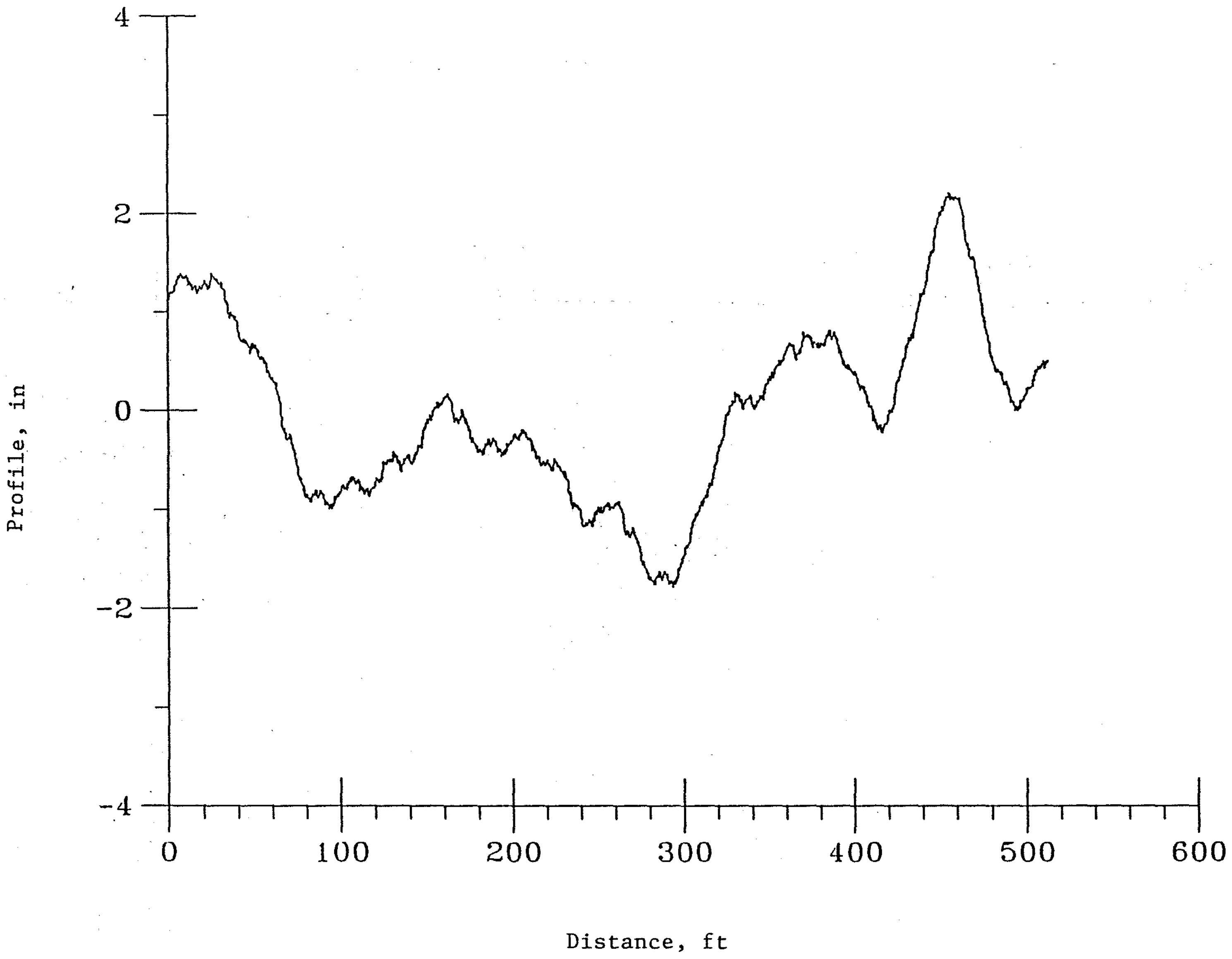


Figure 23. Computer-generated typical profile for bituminous pavements, 5 IPM_{CA}.

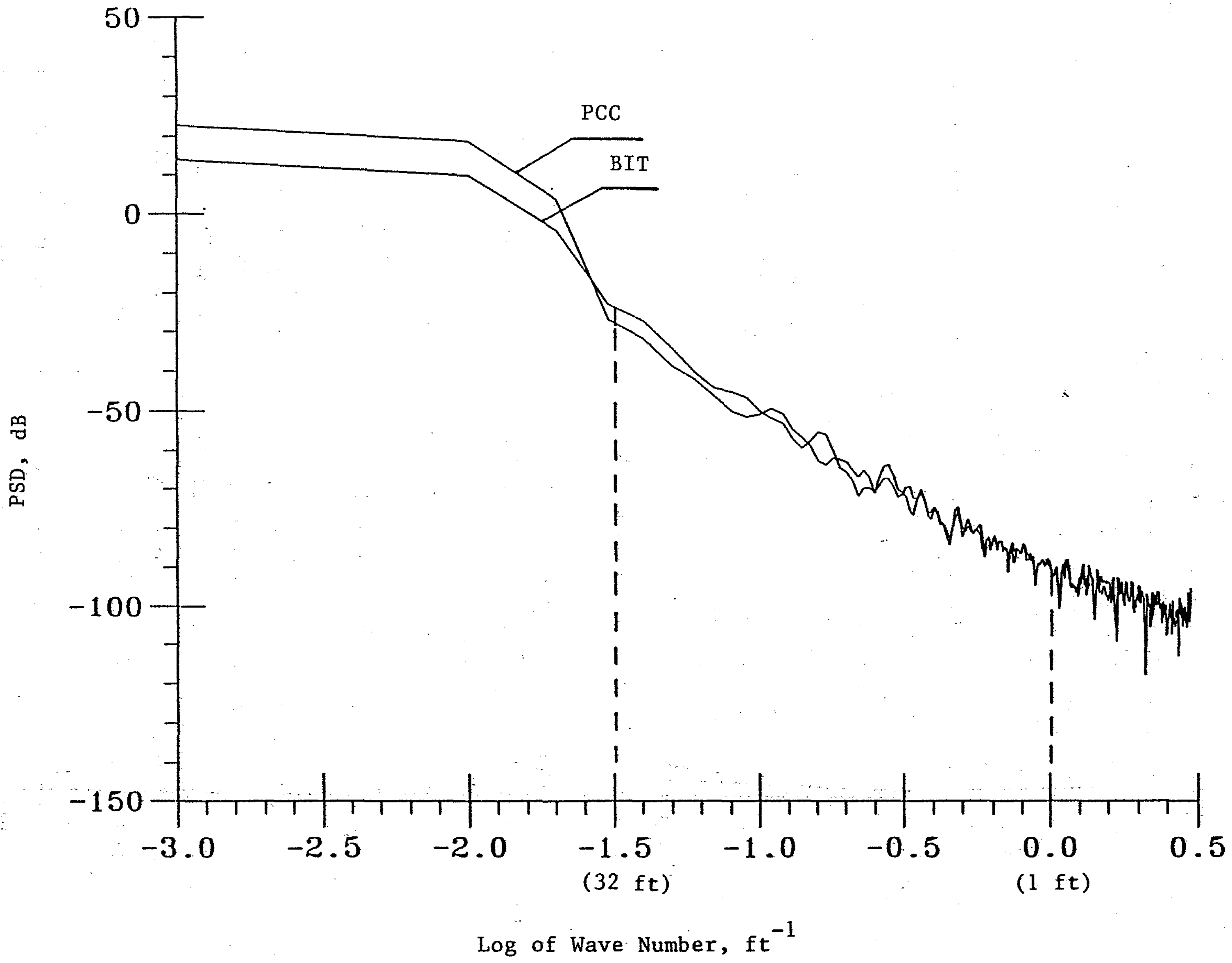


Figure 24. PSD's of typical computer-generated profiles for PCC and bituminous pavements.

4. EVALUATION OF EQUIPMENT PERFORMANCE CHARACTERISTICS

Profiling vehicles (PV)[2], response-type road roughness measuring systems (RTRRMs) and profilographs were evaluated for their ability to measure the roughness of new pavements under the dynamic conditions of highway speeds. To carry this out, PV, RTRRM, and profilograph simulations were used to obtain their frequency responses for speeds of 35 mi/h and 50 mi/h. Responses to sinusoidal roads with the roughness of 1/8 inch in 10 ft (1/8 road) and 7 in/mi (7 road) were developed. Figure 25 shows the amplitude, in inches, needed to give a 1/8 road. This amplitude is a linear function of wavelength, as shown. Figure 26 gives the same information to yield a 7 road.

In addition to the simulations, actual field tests were used to determine performance characteristics, including frequency response, precision, repeatability, reliability, and ease of operation. Each characteristic is discussed below.

ROUGHNESS THRESHOLD AND EQUIPMENT REQUIREMENTS

Based on the results of recent surveys, presented in chapter 1, the following roughness thresholds were proposed for new pavements:

- Bump acceptance criterion = 1/8 inch in 10 ft.
- Overall roughness = 7 in/mi as measured by the California profilograph with 0.2-in blanking.

The 7-in/mi acceptance value is the most common among the roughness thresholds currently used by 36 States that participated in the surveys. There is a tendency, however, to lower the roughness threshold below 7 in/mi, perhaps to 5 in/mi. The equipment used in measuring profiles of new pavements should therefore be capable of measuring roughness below 5 in/mi.

This 5-in/mi value represents a roughness index obtained from the California profilograph and should be transformed into equivalent values for

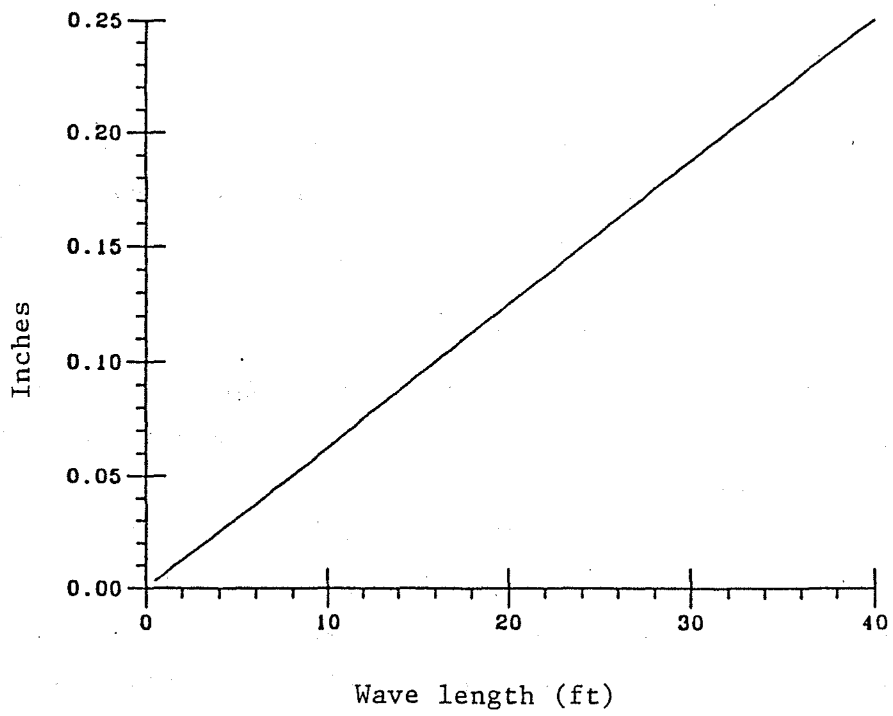


Figure 25. Amplitude of swept sinusoidal profile to give 1/8 inch in 10 ft.

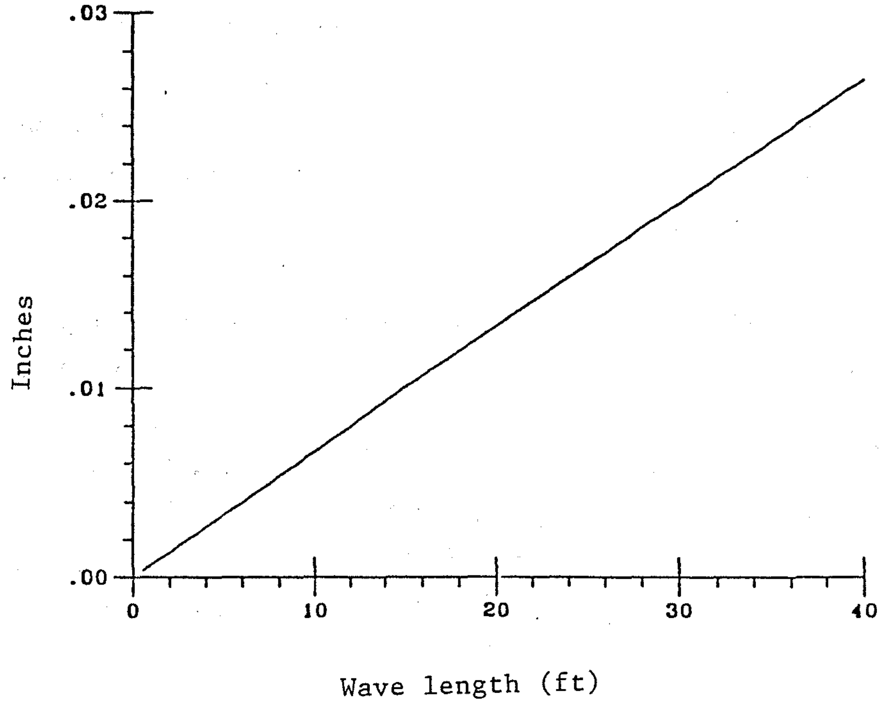


Figure 26. Amplitude of swept sinusoidal profile to give 7 inches per mile.

other devices, including the Rainhart and Ames profilographs and the profilometer. Correlations between the different devices are developed in chapter 5 to determine equivalent measurement results, a main objective of this project.

In addition to the capability to measure roughness below 5 in/mi, the devices used in new pavement profile measurement should have a sufficiently high and uniform gain over a range of wavelengths from 1.6 to 32 ft. This range was determined based on two criteria--truck tire loading and ride comfort. According to NCHRP Report 275, subjective ride quality ratings were found to correlate best with road profile frequency components in the range from 0.125 to 0.63 cycle/ft, which corresponds to wavelengths from 1.6 to 8 ft.[10] Pavement management must also give special attention to those wavelength ranges that correspond to the peaks in frequency characteristics of vertical truck tire forces. Pavement profile frequency components within these ranges excite the truck tire suspension system, generating high dynamic pavement loads. The maxima of truck tire forces occur typically between 3 and 7 Hz and between 15 and 25 Hz (figure 27). For speeds from 35 to 65 mi/h those frequencies correspond to profile wavelengths from 7.5 to 32 ft and from 2 to 6.4 ft. Combining the wavelength ranges critical either for ride comfort or for pavement damage caused by tire loading, as shown in figure 28, gives the range of 1.6 to 32 ft over which the devices used to measure the roughness of new pavements should be sufficiently sensitive.

The range of frequency (or wavelength) over which a profile measuring device should be sufficiently sensitive has been determined based on truck dynamics and human perception of road roughness, which are independent of the road pavement. The other requirement--resolution allowing for measuring roughness below 5 in/mi--was imposed on all types of pavement. Since the same roughness requirements apply to both PCC and bituminous pavements, it is logical to conclude that the same type of equipment can be used regardless of the pavement type.

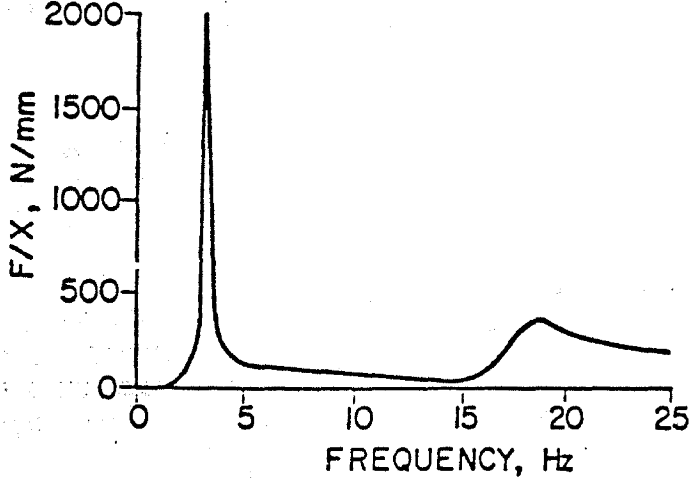


Figure 27. Frequency characteristic of truck tire pavement load.

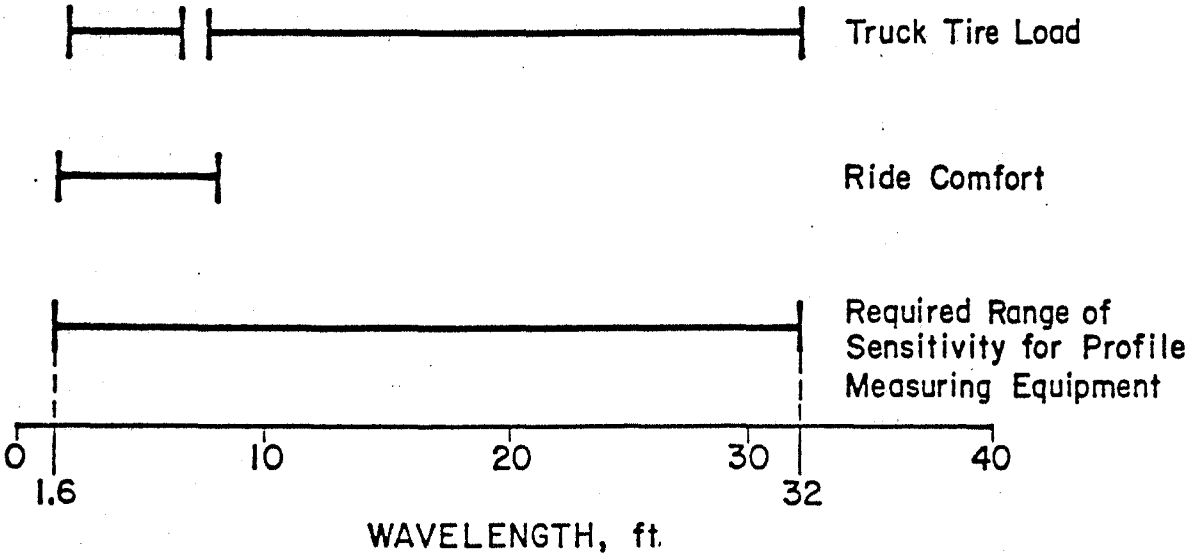


Figure 28. Summary of wavelength requirements for measurements of profiles of new pavements.

FREQUENCY RESPONSE

PROFILING VEHICLES

The response of a PV to both a 1/8 road and 7 road was processed for speeds of 35 and 50 mi/h. Figures 29 and 30 show the response to a 1/8 road, while figures 31 and 32 show the response to a 7 road. For each road, the response is given both in decibels and amplitude ratio.

For the cases of decibel versus wavelength, a correct response is 0 db; similarly for the amplitude versus wavelength, the correct response is 1.0. In all cases, the response deteriorated below wavelengths of 2 ft and was correct for wavelengths above that. Figures 33 and 34 were developed to determine the cause of the incorrect response below 2-ft wavelengths. Figure 33 shows the output for an input road with variable amplitude (7 road), the upper level being the amplitude of the bumps (top or upper level) and the lower level being the bottom of the bumps. The roads were such that the lower level was zero amplitude and upper level was twice the amplitude of the sine wave. In this figure, the lower level is not at zero and the upper level oscillates below 2-ft wavelengths. Figure 34 is the same type of data, except the roughness (bumps) was of a constant amplitude of 0.5 in for all wavelengths. This figure more clearly shows the error of the lower level and the oscillation of the upper level. To correct these results at the shorter wavelengths (higher frequencies), the low-pass filters in the profile calculating programs must be raised to a higher frequency if these are of concern. However, for a 1/8 road or 7 road, the amplitudes at these short wavelengths are so small (less than .002 and .01 in) that they are usually not of concern. In fact, the profilographs have such a large wheel that they do not see roughness in this range.

To measure roughness in this range, the PV can be used by excluding the vehicle body motion and considering only the relative body-to-road displacement since the vehicle frame is a good enough inertial reference at these short wavelengths (high frequencies).

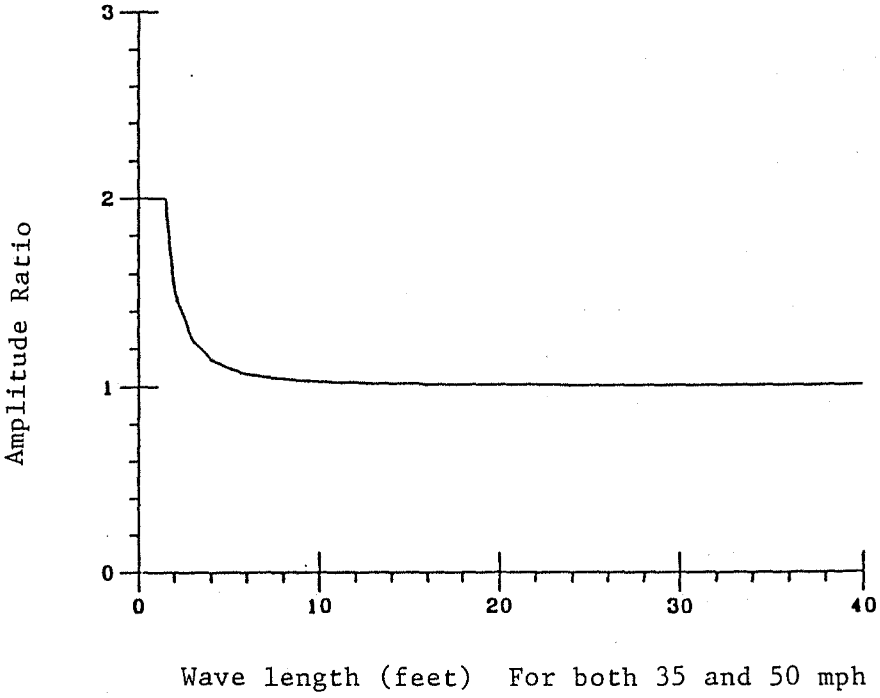


Figure 29. Profilometer simulation to detect 1/8 inch in 10-ft swept sinusoidal profiles (amplitude ratio).

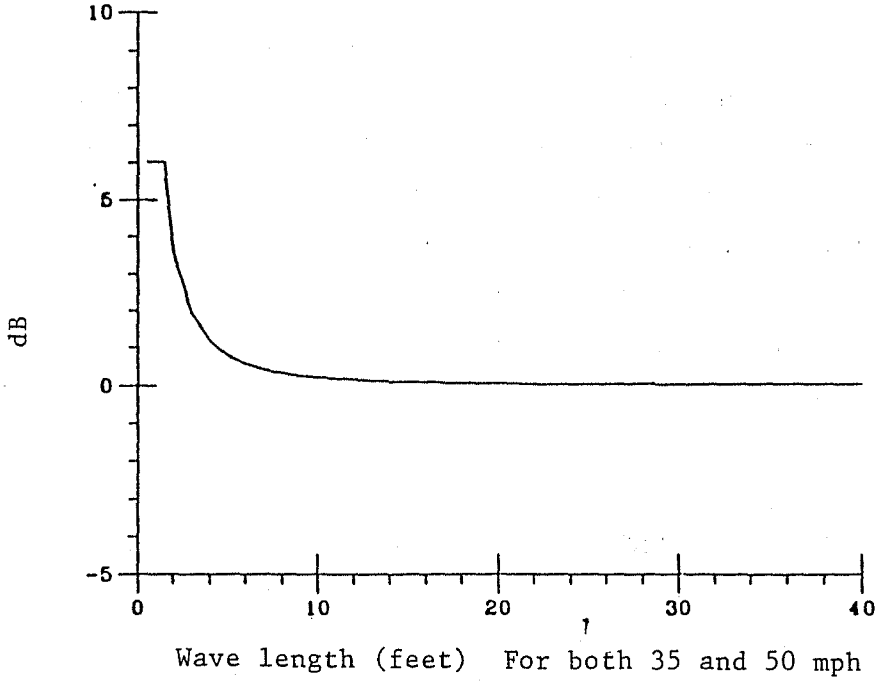


Figure 30. Profilometer simulation to detect 1/8 inch in 10-ft swept sinusoidal profiles (decibels).

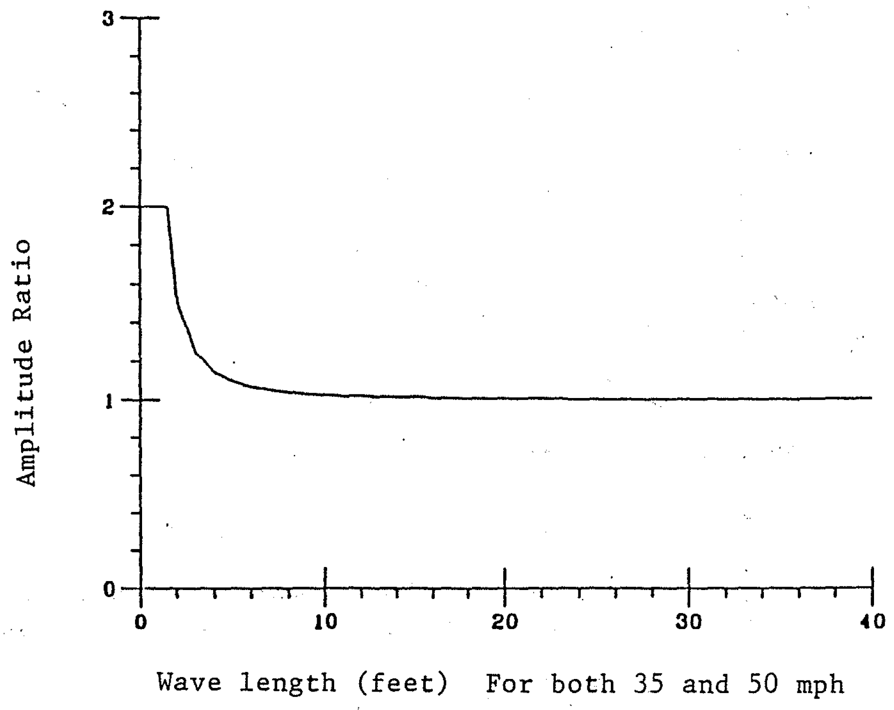


Figure 31. Profilometer simulation to detect 7-IPM swept sinusoidal profiles (amplitude ratio).

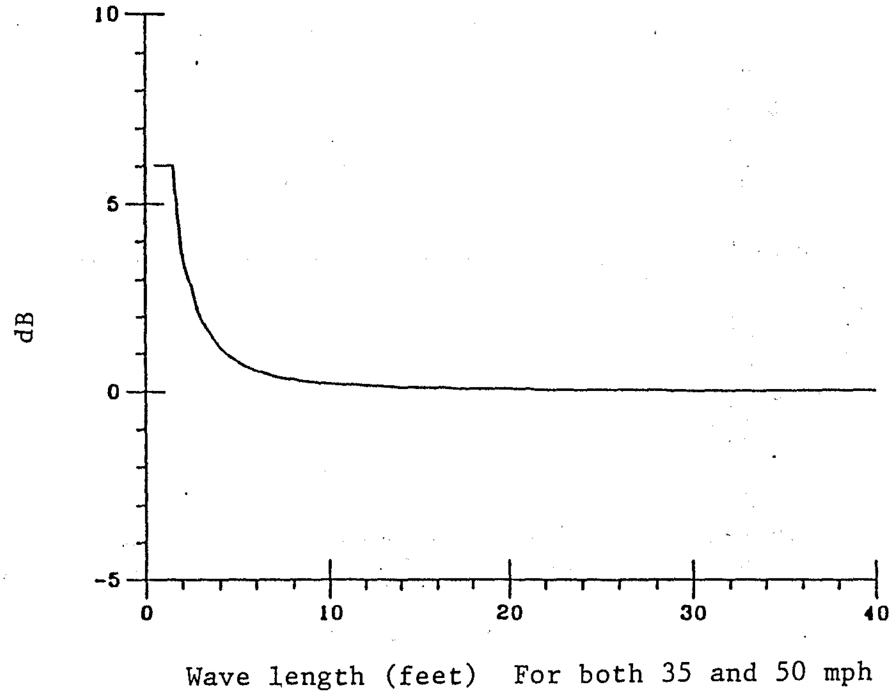


Figure 32. Profilometer simulation to detect 7-IPM swept sinusoidal profiles (decibels).

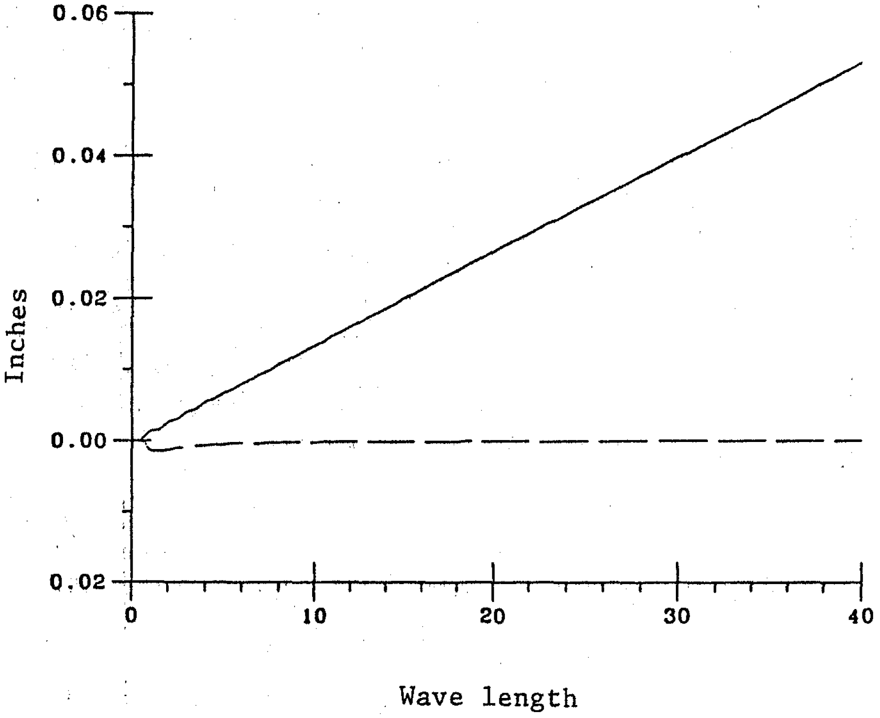


Figure 33. Output amplitude by upper (solid line) and lower (dashed line) levels for constant IPM profile.

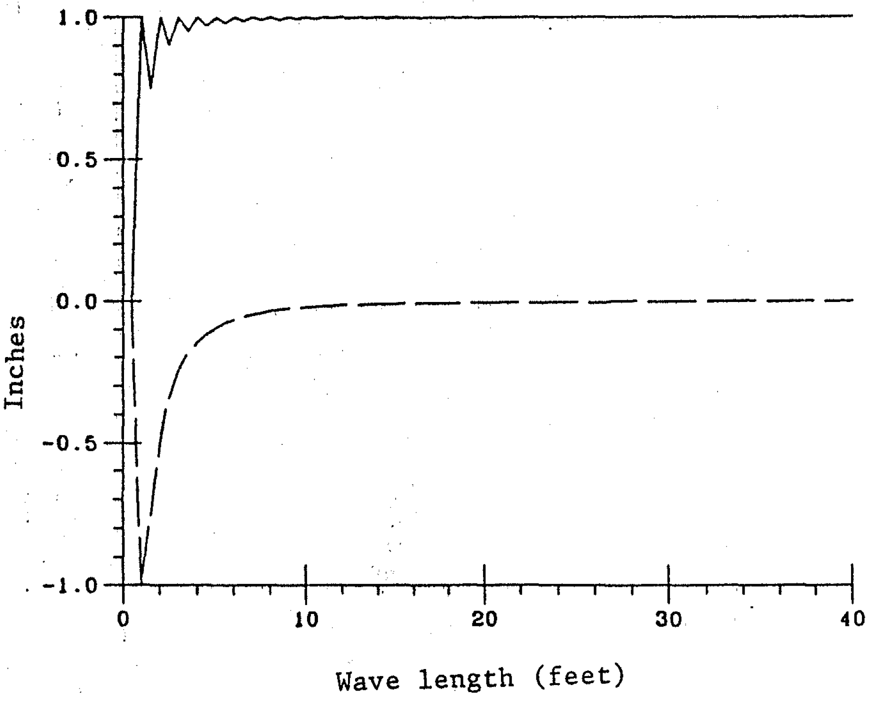


Figure 34. Output amplitude by upper (solid line) and lower (dashed line) levels for constant amplitude input.

RESPONSE-TYPE ROAD ROUGHNESS MEASURING SYSTEMS

The RTRRM simulation was subjected to the same 1/8 road and 7 road as was the PV. Figures 35 and 36 show the inches per mile (IPM) measured by a Mays meter. Because the measure is quantitized, the RTRRM shows no response to a 7 road and responds very poorly to a 1/8 road. No hysteresis was included in the simulation, as it would only make the response worse. In an attempt to investigate what would be required to allow an RTRRM to be used, no hysteresis and no quantizing was used. Figures 37 and 38 show the response to a 1/8 road at both 35 and 50 mi/h. Figure 37 shows the IPM per inch of road amplitude, and figure 38 gives only the IPM. Similarly, figures 39 and 40 give the results for a 7 road. These results show that the RTRRM gives almost no response to wavelengths below 2 ft, an overresponse at 5-ft wavelengths at 35 mi/h (8 ft at 50 mi/h), and then a more flat response at wavelengths above 10 ft. Also, these simulations show that the RTRRMs has a speed dependence (well established). Thus, to use RTRRMs for new construction roughness measurement, a linear displacement transducer to digital encoder with better than .01-in resolution with no hysteresis would be required. Further, the RTRRM would have to be calibrated and its frequency response determined for the speed at which it is to be used. Then the measurement would have to be made at a constant speed, the one used for calibration and response. The data can then be filtered with the frequency response measured to obtain a linear measurement. Such corrections are time-consuming and require a great deal of computer memory, but are considered necessary if the RTRRM system is used. Since other equipment that is much easier and less time-consuming to use can do this work, and because of the insensitivity shown in figure 36, it is recommended that the RTRRM systems are not used in measuring roughness of new pavements.

PROFILOGRAPHS

The frequency response characteristics of profilographs were obtained using the kinematic model of profilograph described in chapter 6.

Equation 31 was used to compute the frequency response transfer functions for the California and Rainhart profilograph. The plots of the

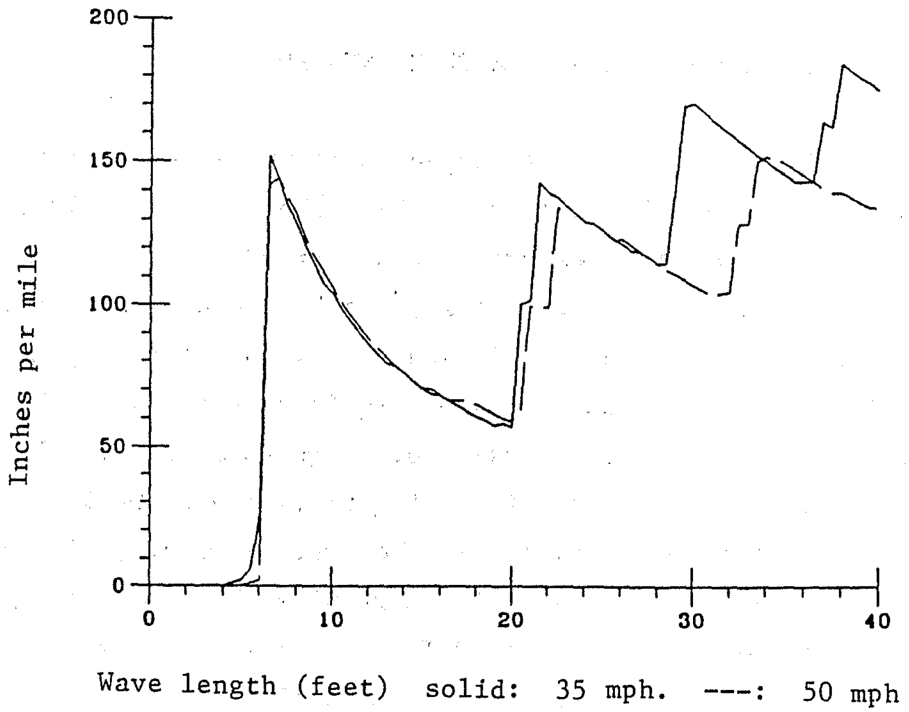


Figure 35. Mays meter quantized simulation to detect 1/8 inch in 10-ft profiles.

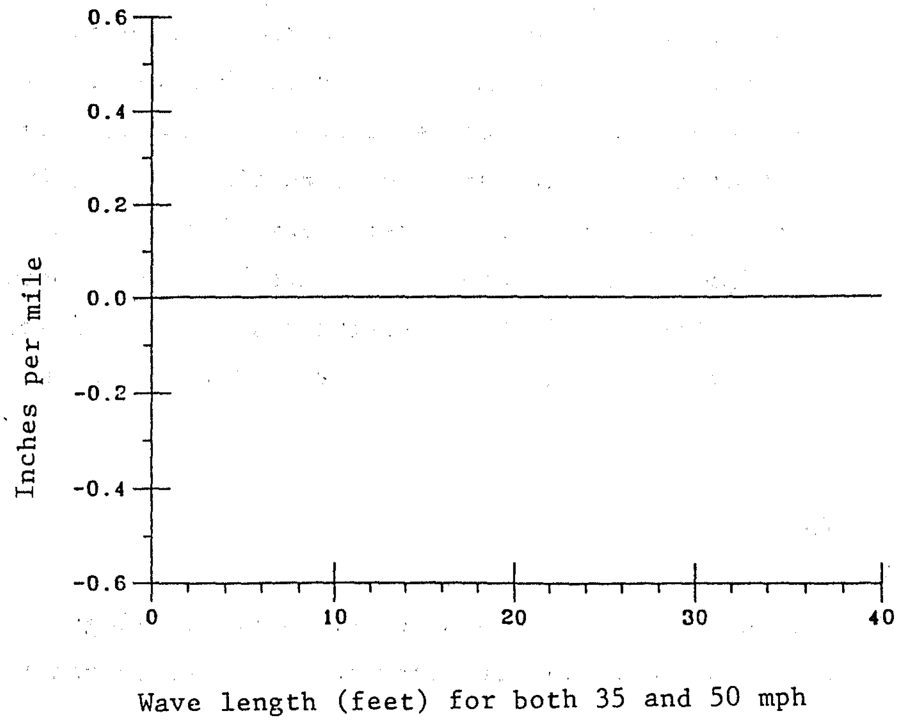


Figure 36. Mays meter quantized simulation to measure 7-IPM swept sinusoidal profiles.

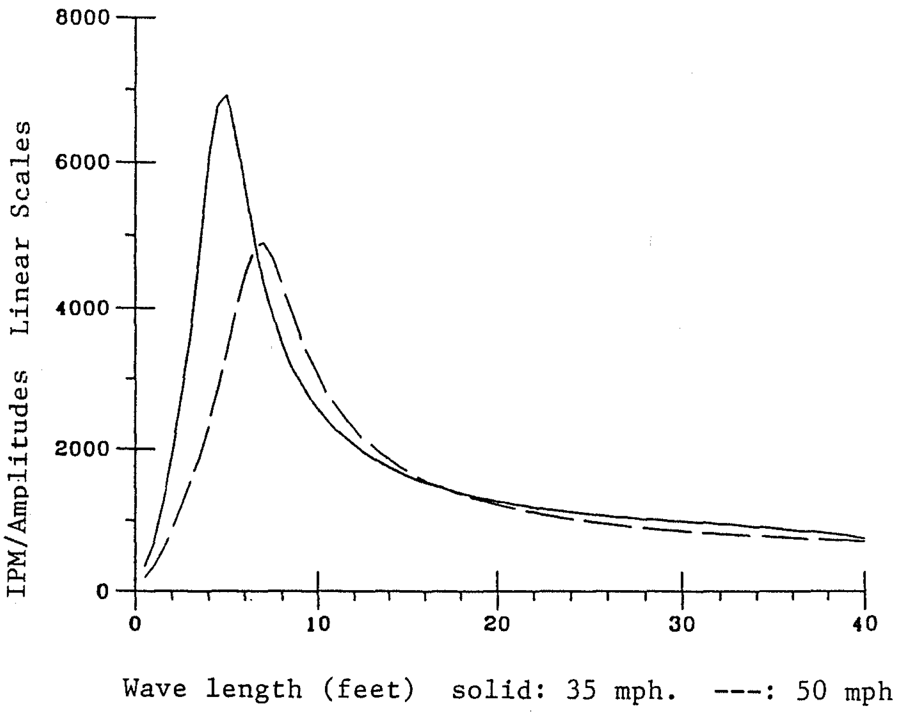


Figure 37. Mays meter simulation to detect 1/8 inch in 10-ft swept sinusoidal profiles (IPM/amplitude).

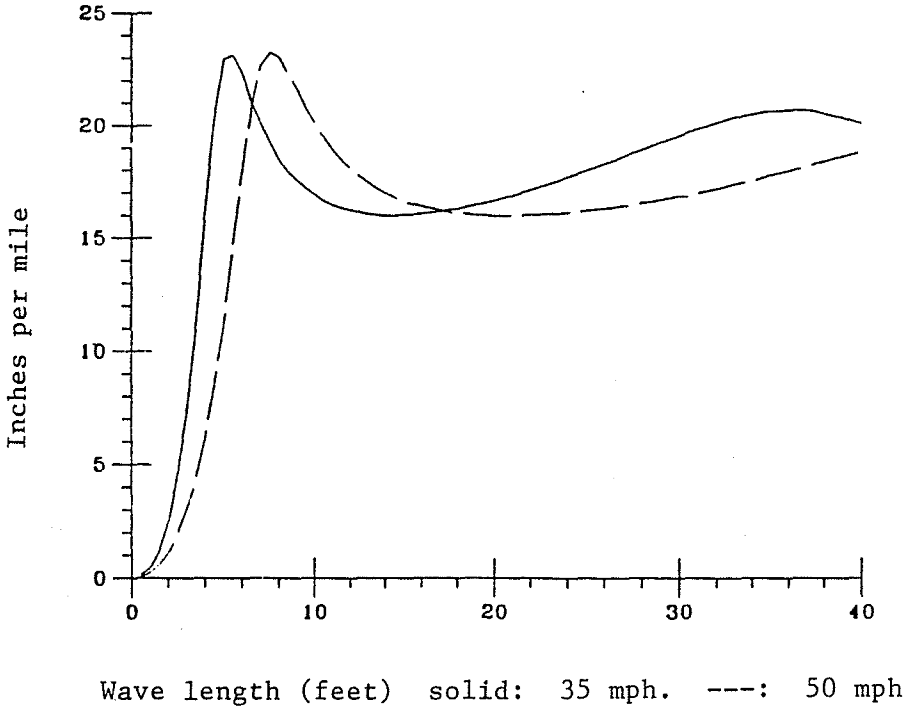


Figure 38. Mays meter simulation to detect 1/8 inch in 10-ft swept sinusoidal profiles (IPM).

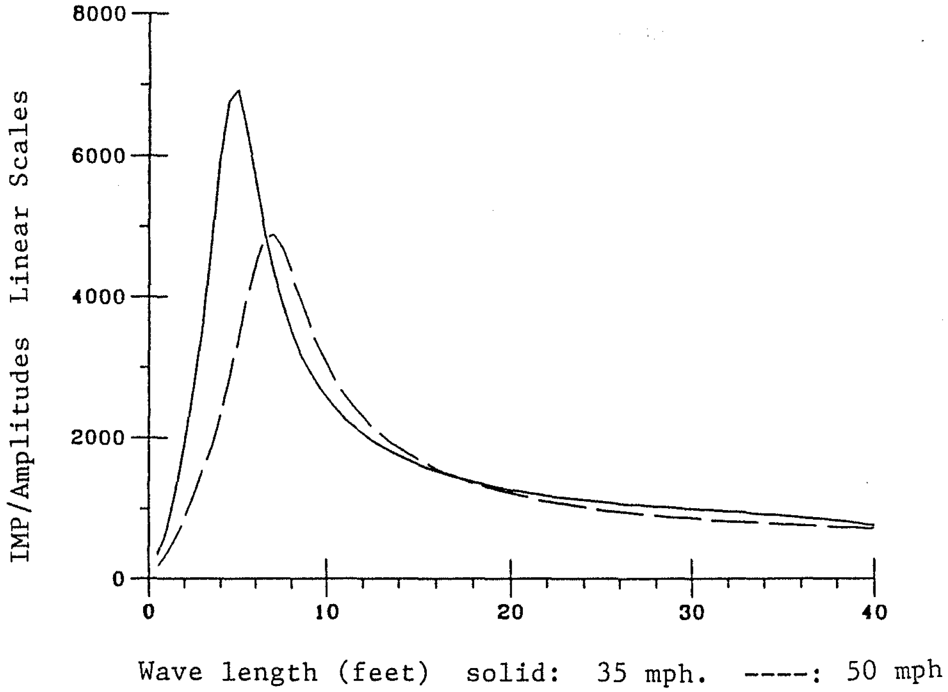


Figure 39. Mays meter simulation to detect 7-IPM swept sinusoidal profiles (IPM/amplitude).

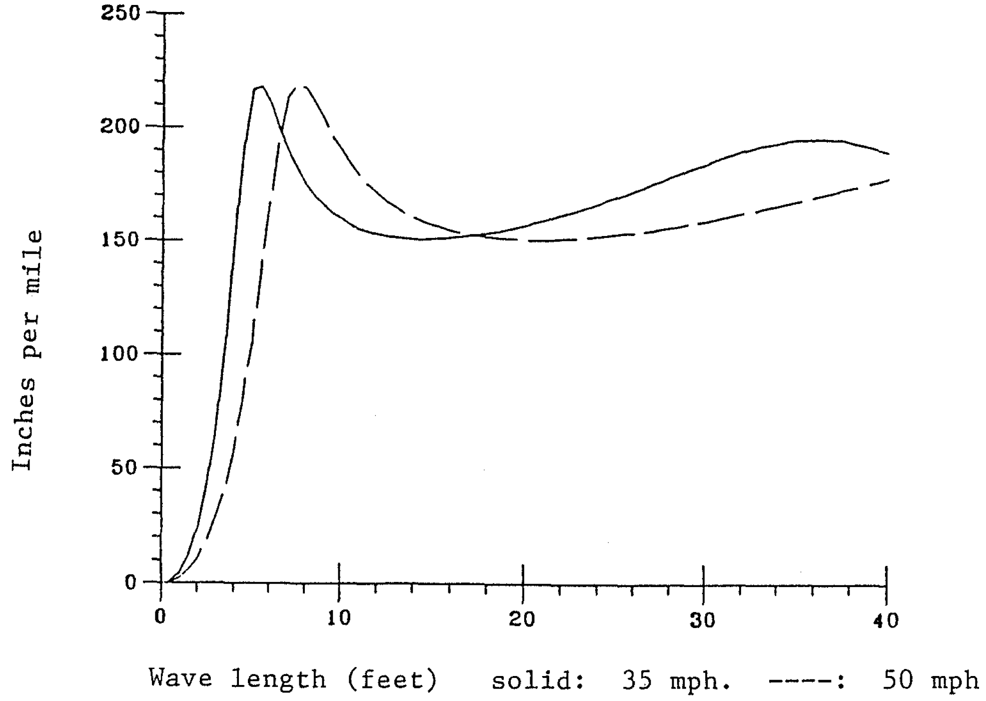


Figure 40. Mays meter simulation to detect 7-IPM swept sinusoidal profiles (IPM).

The magnitude of the transfer function for the 12-wheel California profilograph, shown in figure 41, is very nonuniform. The initial oscillations of the magnitude between 0 and 2.0 level out at wavelengths equal to approximately 4 ft. The magnitude starts oscillating again, at much slower frequency, for wavelengths above 7 ft. The final peak occurs at the wavelength equal to the length of the main truss, 25 ft. The minimum preceding this peak is at the wavelength equal to half of the length of the main truss. Also, note that the two longest wavelengths for which the magnitude of the transfer function is equal to one are 2/3 of L_0 and $2L_0$ (this last point is outside the range of wavelengths shown in figure 41). A thick horizontal line in figure 41 marks the level of unity magnitude. It should be noted that the profile components of the wavelengths for which the magnitude of the transfer function is greater than one are amplified by the profilograph, whereas those for which the magnitude curve is under the unity line are attenuated.

The magnitude of the frequency response transfer function for the Rainhart profilograph shown in figure 42 is more uniform over the range of wavelengths that are of interest, i.e., from 1.6 ft to 32 ft. The better uniformity of the frequency response of the Rainhart profilograph compared with the California profilograph is achieved because of the more uniform pattern of supporting wheels.

REPEATABILITY AND PRECISION

To evaluate the precision or repeatability of each device under test, multiple runs were made at several sites. Ten runs were made using the Mays meter on 3 sites; 5 runs, using the California profilograph on 3 sites; 5 runs, using the Rainhart profilograph on 3 sites; 5 runs, using the Ames profilograph on 1 site; and 5 runs, using the profilometer on 3 sites.

The precision and repeatability of the California and Rainhart profilographs were determined for both manual and computer data reduction. Also, in one test, five persons performed the run manually to determine the

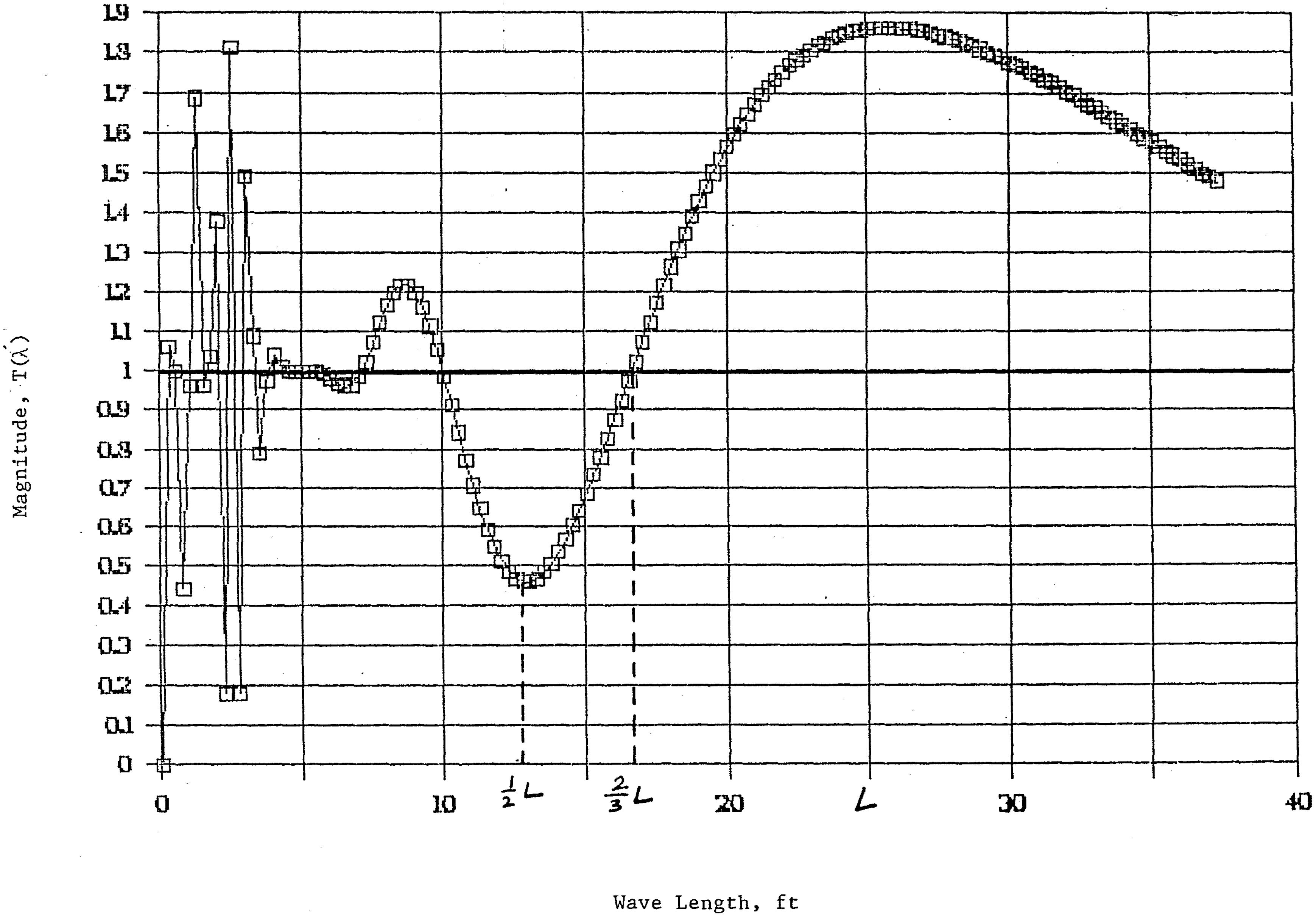


Figure 41. Frequency response of 12-wheel California profilograph.

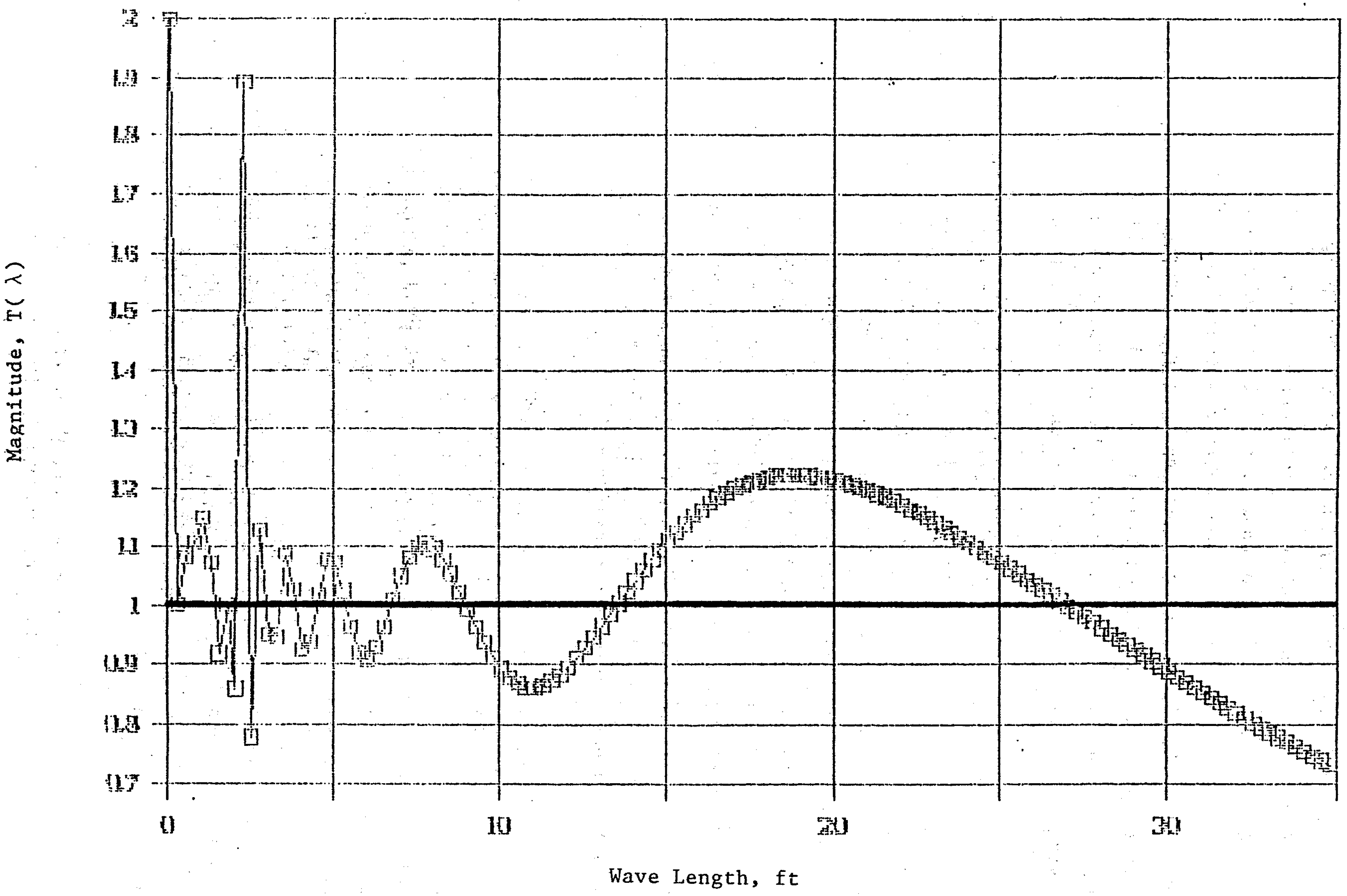


Figure 42. Frequency response for 12-wheel Rainhart profilograph.

effect of different persons manually reducing the same record. Tables 6 through 10 give the results of the repeatability tests for the Mays meter, California profilograph, Rainhart profilograph, Ames profilograph, and profilometer. Table 11 is a summary of all of the repeatability tests. The units of measurement for the Mays meter are inches of axle/body motion per mile of travel. The units of measurement for the three profilographs are inches of profile per mile of travel. The units for the profilometer are the same as the Mays meter computed from the quarter-car model. Table 12 gives the variations when several persons reduce the same piece of data.

From the summary, table 11, several important results are shown. First, the repeatability of the California and Rainhart profilographs appears to be improved when the data is reduced by computer rather than by hand. This is expected since the hand calculations also include variations due to subjective evaluation, and this is eliminated with computer calculations. Thus, with the calculations removed, the California profilograph had a percent coefficient of variation of around 9.2 percent versus a 3.7-percent coefficient of variation for the Rainhart. The Ames profilograph gave the best result, 2.1 percent, but it was not in the original equipment list to be tested; five runs on only one site were made with this profilograph. More testing is needed to validate this result.

The Mays meter had a 5-percent coefficient of variation, and the profile vehicle gave a percent variation of 4.2. It should also be pointed out that when hand calculations are not included the devices generally had a poor repeatability on site 4, which was almost twice as smooth as sites 1 and 2. This shows that as smoother pavements are measured, the repeatability of the device becomes more important.

In comparing table 12 and table 11, it should be noted that the variations of people hand calculating data from the strip chart recordings were the same size as total variations of multiple runs with one person reducing the data.

Table 6. Repeatability of Mays meter.

	Run No.												
Site	1	2	3	4	5	6	7	8	9	10	Mean	σ	Coeff. of Variation, %
1	298	322	298	303	298	281	294	304	274	291	296	13.1	4.4
2	343	341	342	322	323	357	338	338	339	348	339	10.3	3.0
3	142	161	178	170	186	183	169	166	175	184	171	13.2	7.7

Table 7. Repeatability of California profilograph.

		Run No.							
Site	Data Reduction Method	1	2	3	4	5	Mean	σ	Coeff. of Variation, %
1	Hand	51.5	47.5	60.0	56.0	62.0	55.3	6.9	12.5
	Computer	49.85	46.80	53.49	---	56.90	51.76	4.38	8.5
2	Hand	66.5	67.0	61.5	62.5	80.5	67.6	7.6	11.2
	Computer	75.26	71.72	73.13	70.45	72.60	72.63	1.79	2.5
4	Hand	33.5	44.0	35.0	40.5	40.5	38.7	4.3	11.1
	Computer	35.50	45.15	40.51	44.15	55.49	44.16	7.38	16.7

Table 8. Repeatability of Rainhart profilograph.

Site	Data Reduction Method	Run No. 1	2	3	4	5	Mean	σ	Coeff. of Variation, %
1	Hand	41.0	--	41.0	47.0	42.0	42.8	2.9	6.8
	Computer	36.49	--	37.88	37.51	34.21	36.52	1.65	4.5
2	Hand	51.5	--	53.0	54.0	52.5	52.8	1.0	1.9
	Computer	55.69	--	50.0	45.69	51.47	50.71	4.13	8.1
4	Hand	28.5	26.5	29.0	34.5	28.5	30.1	2.9	9.6
	Computer	27.95	--	25.01	25.81	26.09	26.22	1.24	4.7

Table 9. Repeatability of Ames profilograph (site Rt 220/1).

Run No. 1	2	3	4	5	Mean	σ	Coeff. of Variation, %
16.0	16.5	17.0	16.5	16.5	16.5	.35	2.1

Table 10. Repeatability of profilometer.

Site		Run No. 1	2	3	4	5	Mean	σ	Coeff. of Variation, %
1	Quantized	181	181	174	179	167	176	5.9	3.3
2	Quantized	190	193	206	200	202	198	7.2	3.7
4	Quantized	107	109	102	95	95	102	5.9	5.7

Table 11. Summary of repeatability tests coefficient of variation (standard deviation/mean in percent).

Device	Method of Calculation	Site No. 1	2	4	Average
California profilograph	Hand	12.5	11.2	11.1	11.6
	Computer	8.5	2.5	16.7	9.2
Rainhart profilograph	Hand	6.8	8.1	9.6	8.2
	Computer	4.5	1.9	4.7	3.7
Mays meter	Computer	4.4	3.0	7.7	5.0
Profile vehicle	Computer	3.3	3.7	5.7	4.2
Ames*	Hand	---	---	---	2.1

* Only one site in the field

Table 12. Comparison of hand calculations of site 4 by five persons reducing California profilograph records.

Person							
1	2	3	4	5	Mean	σ	Coeff. of Variation, %
34	39.5	36	37.5	27.5	34.9	4.6	12.2

RELIABILITY AND OPERATIONS

To facilitate data collection, several characteristics are desirable in the design of a field profilograph. The structural design must be sufficiently rigid to minimize vibrations caused by road macrotexture and must provide a suitable foundation for the recording mechanism. The profilograph should be constructed from parts that are easily replaced or fabricated. It is desirable that the overall design and configuration minimize the effort required to propel, maneuver, and transport the profilograph. The recording mechanism should be easy to operate and maintain.

Of the three profilographs tested, the Rainhart profilograph was structurally the most complex; it was constructed from many custom designed parts. The design provided good vibration dampening. However, the Rainhart profilograph was the heaviest and the least maneuverable. Its recording mechanism was cumbersome and difficult to operate and maintain. The profilograph was easily transported to and from the test sites by lowering the attached tow wheels. No provisions are made for disassembling the profilograph for transport inside a vehicle.

The California profilograph was structurally rigid and more maneuverable and considerably lighter than the Rainhart profilograph. The instrument was easily assembled and disassembled. The recording mechanism was easy to operate and maintain. The profilograph was constructed with few custom parts and the disassembled package fit easily inside a van or pick-up truck.

The Ames profilograph was the simplest in design and construction; however, this profilograph was also the least rigid. The poor structural rigidity made the instrument susceptible to vibrations caused by the pavement macrotexture. Of the instruments tested, the Ames profilograph was the lightest and the easiest to maneuver. It was very easy to assemble, disassemble, and transport. The recording mechanism uses standard fan-fold computer paper and was easy to operate and maintain. The profilograph is constructed from readily available items.

5. CORRELATION AMONG ROUGHNESS MEASURING DEVICES

DESCRIPTION OF DATA SETS

Four devices were used in the full-field testing program: the California profilograph, Rainhart profilograph, profilometer, and Mays meter. The measurements made with the two profilographs were simultaneously recorded by two independent recording systems, a conventional analog recorder and a computer data acquisition system, producing two data sets for each profilograph. The computer-recorded data from the profilographs as well as the data measured by the profilometer were further processed in several different ways, producing additional data sets. Eleven data sets were used in the correlation and regression analysis and are presented below. Names and brief descriptions of the data sets are given in table 13. The numerical values of the data are listed in table 14.

CORRELATION AND REGRESSION MODELS OBTAINED FROM FIELD TEST DATA

Table 15 shows values of the coefficient of correlation calculated for all combinations of data sets listed in table 13.

It is assumed here that a relationship between two variables is statistically significant if the coefficient of correlation between them is equal to or greater than 0.75. The correlations obtained for each set of data are briefly reviewed:

- PROFC--This set correlates well with all other sets of data except RAINHA, the set of roughness values measured with the Rainhart profilograph and processed manually. The average coefficient of correlation with all other sets of data is $\bar{R} = 0.834$.

- PROFQ--This set has the same general pattern as PROFC, although the values of the coefficients of correlation are slightly lower in most

Table 13. Data sets used in the correlation of roughness measuring devices.

Name	Measuring Device	Recording System	Data Processing Method	Units of Roughness
CALIFA	California Profilograph	Analog Strip Chart	Standard California Profilograph Procedure	IPM_{CA}
CALIFQ	California Profilograph	Computer Data Acquisition System (CDAS)	Computerized Standard California Profilograph Procedure with Quantized Roughness Scale	IPM_{CA}
CALIFC	California Profilograph	CDAS	Computerized California Profilograph Procedure with Continuous Roughness Scale	IPM_{CA}
RAINHA	Rainhart Profilograph	Analog Strip Chart	Standard Rainhart Profilograph Procedure	IPM_{RH}
RAINHQ	Rainhart Profilograph	CDAS	Standard Rainhart Profilograph Procedure with Quantized Roughness Scale	IPM_{RH}
RAINHC	Rainhart Profilograph	CDAS	Rainhart Profilograph Procedure with Continuous Roughness Scale	IPM_{RH}
QCARQ	Profilometer	CDAS	Quarter-Car Simulation with Quantized Roughness Scale	IPM_{QC}
QCARC	Profilometer	CDAS	Quarter-Car Simulation with Continuous Roughness Scale	IPM_{QC}
PROFQ	Profilometer	CDAS	Computerized Standard California Profilograph Procedure with Quantized Roughness Scale	IPM_{CA}

Table 13. Data sets used in the correlation of roughness measuring devices (continued).

Name	Measuring Device	Recording System	Data Processing Method	Units of Roughness
PROFC	Profilometer	CDAS	Computerized California Profilograph Procedure with Continuous Roughness Scale	IPM_{CA}
MAYS	Mays Meter	On-Board Computer	No Data Processing	IPM_{MM}

Table 14. Roughness data used in the correlation analysis.

Road/ Site No.	CALIFA	CALIFQ	CALIFC	RAINHA	RAINHQ	RAINHC	QCARQ	QCARC	PROFQ	PROFC	MAYS
Rt. 220/1	11.00	--	--	17.50	21.27	5.69	36.19	102.86	3.81	3.90	98.0
Rt. 220/2	8.50	13.99	15.10	10.50	30.41	7.33	34.95	101.25	1.94	2.70	76.0
Rt. 220/3	6.00	6.00	5.68	13.00	20.29	5.16	30.10	100.52	1.46	1.21	80.0
Rt. 220/4	6.50	5.00	5.86	14.50	28.99	6.78	20.39	90.11	0.00	0.59	78.0
Rt. 220/5	7.00	2.00	3.26	14.50	15.99	4.30	29.13	96.20	0.00	0.40	73.0
I 80/1	6.25	12.00	11.80	8.75	29.99	7.11	43.14	135.62	6.38	5.40	82.0
I 80/2	9.50	22.99	23.94	10.25	33.00	8.01	42.16	144.97	10.30	8.01	104.0
I 80/3	17.50	35.00	35.29	22.50	70.98	18.57	81.18	167.49	19.81	20.42	138.0
I 80/4	10.25	24.99	24.84	14.25	42.99	10.55	43.56	124.44	8.91	7.62	97.0
I 80/5	6.25	18.99	19.70	6.50	20.00	4.49	28.71	107.19	2.97	3.08	73.0
I 70/1	8.00	11.50	11.33	3.00	11.00	2.33	33.65	93.76	5.77	5.87	74.0
I 70/2	7.00	10.00	10.58	2.00	6.00	1.82	17.31	69.31	1.44	1.75	37.0
I 70/3	2.00	6.50	6.63	3.00	5.00	1.34	13.46	69.87	1.92	1.95	57.5
I 70/4	4.00	10.00	9.92	1.00	5.02	1.46	19.23	76.61	2.89	2.85	73.3
I 70/5	2.00	7.00	5.91	0.00	3.00	0.85	6.73	75.57	0.48	0.35	48.0
I 83/1	0.00	8.00	7.99	1.00	6.00	1.69	14.29	75.80	0.48	0.29	63.2
I 83/2	0.00	7.50	7.10	1.00	1.00	0.18	15.24	70.78	0.00	0.00	43.4
I 83/3	0.00	--	--	3.00	15.00	3.63	13.34	71.72	0.95	0.88	43.8
I 83/4	0.00	6.00	6.48	1.00	0.00	0.00	13.33	68.33	0.48	0.29	36.6
I 83/5	0.00	2.00	2.11	0.00	1.00	0.13	17.15	72.11	0.95	0.72	41.0
Rt. 15/1	15.50	15.99	15.40	13.00	45.00	11.39	47.68	119.73	7.63	9.03	109.6
Rt. 15/2	11.00	21.00	21.44	6.00	10.00	2.47	22.88	94.17	4.77	3.51	65.8
Rt. 15/3	7.00	20.50	20.36	4.00	10.00	2.75	27.65	92.72	3.34	3.20	80.2
Rt. 15/4	12.00	11.50	11.80	6.50	24.99	6.11	29.55	87.13	4.77	4.98	89.4
Rt. 15/5	7.50	8.00	9.57	3.50	4.00	0.82	32.41	107.90	4.29	4.01	82.2

Table 15. Coefficient of correlation between the field data sets.

	PROFC	PROFQ	RAINHA	CALIFA	MAYS	QCARQ	QCARC	CALIFQ	CALIFC	RAINHQ	RAINHC
PROFC	1.000	.986	.617	.788	.832	.925	.843	.828	.825	.846	.851
PROFQ	.986	1.000	.586	.757	.818	.907	.869	.857	.855	.812	.819
RAINHA	.617	.586	1.000	.754	.813	.786	.751	.518	.530	.872	.861
CALIFA	.788	.757	.754	1.000	.858	.834	.752	.719	.729	.791	.791
MAYS	.832	.818	.813	.858	1.000	.902	.878	.716	.720	.858	.859
QCARQ	.925	.907	.786	.834	.902	1.000	.932	.753	.759	.907	.898
QCARC	.843	.869	.751	.752	.878	.932	1.000	.752	.760	.848	.849
CALIFQ	.828	.857	.518	.719	.716	.753	.752	1.000	.997	.707	.720
CALIFC	.825	.855	.530	.729	.720	.759	.760	.997	1.000	.704	.719
RAINHQ	.846	.812	.872	.791	.858	.907	.848	.707	.704	1.000	.991
RAINHC	.851	.819	.861	.791	.859	.898	.849	.720	.719	.991	1.000

cases. The average coefficient of correlation with all other sets of data is $\bar{R} = 0.827$.

- RAINHA--This set of manually calculated roughness values from the Rainhart profilograph correlates poorly with all other data sets with roughness values calculated using the data processing procedure for the California profilograph (PROFC, PROFQ, CALIFA, CALIFQ, CALIFC). As explained in the next section, the California and Rainhart procedures' roughness values cannot correlate well because of the nonlinearities of the two procedures. However, the correlation with the manually calculated values of roughness from the California profilograph is statistically significant with a 0.75 coefficient of correlation. The average coefficient of correlation with all other sets of data is $\bar{R} = 0.708$.

- CALIFA--The only insignificant correlations occur with the roughness measures obtained from the California profilograph but recorded and processed by a computer data acquisition system. This unexpected observation is difficult to explain. The average coefficient of correlation with all other sets of data is $\bar{R} = 0.777$, which is considerably higher than the value of $\bar{R}$ obtained for the Rainhart profilograph.

- MAYS--The measurements obtained with the Mays meter correlate better than expected (based on simulation results) with other sets of data, except computer processed data from the California profilograph. This performance can be explained by the fact that many sites were much rougher than the road profile used in the simulation. Particularly high correlations are observed with the sets of data produced by other RTRRM systems, QCARQ, and QCARC. The average coefficient of correlation with all other sets of data is $\bar{R} = 0.825$.

- QCARQ--Statistically significant correlations are obtained with all other sets of data. The values of roughness in this data set, as well as in QCARC, are computed using a data processing procedure that does not involve any significant nonlinearities. The average coefficient of correlation with all other sets of data is $\bar{R} = 0.860$.

- QCARC--The comments given concerning QCARQ apply to this set of data. The average coefficient of correlation with all other sets of data is $\bar{R} = 0.823$.

- CALIFQ--This set correlates poorly with manually calculated roughness values for the California profilograph and with all Rainhart profilograph data sets. Again, the lack of correlation can be attributed to the nonlinearities in the data processing procedure. The average coefficient of correlation with all other data sets is $\bar{R} = 0.757$.

- CALIFC--The same pattern as that observed with CALIFQ is seen with this set. The average coefficient of correlation with all other data sets is $\bar{R} = 0.760$.

- RAINHQ--This set of computer processed data from the Rainhart profilograph correlates considerably better with all other sets of data than the set of manually calculated roughness values, RAINHA. The only insignificant correlations are observed with CALIFQ and CALIFC which, again, can be explained by the differences in the data processing procedures used to generate those sets of data. However, the overall improvement due to the use of the computer data acquisition system is remarkable. The average coefficient of correlation with all other sets of data is $\bar{R} = 0.834$.

- RAINHC--The comments given concerning RAINHQ apply to RAINHC. The average coefficient of correlation with all other sets of data is $\bar{R} = 0.836$.

Several general observations can be made on the basis of the results of the correlation analysis. First, it is quite clear that data sets containing roughness measurements obtained with the RTRRM systems, i.e., MAYS, QCARQ, and QCARC, correlate very well among themselves. Second, the data sets produced by different nonlinear data processing procedures do not correlate well. Finally, the computer data acquisition system proved to be extremely beneficial when applied with the Rainhart profilograph. No improvement was observed as a result of using the computer system with the California profilograph.

Following the correlation analysis, the linear regression models were developed for all those combinations of data sets having the coefficient of correlation equal to or greater than 0.75. The general form of the regression models was

$$y = a_1x + a_0 \tag{11}$$

where a_1 is the slope and a_0 is the intercept of the regression line. The values of the parameters together with their standard error of estimate and the values of standard deviation around the regression line for each model are given in table 16.

A reduced field testing program was conducted in the final stage of this study to compare the performance of the Ames profilograph with the performance of the California profilograph. The measurements were conducted on five PCC sites on U.S. Rt. 220. The roughness of each site, 0.1 mile in length, was measured with the two profilographs, and the results are shown in table 17. The linear regression equation developed for these data is:

$$y = -0.38 + 0.772x \tag{12}$$

where y is the roughness measured with the California profilograph and x is the roughness measured with the Ames profilograph. The coefficient of correlation is 0.851, and the model standard deviation is 1.35. The same data processing procedure with a blanking band of 0.2 in was used with both profilographs. The correlation between the measurements is strong; the slope parameter in the regression model is equal to 0.772, which indicates that the results obtained with the California profilograph are, on the average, equal to approximately 77.2 percent of the results produced by the Ames profilograph. This difference is explained by the presence of high-frequency noise in the Ames profilograph. This profilograph has a much smaller mass

Table 16. Results of regression analysis.

		Model Parameters (Std. Error of Estimate)			
Dependent Variable, y	Independent Variable, x	a_0	a_1	Standard Deviation Around the Regression Line	Coeff. of Correlation
PROFQ	PROFC	0.113(0.200)	0.999(0.035)	0.75340	.986
CALIFA	PROFC	3.32 (0.808)	0.879(0.143)	3.042	0.788
MAYS	PROFC	56.1 (3.72)	4.74 (0.659)	14.01	0.832
QCARQ	PROFC	16.1 (1.62)	3.34 (0.286)	6.088	0.925
QCARC	PROFC	77.9 (3.78)	5.03 (0.668)	14.21	0.843
CALIFQ	PROFC	6.67 (1.30	1.51 (0.223)	3.560	0.828
CALIFC	PROFC	6.89 (1.32)	1.51 (0.226)	3.513	0.825
RAINHQ	PROFC	1.24 (0.635)	0.856(0.112)	2.389	0.846
RAINHC	PROFC	1.44 (0.618)	0.849(0.109)	2.327	0.851
CALIFA	PROFQ	3.40 (0.864)	0.833(0.150)	3.231	0.757
MAYS	PROFQ	56.2 (3.88)	4.60 (0.673)	14.51	0.818
QCARQ	PROFQ	16.2 (1.81)	3.23 (0.313)	6.754	0.907
QCARC	PROFQ	77.1 (3.50)	5.11 (0.608)	13.10	0.869
CALIFQ	PROFQ	6.36 (1.20)	1.54 (0.202)	3.814	0.858
CALIFC	PROFQ	6.58 (1.22)	1.54 (0.205)	3.791	0.855
RAINHQ	PROFQ	1.32 (0.700)	0.811(0.121)	2.617	0.812
RAINHC	PROFQ	1.51 (0.680)	0.806(0.118)	2.542	0.819
RAINHA	CALIFA	0.668(1.46)	0.987(0.179)	4.255	0.754
RAINHA	MAYS	-8.20 (2.42)	0.208(0.031)	3.772	0.813
RAINHA	QCARQ	-1.91 (1.68)	0.318(0.052)	3.991	0.787
RAINHA	QCARC	-10.6 (3.36)	0.184(0.034)	4.263	0.752
RAINHA	RAINHQ	1.60 (0.910)	1.26 (0.147)	3.171	0.872
RAINHA	RAINHC	1.38 (0.972)	1.26 (0.155)	3.296	0.861
CALIFA	MAYS	-5.80 (1.63)	0.168(0.021)	2.537	0.858
CALIFA	QCARQ	-0.76 (1.152)	0.257(0.036)	2.730	0.834

Table 16. Results of regression analysis (continued).

Dependent Variable, y	Independent Variable, x	Model Parameters (Std. Error of Estimate) a_0	a_1	Standard Deviation Around the Regression Line	Coeff. of Correlation
CALIFA	QCARC	-6.99 (2.57)	0.141(0.026)	3.259	0.752
CALIFA	RAINHQ	2.73 (0.867)	0.872(0.140)	3.021	0.791
CALIFA	RAINHC	2.53 (0.892)	0.884(0.142)	3.023	0.791
MAYS	QCARQ	3.2 (4.61)	1.42 (0.142)	10.92	0.902
MAYS	QCARC	-7.26 (9.51)	0.838(0.095)	12.07	0.878
RAINHQ	MAYS	-6.81 (1.48)	0.152(0.019)	2.307	0.858
RAINHC	MAYS	-6.51 (1.45)	0.151(0.019)	2.264	0.859
QCARC	QCARQ	52.7 (4.04)	1.54 (0.125)	9.581	0.932
CALIFQ	QCARQ	1.31 (2.42)	0.386(0.074)	3.787	0.753
CALIFC	QCARQ	1.41 (2.40)	0.390(0.073)	3.777	0.759
RAINHQ	QCARQ	-2.82 (0.799)	0.254(0.025)	1.892	0.907
RAINHC	QCARQ	-2.48 (0.823)	0.248(0.025)	1.950	0.898
CALIFQ	QCARC	-10.2 (4.48)	0.232(0.044)	4.300	0.752
CALIFC	QCARC	-10.31 (4.44)	0.236(0.044)	4.318	0.760
RAINHQ	QCARC	-9.47 (1.87)	0.144(0.019)	2.380	0.848
RAINHC	QCARC	-9.13 (1.84)	0.142(0.018)	2.336	0.849
CALIFQ	CALIFC	0.137(0.257)	0.993(0.017)	0.4518	0.997
RAINHC	RAINHQ	0.269(0.170)	0.977(0.027)	0.5906	0.991

than the California profilograph, which makes the Ames dynamic response to the pavement profile significant and results in the addition of a high-frequency component to the profile measurements.

Table 17. Roughness measurements in IPM_{CA} obtained with California and Ames profilographs.

Site Number	1	2	3	4	5
California	13.50	10.50	7.00	8.50	8.00
Ames	16.00	15.50	9.00	11.00	12.50

REGRESSION MODELS OBTAINED FROM COMPUTER SIMULATION DATA

Profilographs are relatively simple devices and can be modeled accurately with simple mathematical models. The main reason for the relative accuracy and simplicity of mathematical modeling is the lack of significant dynamic effects in the operation of the majority of profilographs. The dynamic effects may become significant, despite the low speed of operation, if the mass of the profilograph is too small, as, for instance, is the case with the Ames profilograph.

Mathematical models of profilographs were applied here to develop idealized mathematical relationships between the roughness measurements obtained with the California and Rainhart profilographs. These mathematical models are discussed in detail in section 6 of this report.

The data were obtained using computer simulation. The computer model of a profilograph was subjected to input signals representing sequences of the typical profile data generated by the computer program described earlier in this report. The output from the model represented a sequence of profile measurements obtained with the profilograph being modeled in the simulation. The roughness index values of the input (true profile) and the output (measured profile) were then computed. By multiplying the typical profile data by different gain factors, a range of roughness of the input profile was obtained.

The results of simulation of the California profilograph are shown in figures 43 and 44. The roughness scale for both axes is the same, inches per mile, calculated using the procedure for the California profilograph. The curve plotted in figure 43 was obtained by accumulating profile amplitudes exceeding the blanking band of 0.2 inches in a quantized manner, reflecting the manual procedure used with the California profilograph. The curve in figure 44 was obtained using a continuous scale of roughness. Both curves shown in figures 43 and 44 are obviously strongly nonlinear although the continuous procedure produced a slightly smoother curve. The primary cause of these nonlinearities apparently is the nonlinear data processing procedure used to calculate the roughness index. The 0.2-in blanking band affects both the input actual profile and the output measured profile. However, the effect is different for each profile because the profiles are different (the output profile is obtained by transforming the input profile through the profilograph transfer function!). As a result, the slope of the curves varies from relatively steep to zero for the discrete procedure, and almost zero for the continuous procedure. The low- or zero-sloped sections of the curves mean that the California profilograph together with this data processing procedure will yield the same value of measured roughness for a range of roughness of the actual road profile. For example, figure 43 shows that the measured roughness would be constant and equal to 4.00 IPM_{CA}, while the actual profile roughness changes from 4.50 to 7.50 IPM_{CA}. The linear regression model equation for the discrete data processing is:

$$y = 0.486x \tag{13}$$

and for the continuous data processing procedure is:

$$y = 0.490x \tag{14}$$

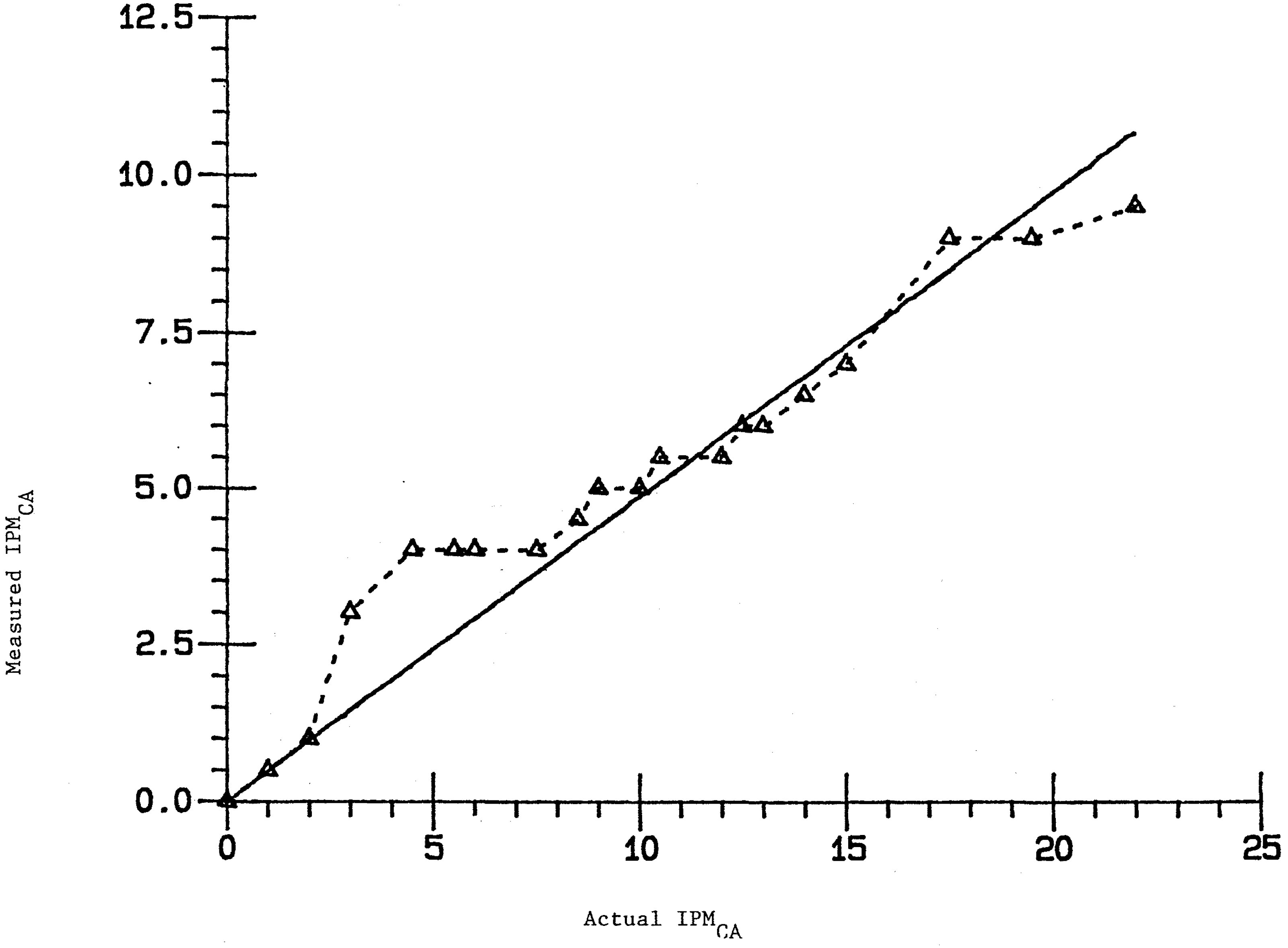


Figure 43. Discrete roughness index of measured vs. actual profile for 12-wheel California profilograph.

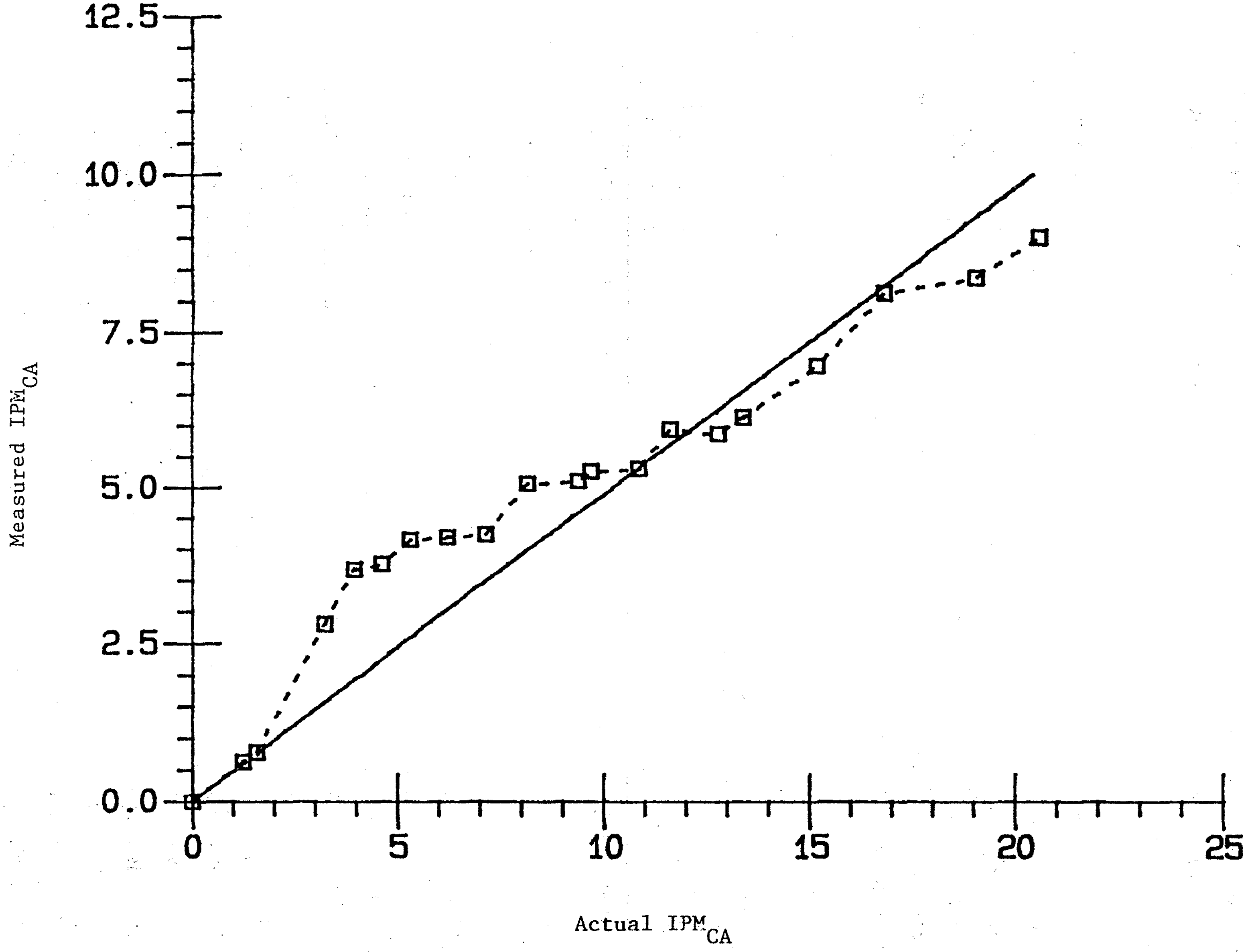


Figure 44. Continuous roughness index of measured vs. actual profile for 12-wheel California profilograph.

where y is the roughness of the profile measured by the California profilograph and x is the roughness of the actual road profile, with both roughness indices measured in IPM_{CA}. The accuracy of this model is good within the range of roughness of the true profile from 7 to 20 IPM_{CA}.

The results of computer simulation for the Rainhart profilograph are shown in figures 45 and 46. These plots are similar to those shown in figures 43 and 44 although the degree of nonlinearity is noticeably smaller, which can be attributed to the smaller blanking band used in processing data from the Rainhart profilograph. The regression equation for both the discrete and continuous case is the same:

$$y = 0.61x \qquad (15)$$

where y is the roughness of the profile measured by the Rainhart profilograph, and x is the roughness of the profile applied as the input to the simulation program. Both roughness measures in equation 15 are in terms of inches per mile for the Rainhart profilograph, IPM_{RH}.

All data presented in this section were obtained from computer simulation and are thus free of any measuring noise. Yet the relationships between the roughness of profiles measured by the profilographs and the roughness of true profiles are far from ideal. A great deal of nonlinearity in those relationships is attributed primarily to the nonlinear data processing procedures used to calculate roughness indices, in particular, to the use of blanking bands. These results also show clearly that enforcing acceptance criteria tighter than 7 IPM_{CA} for new pavements cannot be justified by the results obtained with the data processing methods currently in use. It is recommended that a linear data processing procedure be developed for the calculation of roughness from profilograph profiles. One possibility would be to use the International Roughness Index (IRI), which is becoming the roughness measure most widely accepted by the highway community.

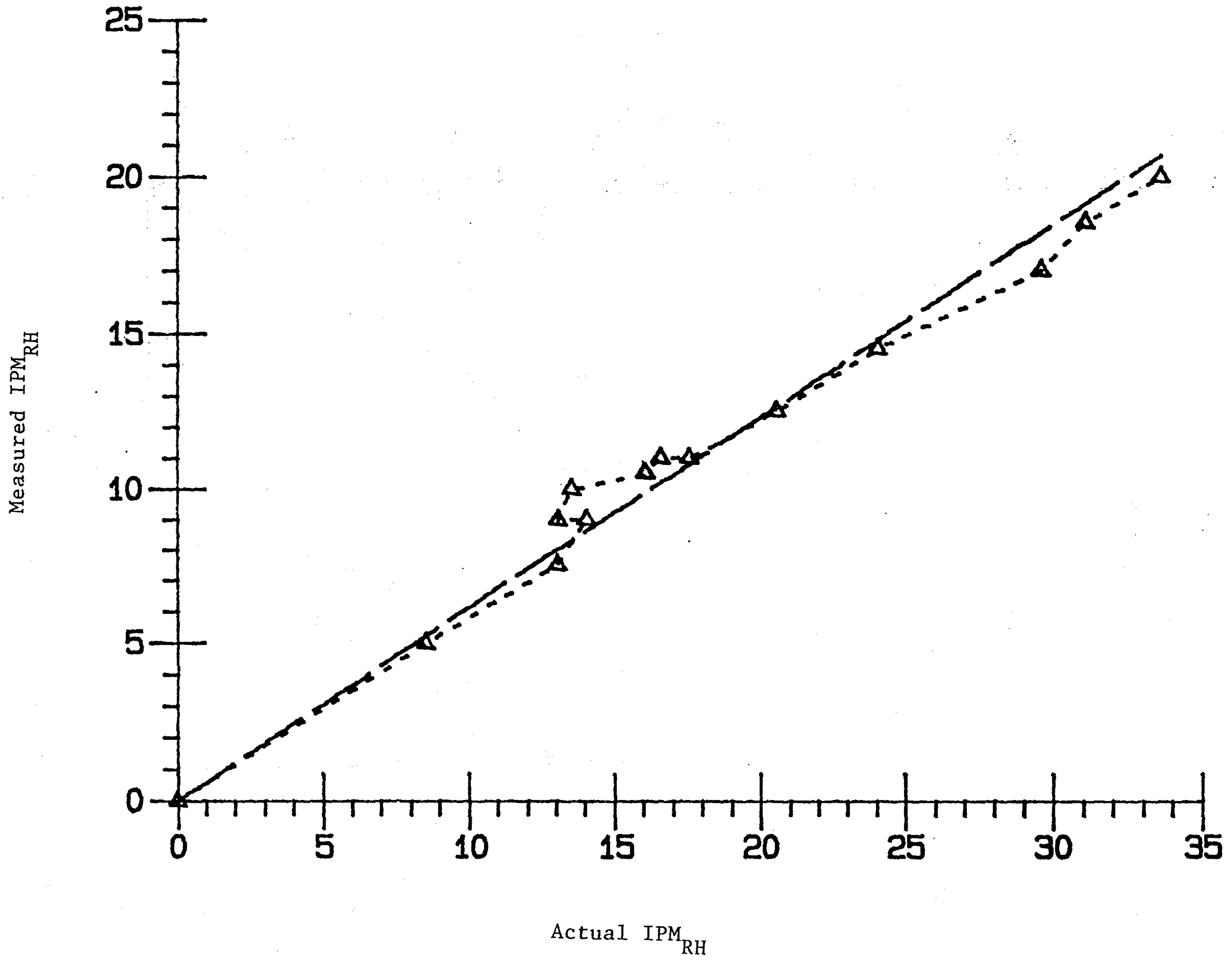


Figure 45. Discrete roughness index of measured vs. actual profile for 12-wheel Rainhart profilograph.

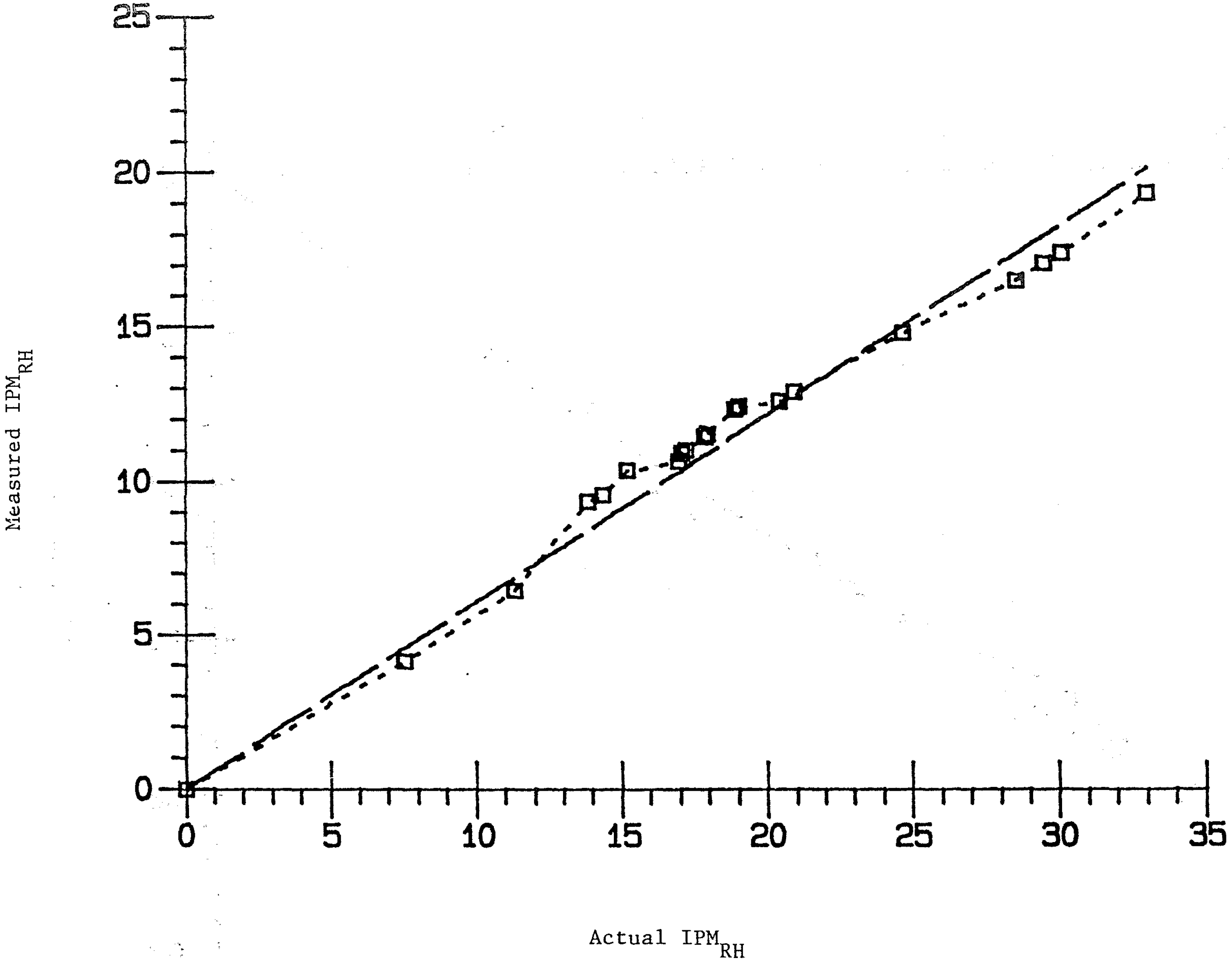


Figure 46. Continuous roughness index of measured vs. actual profile for 12-wheel Rainhart profilograph.

6. MATHEMATICAL MODEL OF PROFILOGRAPH

KINEMATIC MODEL OF PROFILOGRAPH

In section 4 of this report, it was determined that the profile measuring devices used on new or newly surfaced pavements should be sufficiently sensitive to profile wavelengths from 1.6 to 32 ft. Combined with the speed of a profilograph, approximately 2 mi/h, this range of wavelengths corresponds to the range of frequencies from 0.1 to 1.8 Hz. In such a low range of frequencies, the dynamics of a profilograph has negligible effects on its performance. Therefore, a mathematical model of profilographs (both California and Rainhart type) does not include the system dynamics. In addition, the following assumptions are made:

- All structural connections are perfectly rigid.
- All hinge joints and wheel bearings are frictionless.
- All wheels are at a point-contact with road surface at all times.

Under these assumptions, the generic mathematical model of a profilograph is given by the following equation:

$$\hat{P}(x) = P(x) - \sum_{i=1}^{N} c_i P(x-d_i) \qquad (16)$$

where

$\hat{P}$ = Measured road profile

P = Actual road profile

x = Longitudinal position coordinate

N = Number of supporting wheels

d_i = Distance between i-th wheel and the center of the measuring wheel parallel to the axis of the profilograph

c_i = Coefficient representing the effect of the i-th wheel on result of measurement

For a 12-wheel California profilograph, the model equation takes the following form:

$$\hat{P}(x) = P(x) - \frac{1}{2}\left\{\frac{1}{2m}\sum_{\ell=1}^{m}[P(x+\delta_\ell) + P(x-\delta_\ell)] + \frac{1}{2n}\sum_{r=1}^{n}[P(x+\delta_r) + P(x-\delta_r)]\right\} \tag{17}$$

where

m = 4, half of the number of wheels on the right-hand side of profilograph

n = 2, half of the number of wheels on the left-hand side of profilograph

δ_1 = Distance between the 1-th wheel and the center of the measuring wheel measured in the x-direction (1 = 1,2,3,4)

δ_r = Distance between the r-th wheel and the center of the measuring wheel measured in the x-direction (r = 1,2)

The values of δ_ℓ and δ_r are calculated from the equations:

$$\delta_\ell = \begin{cases} \frac{L_0}{2} - \frac{m-1}{2} L_1 & \text{for } \ell = 1 \\ \delta_1 + (\ell-1)L_1 & \text{for } \ell = 2,3,4 \end{cases} \tag{18}$$

and

$$\delta_r = \begin{cases} \frac{L_0}{2} - \frac{n-1}{2} L_1 & \text{for } r = 1 \\ \delta_1 + (r-1)L_1 & \text{for } r = 2 \end{cases} \tag{19}$$

where

L_0 = Length of the main truss

L_1 = Distance between two supporting wheels attached to the same minor truss

For the 12-wheel California profilograph with L_0 = 25 ft and L_1 = 2.5 ft, the values of δ are

$$\delta_1 = 8.75 \text{ ft}, \ \delta_2 = 11.25 \text{ ft}, \ \delta_3 = 13.75 \text{ ft}, \text{ and } \delta_4 = 16.25 \text{ ft}$$

for the right-hand side wheels and

$$\delta_1 = 11.25 \text{ ft and } \delta_2 = 13.75 \text{ ft}$$

for the left-hand side wheels.

The mathematical model of the 12-wheel Rainhart profilograph is:

$$\hat{P}(x) = P(x) - \frac{1}{N} \sum_{i=1}^{N/2} [P(x + \delta_i) + P(x - \delta_i)] \tag{20}$$

where N is the total number of wheels and the values of δ_i are

$$\delta_i = \begin{cases} \dfrac{L_0}{2} - \dfrac{n-1}{2} L_1 & \text{for } i = 1 \\ \delta_1 + (i-1) L_1 & \text{for } i = 2,3,\ldots,6 \end{cases} \tag{21}$$

The length of the main truss is $L_0 = 13.5$ ft and the distance of the supporting wheels in the x-direction is $L_1 = 2.25$ ft. For these basic dimensions, the values of δ_i, $i = 1,2,\ldots,6$, are:

$\delta_1 = 1.125$ ft $\delta_2 = 3.375$ ft $\delta_3 = 5.625$ ft
$\delta_4 = 7.875$ ft $\delta_5 = 10.125$ ft $\delta_6 = 12.375$ ft

FREQUENCY RESPONSE CHARACTERISTICS

A frequency response characteristic provides complete information about the behavior of a system subjected to sinusoidal input signals. A system frequency response transfer function is defined as

$$T(j\omega) = \frac{Y(j\omega)}{X(j\omega)} \tag{22}$$

where $X(j\omega)$ represents a sinusoidal input signal of frequency ω and $Y(j\omega)$ is the output of the same frequency. The system transfer function is a complex quantity that can be presented in an exponential form as

$$T\,(j\omega) = |T(j\omega)|e^{j\phi(\omega)} \tag{23}$$

where $|T(j\omega)|$ is the magnitude of the transfer function and $\phi(\omega)$ is the phase angle between the input and output components of frequency ω. In the analysis of performance of profilographs, only the magnitude of the frequency response transfer function is of interest. Plots of magnitudes of the profilograph frequency response were developed for a range of profile wavelengths.[5] In that computational procedure a sinusoidal input signal of unit amplitude and frequency ω is fed into the profilograph model and the simulated output signal is recorded. The amplitude of the sinusoidal output signal gives the magnitude value of the frequency response characteristic for frequency ω. This time-consuming method requires numerous computer runs to determine the frequency response over a wide range of frequencies, especially in a high frequency spectrum.

In this study, an analytical expression for the magnitude of the profilograph transfer function was derived. The Laplace transformation of the profilograph model equation 16 gives

$$\hat{P}(s) = P(s) - \sum_{i=1}^{N} c_i\, P(s)e^{-d_i s} \tag{24}$$

where s is a complex variable and $\hat{P}(s)$ and $P(s)$ are Laplace transforms of $\hat{P}(x)$ and $P(x)$, respectively. The system transfer function in the domain of Laplace variable s is

$$T(s) = \frac{\hat{P}(s)}{P(s)} = 1 - \sum_{i=1}^{N} c_i e^{-d_i s} \tag{25}$$

By substituting $s = j\omega$, the frequency response transfer function is obtained:

$$T(j\omega) = 1 - \sum_{i=1}^{N} c_i e^{-j\omega d_i} \tag{26}$$

It is assumed that the number of supporting wheels, N, is even, and that there are pairs of supporting wheels in equal distance from the measuring wheel, one pair in front and the other behind the measuring wheel. Both assumptions are satisfied by the 12-wheel California and Rainhart profilographs. The exponential term in equation 26 can be replaced by an equivalent trigonometric expression:

$$e^{-j\omega d_i} = \cos\omega d_i - j\sin\omega d_i \tag{27}$$

For the two assumptions made above, equation 26 reduces to the following form:

$$T(j\omega) = 1 - 2\sum_{i=1}^{N/2} c_i \cos\omega d_i \tag{28}$$

Substituting

$$\omega = \frac{2\eta}{\lambda} \tag{29}$$

into equation 28 gives an expression for the frequency response transfer function of the profilograph as a function of profile wavelength λ:

$$T(j\omega) = 1 - 2\sum_{i=1}^{N/2} c_i \cos\,(2\eta\; d_i/\lambda) \tag{30}$$

Since the expression on the right-hand side of equation 30 is real, it also represents the magnitude of the transfer function:

$$|T(\lambda)| = 1 - 2\sum_{i=1}^{N/2} c_i \cos\,(2\eta d_i/\lambda) \tag{31}$$

This equation gives the magnitude of the frequency response transfer function of a profilograph represented by the parameters c_i and d_i $(i = 1,2,\ldots,N/2)$, and can be used to calculate $|T(\lambda)|$ for any value of wavelength λ.

EFFECT OF DESIGN PARAMETERS ON PERFORMANCE OF PROFILOGRAPHS

As it has been shown, the frequency response characteristics of both California and Rainhart profilographs are far from ideal. The desired frequency response characteristic would be that of an ideal band pass filter (shown in figure 47). A profilograph with such a frequency response would measure the profile containing components of wavelengths from 1.6 ft to 32 ft without deformation and would not respond to profile components of wavelengths outside this range. It is clear from the plots displayed in figure 47 that the 12-wheel California profilograph provides a poor match to the frequency response requirements.

The most important design parameters for profilograph performance are the number and locations of the supporting wheels and the length of the main truss. This section presents the results of the investigation of the effects of these design parameters on the performance of profilographs. The quality of the profilograph performance is evaluated on the basis of the frequency response characteristic and the error in measuring profile roughness index.

Figures 48 through 52 show frequency response characteristics of California-type profilographs with a reduced number of supporting wheels: 10, 8, 6, 4, and 2. These plots show that the uniformity of the frequency response curve improves with an increasing number of supporting wheels. However, the improvement is moderate, as even the characteristic of the 12-wheel profilograph is still very nonuniform over the range of wavelengths of interest. In other words, the sole effect of the number of supporting wheels on the frequency response characteristic is not sufficient to fully justify the 12-wheel rather than 8- or 6-wheel design to support the profilograph.

The effect of the number of wheels was further evaluated by comparing the roughness index calculated from the profile measured by a profilograph with the roughness index obtained from the actual profile data. The following computational procedure was employed in this analysis. First, a sequence of typical new pavement profile data was generated. The gain factor in the computer program was adjusted to obtain a roughness index of 5.5 IPM_{CA} for the set of data representing a 0.1-mi section of new pavement. Next, this profile data sequence was applied to the profilograph model and the roughness of the profile produced by the computer model of the profilograph was calculated. Several computer simulations were executed with different numbers of supporting wheels in the model. The roughness index obtained from the

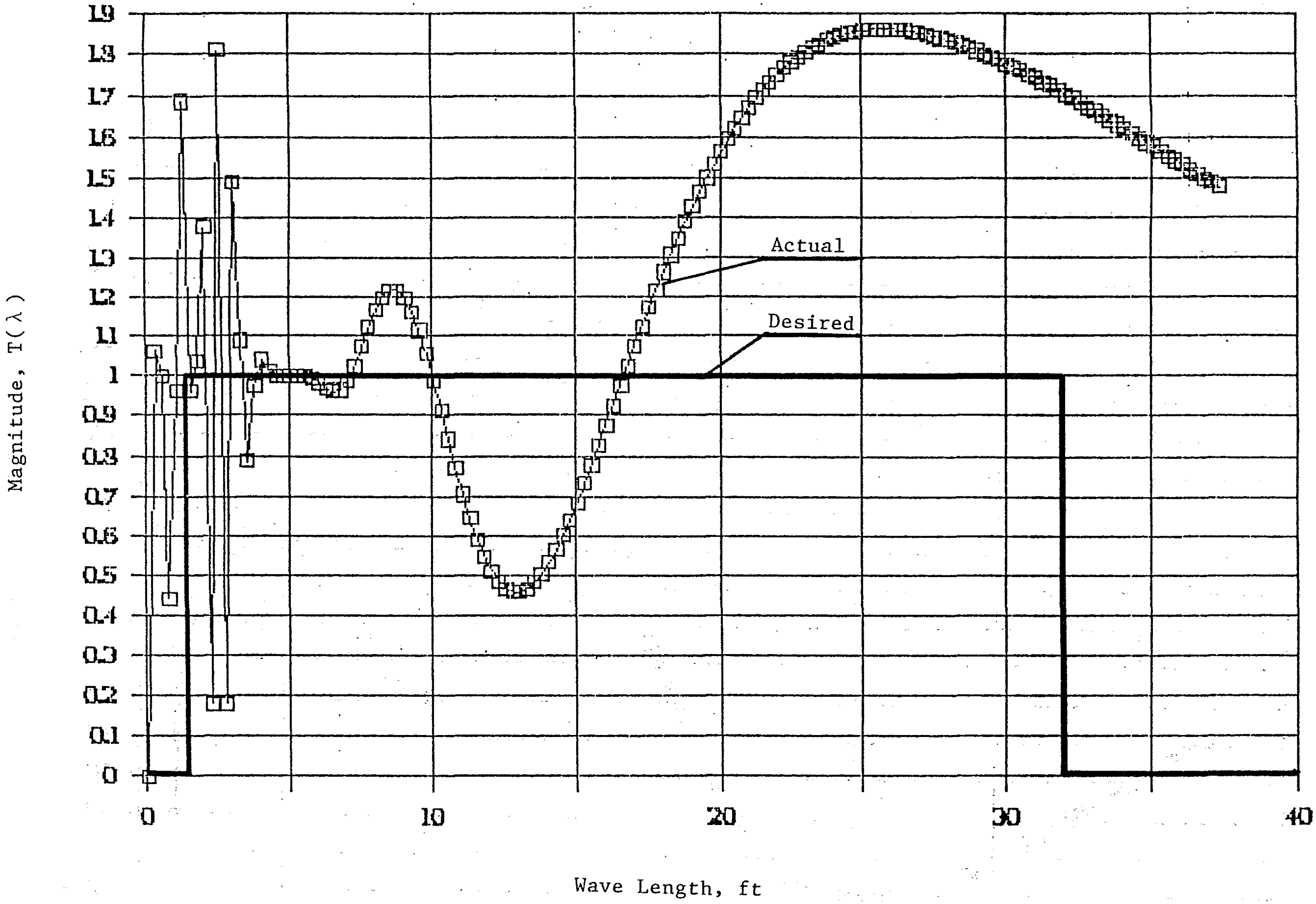


Figure 47. Desired and actual frequency response of 12-wheel California profilograph.

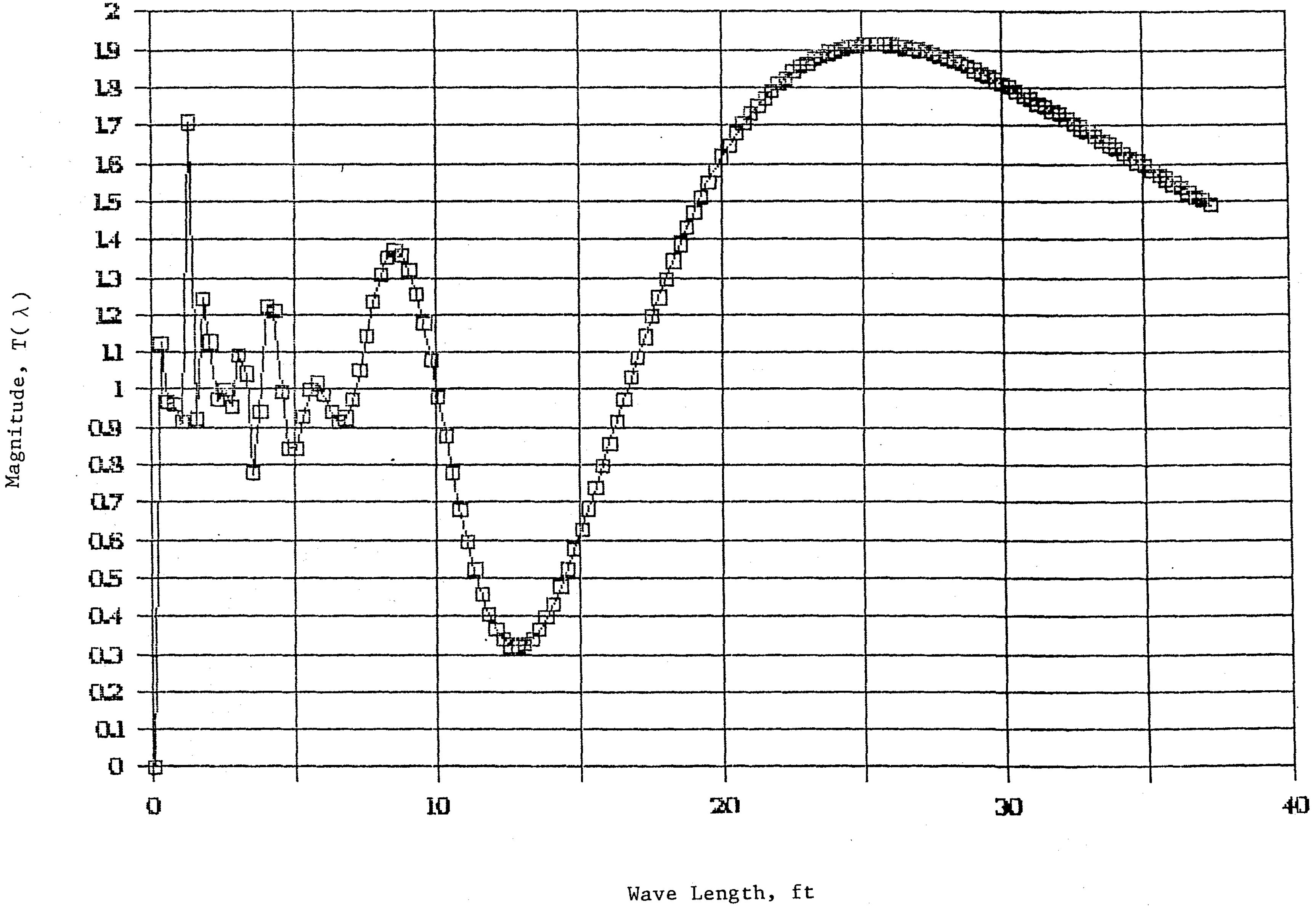


Figure 48. Frequency response of 10-wheel California profilograph.

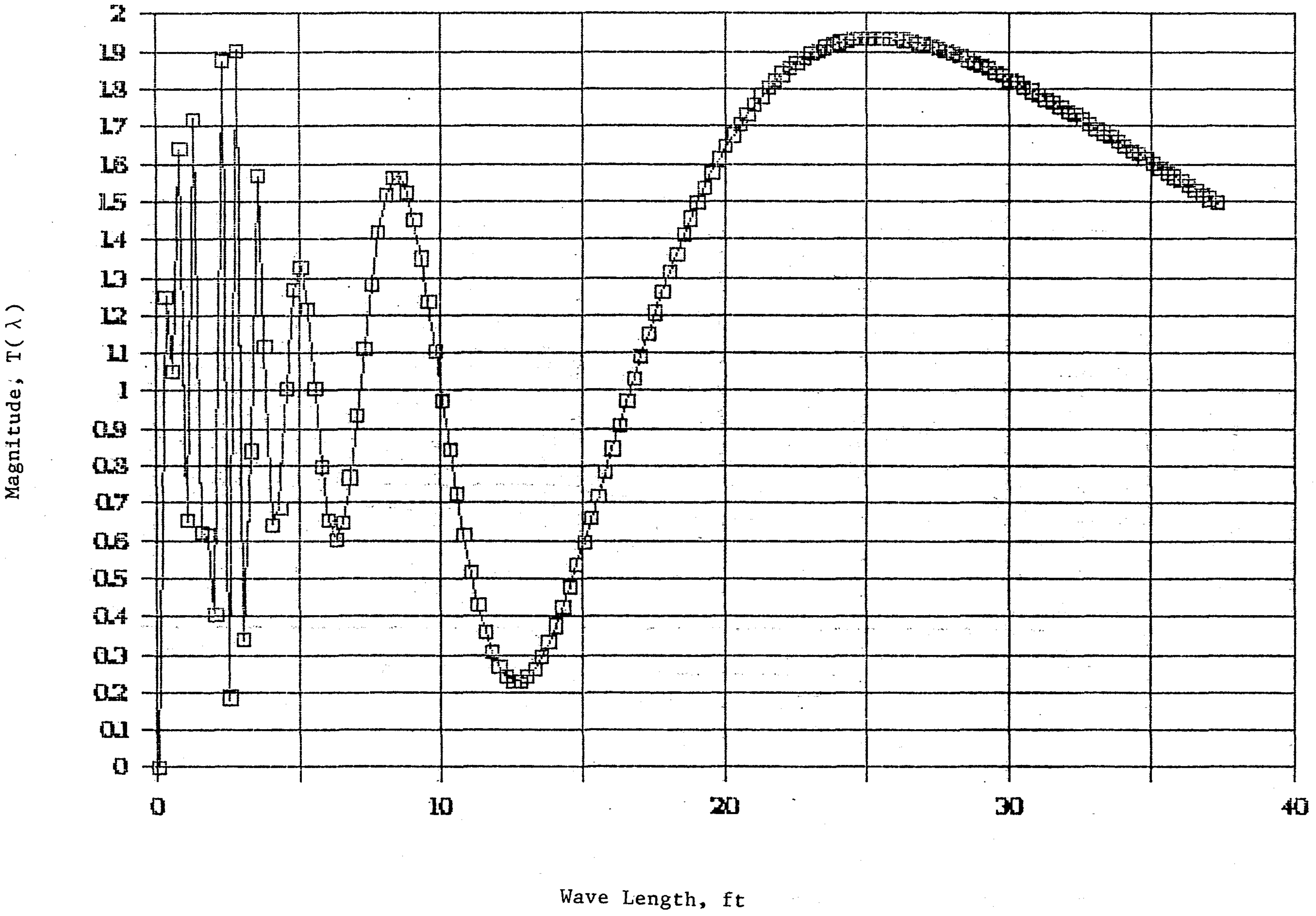


Figure 49. Frequency response of eight-wheel California profilograph.

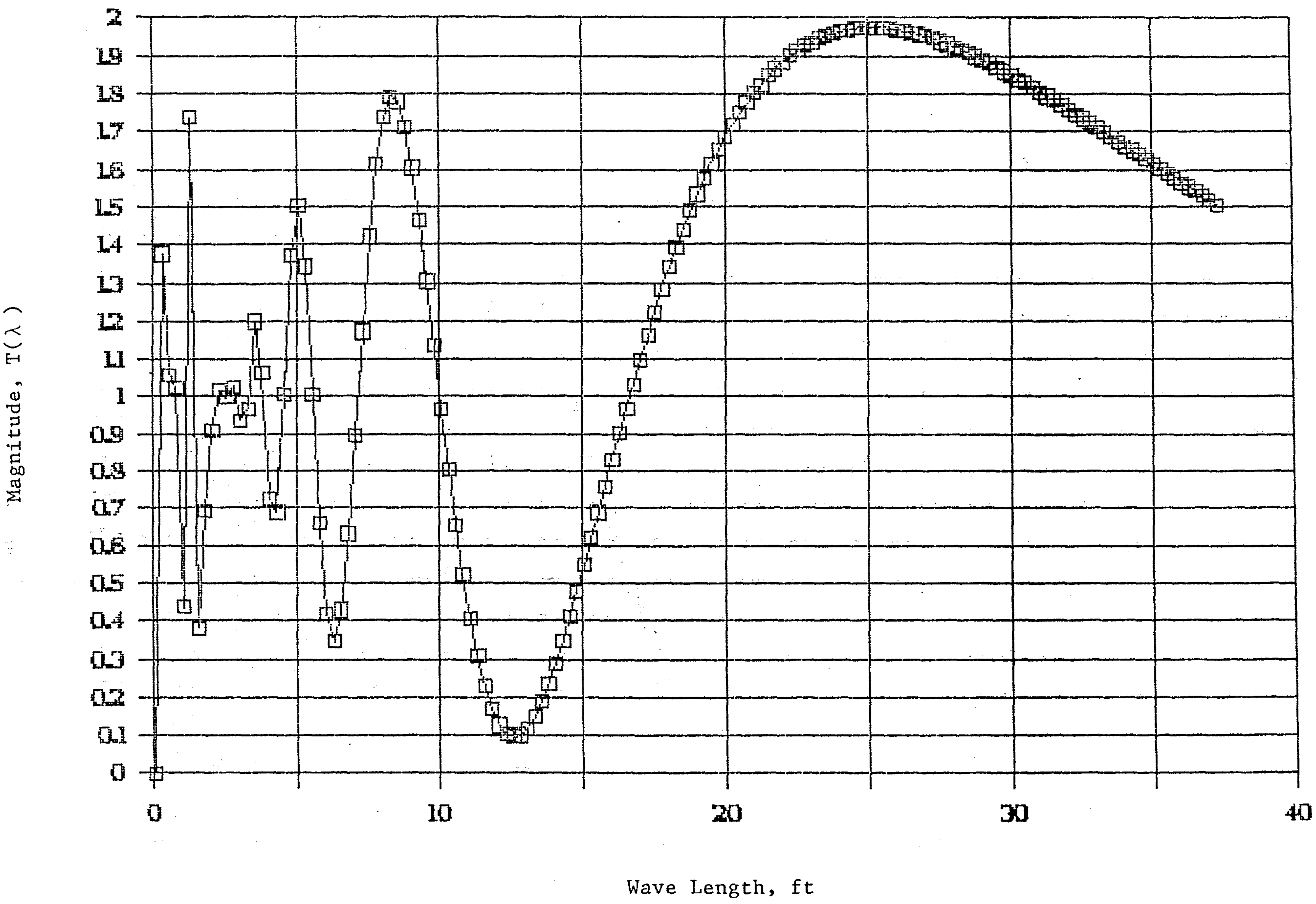


Figure 50. Frequency response of six-wheel California profilograph.

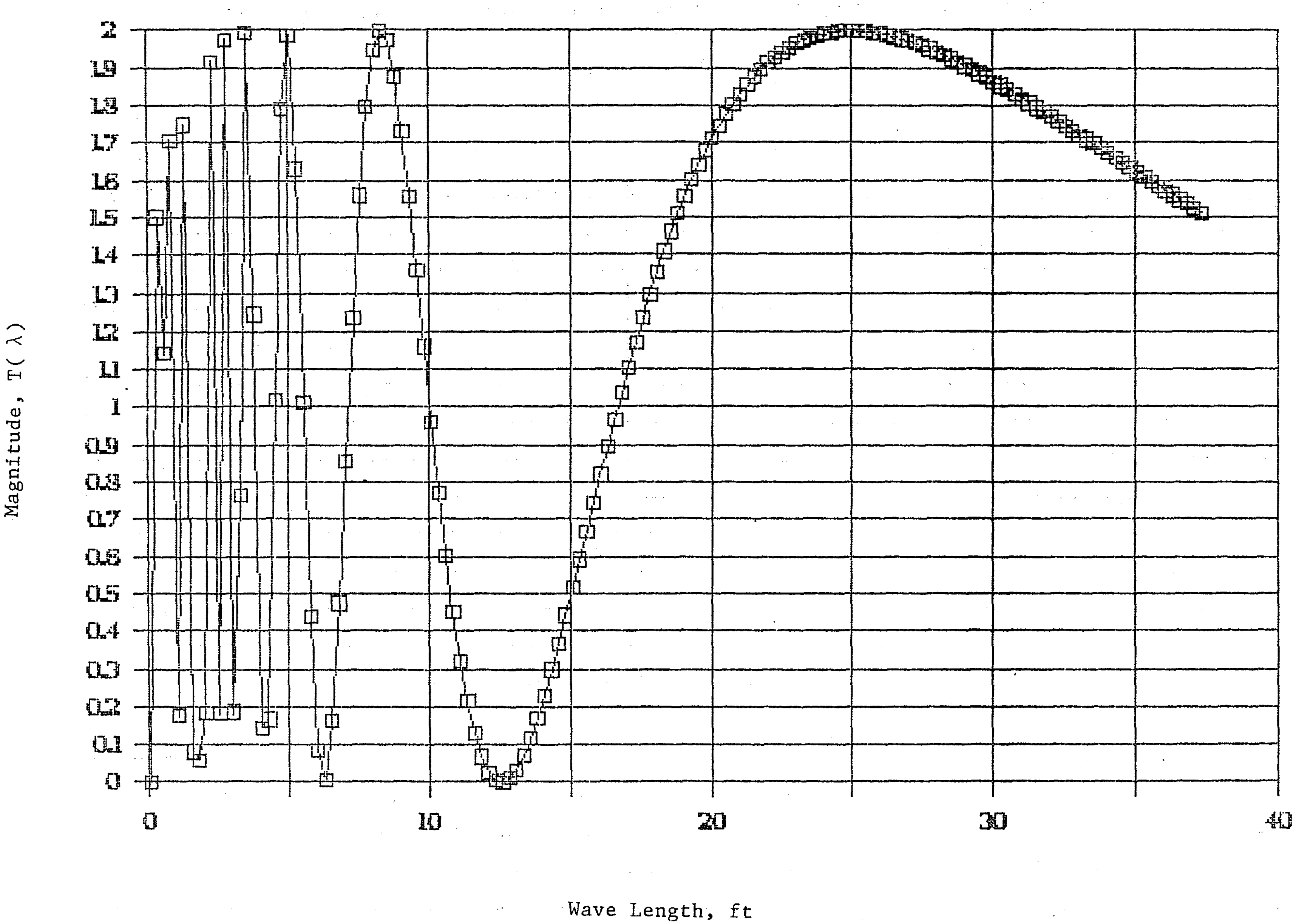


Figure 51. Frequency response of four-wheel California profilograph.

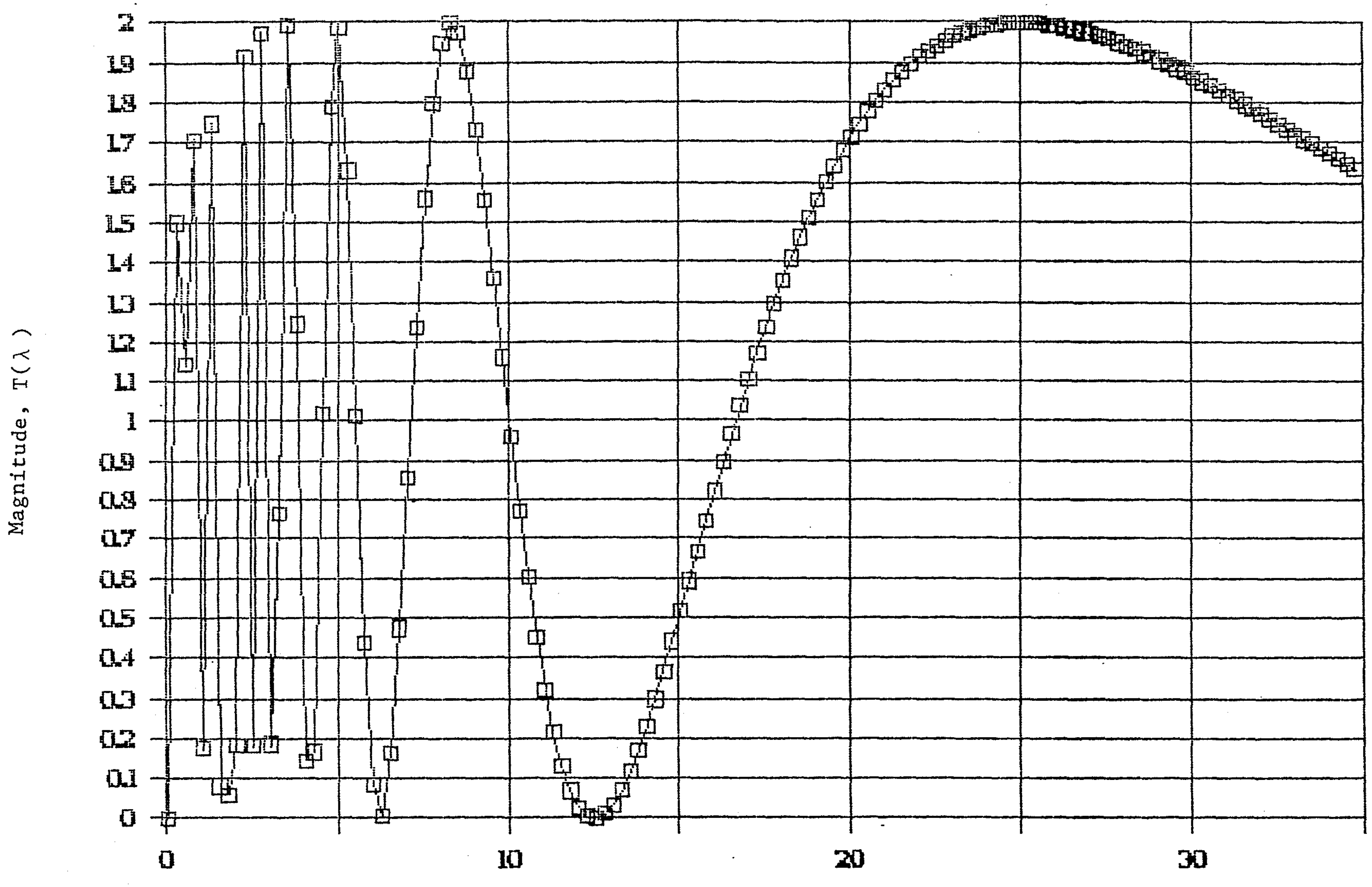


Figure 52. Frequency response for two-wheel California profilograph.

computer simulation of the California-type profilograph with 2, 4, 6, 8, 10, and 12 wheels is plotted in figure 53. It can be seen that all profilographs underestimate roughness and that the measuring error is smaller for 2-, 4-, 6- and 8-wheel profilographs than for 10- and 12-wheel models. It should be noted that although the uniformity of the frequency response is better for a larger number of wheels, the average magnitude of the frequency transfer function is closer to unity for a smaller number of supporting wheels.

To further evaluate the effect of the number of wheels on the performance of profilographs, the coefficient of correlation between the actual profile sequence and the sequence obtained from the computer model of profilograph was calculated. The results of the correlation analysis are plotted in figure 54. The lowest value of the coefficient of correlation, 0.87, was obtained for 2- and 4-wheel profilographs, whereas the highest value, 0.89, was calculated for 8-, 10-, and 12-wheel profilographs. The primary reason for the higher coefficient of correlation for profilographs with a greater number of wheels is the better uniformity of the frequency response characteristic discussed earlier. However, the improvement of correlation that occurs as the number of wheels increases from 2 or 4 to 8, 10, or 12 is not large.

In all computer simulations described so far, the basic dimensions of the profilograph, the length of the main truss and the distance between supporting wheels attached to the minor truss, were kept constant. The length of the main truss was $L_0 = 25$ ft, and the distance between the supporting wheels was $L_1 = L_2 = 2.5$ ft. The computer simulation model of a profilograph was used to investigate the effects of the basic dimensions on performance.

Three basic profilograph configurations with 2, 6, and 12 supporting wheels were investigated (shown in figure 55). Two measures of performance were used in the evaluation. The first measure was the roughness measuring error defined as the difference between the roughness of the actual profile, used as the input to the computer model, and the roughness of the profile generated by the computer model of the profilograph. The input profile roughness index was constant and equal to 5.5 IPM_{CA} in all cases. The roughness indices of the output profiles for the three profilograph

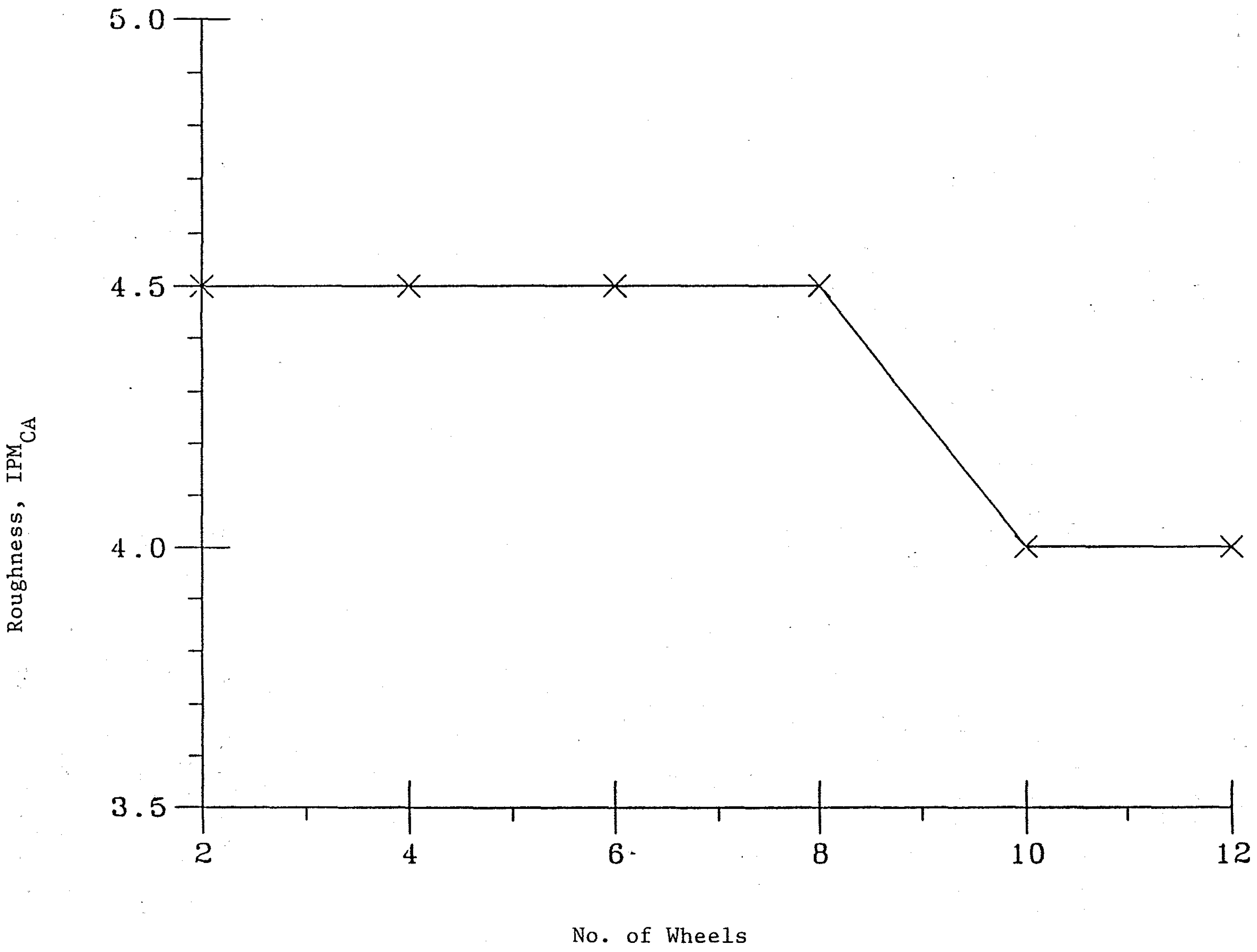


Figure 53. Effect of number of wheels on roughness measurement for California profilograph (actual roughness 5.5 IPM_{CA}).

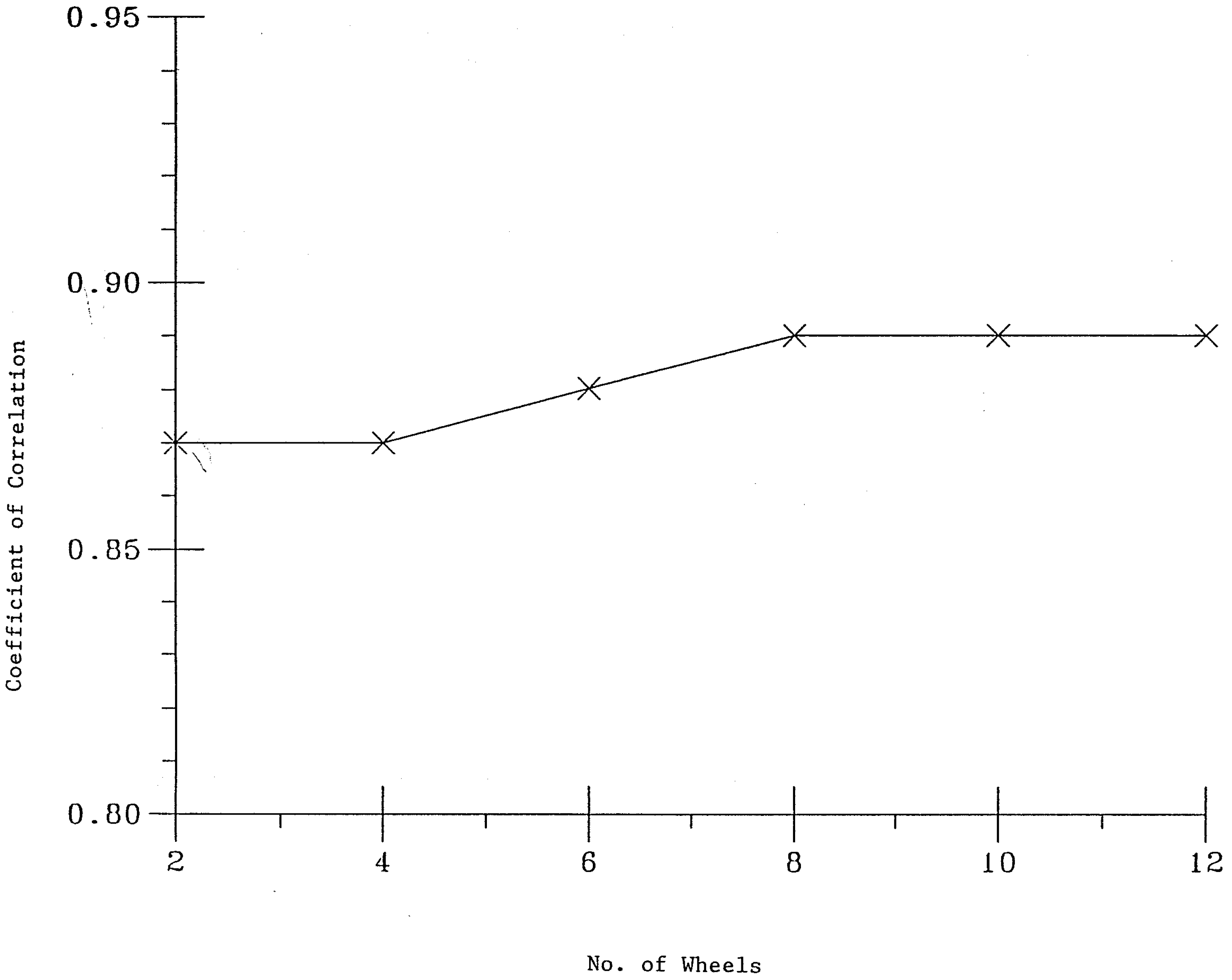
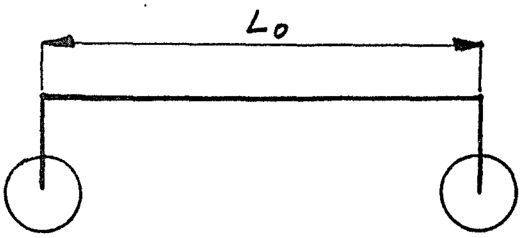
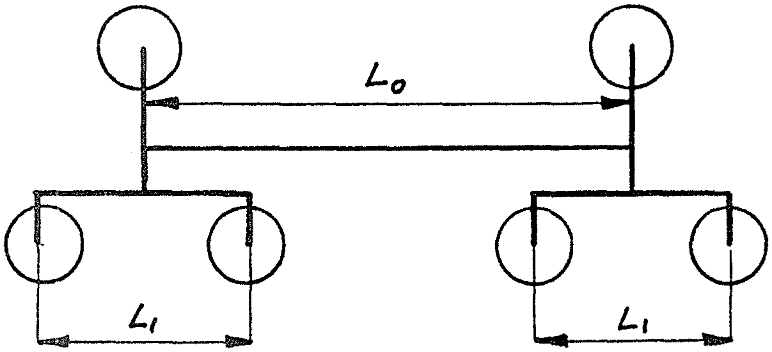


Figure 54. Effect of number of wheels on correlation between actual and measured profiles for California profilograph.

A) 2-WHEEL MODEL



B) 6-WHEEL MODEL



C) 12-WHEEL MODEL

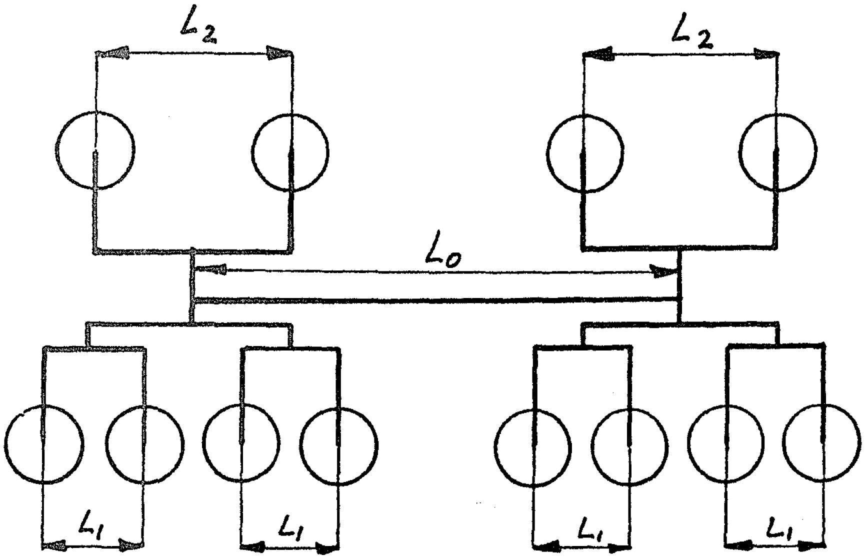


Figure 55. Configuration of profilograph.

configurations are plotted versus the length of the main truss in figures 56, 57, and 58. As can be seen from these figures, the roughness measuring error is minimal for the 30-ft main truss for all three models. A shorter main truss results in an underestimation of roughness, whereas a profilograph with a main truss longer than 35 ft significantly overestimates profile roughness. A sharp rise occurs in all three plots for truss length greater than 30 ft. On the other hand, reducing the truss length below 30 ft has a considerably smaller effect on the measured roughness index. The spacing of the supporting wheels over the range from 1.5 ft to 3.0 ft has a negligible effect on the measuring error.

The second measure of the profilograph performance was the coefficient of correlation between the input and output profiles obtained from the computer simulation. Plots of the coefficient of correlation versus the length of the main truss for different spacings of supporting wheels are shown in figures 59, 60, and 61. In general, the correlation increases with an increasing length of the main truss for all three configurations. However, the improvement becomes very small for the truss length greater than 30 ft, especially for the 12-wheel model. The wheel spacing has no effect on correlation for two- and six-wheel models. For the 12-wheel profilograph, the coefficient of correlation increases slightly for larger spacing of the supporting wheels.

On the basis of the computer simulation results presented in this section, the following design specifications are recommended:

- Length of the main truss: 30 ft.
- Number of supporting wheels: four or six.
- Spacing between supporting wheels: 2 to 3 ft.

It must be stressed that these recommendations are subject to two conditions implied by the method of computer simulation used in this study. First, the California profilograph procedure is used to calculate profile roughness. Although this procedure for processing profile data was criticized earlier in this report, it is still the most common method of calculating roughness index for new pavements. Second, it was assumed in the computer

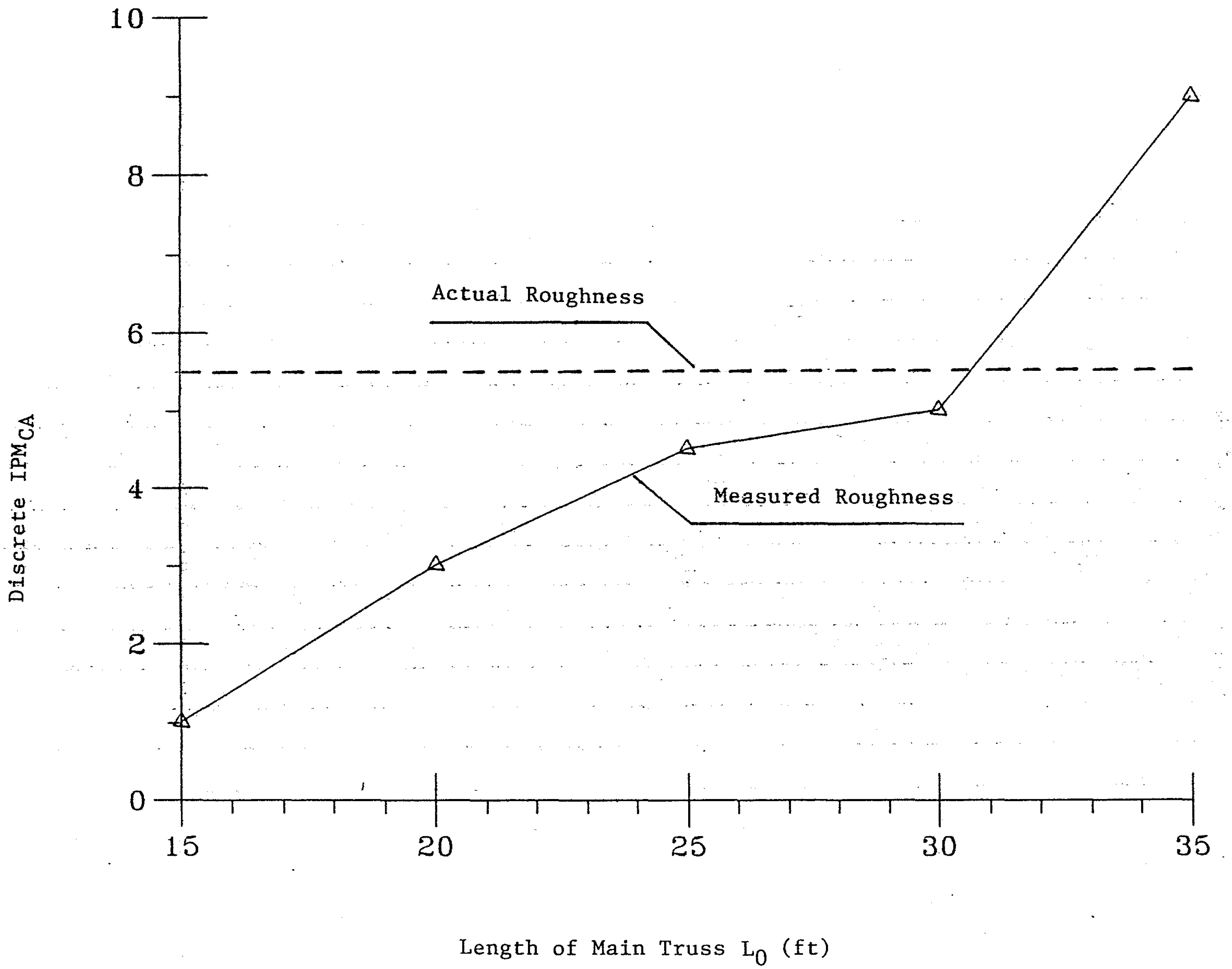


Figure 56. Effect of length of main truss on roughness measurement for two-wheel profilograph.

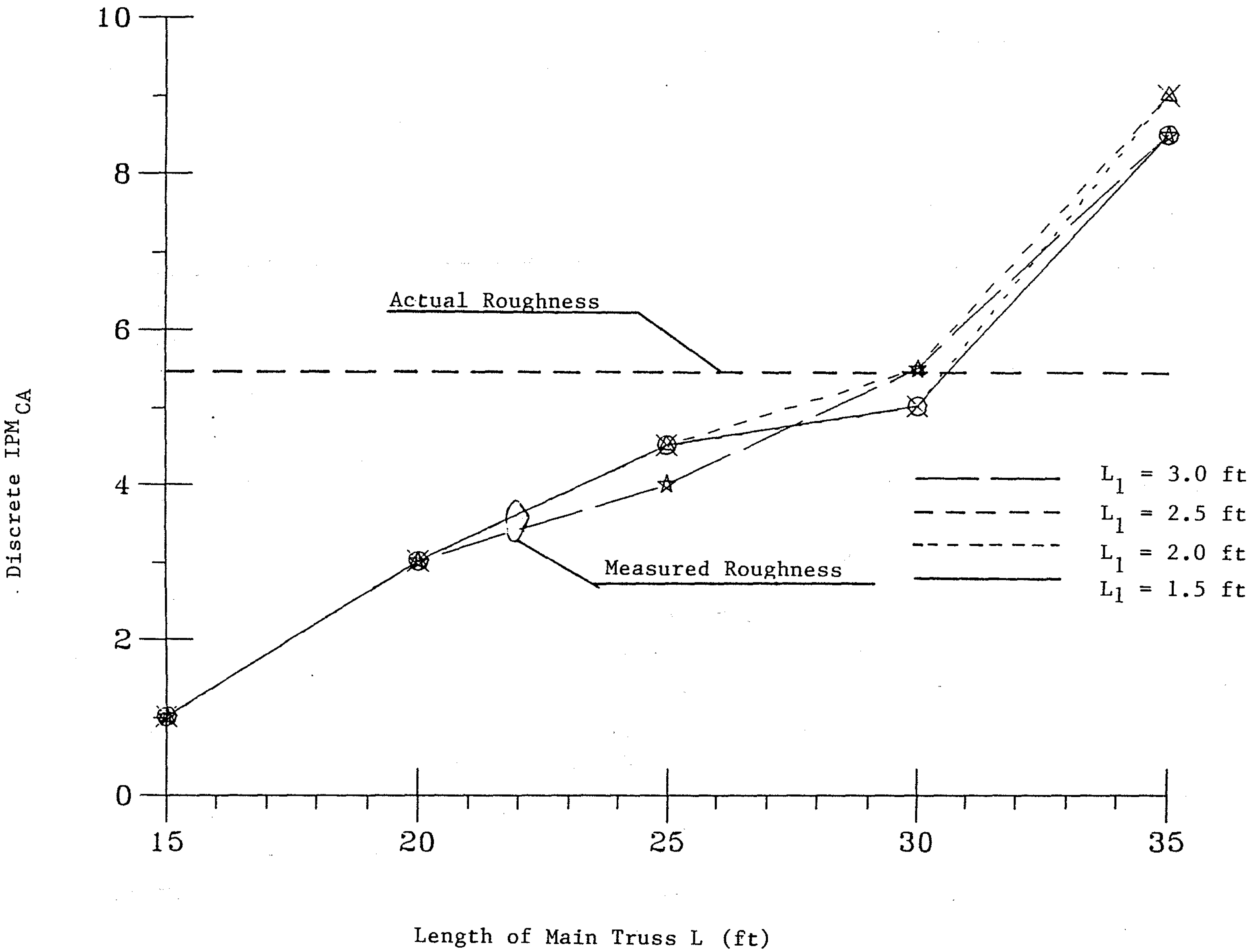


Figure 57. Effect of length of main truss, L, and spacing between supporting wheels, L_1, on roughness measurement for six-wheel profilograph.

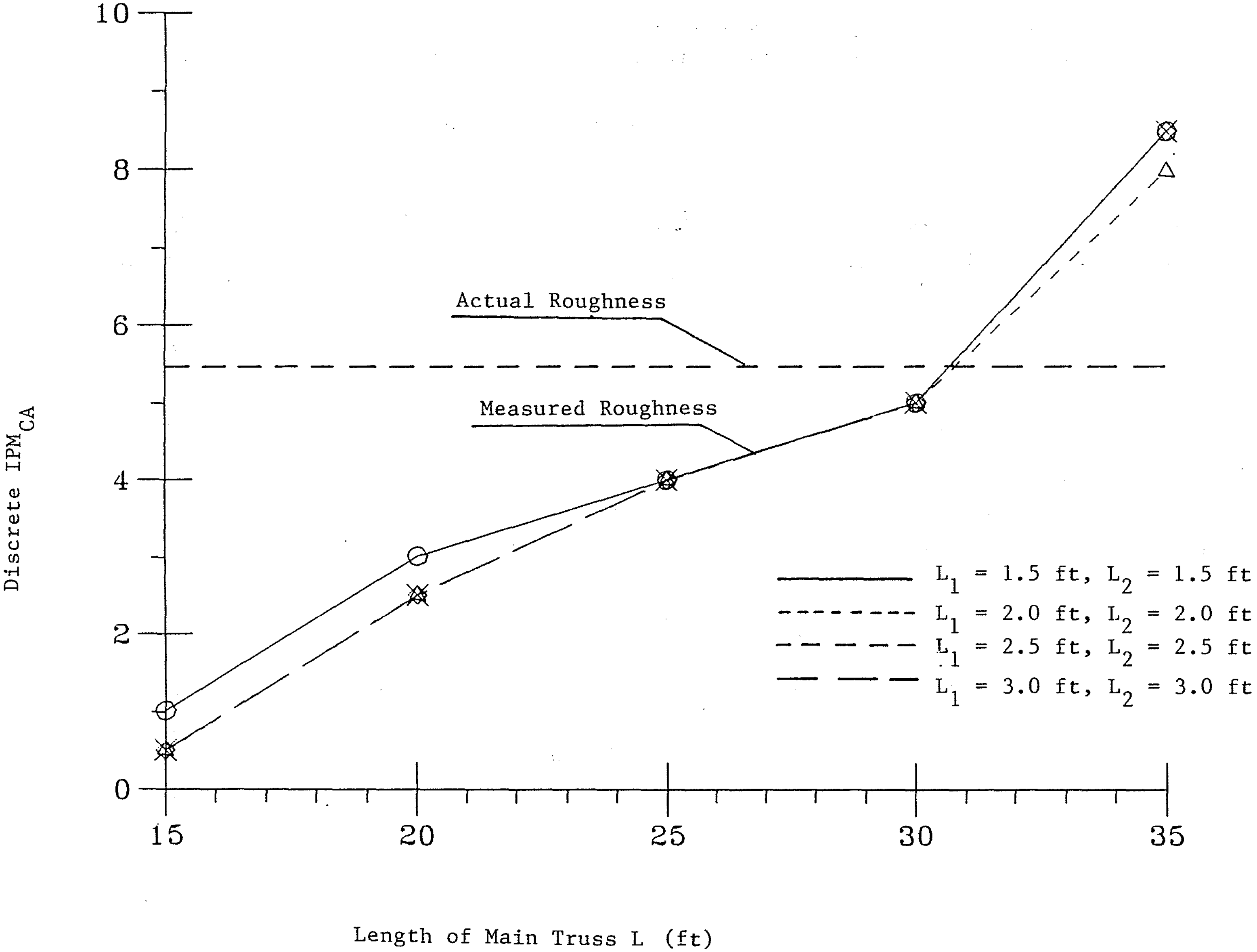


Figure 58. Effect of length of main truss, L, and spacing between supporting wheels, L_1, on roughness measurement for 12-wheel profilograph.

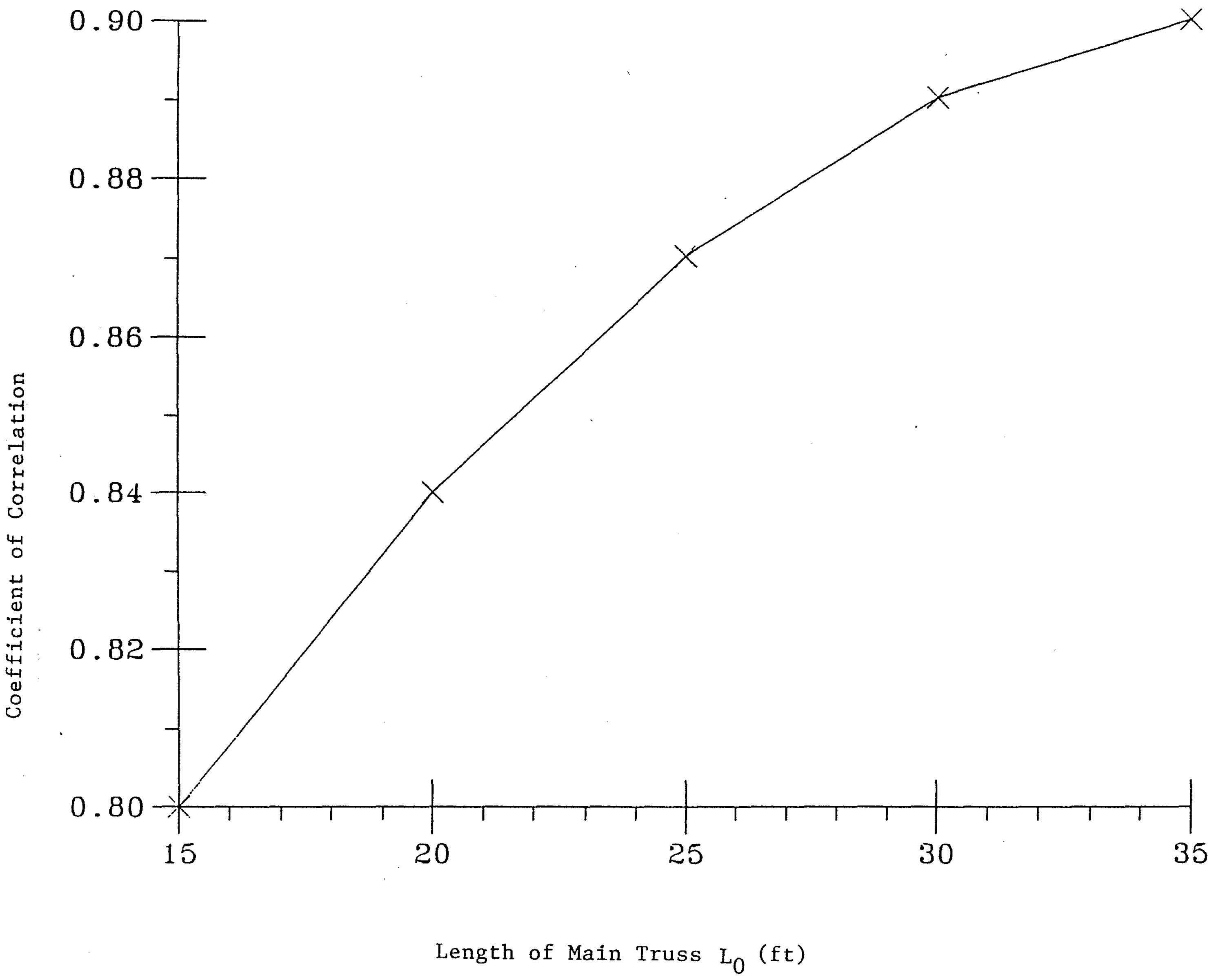


Figure 59. Effect of length of main truss on correlation between actual and measured profiles for two-wheel profilograph.

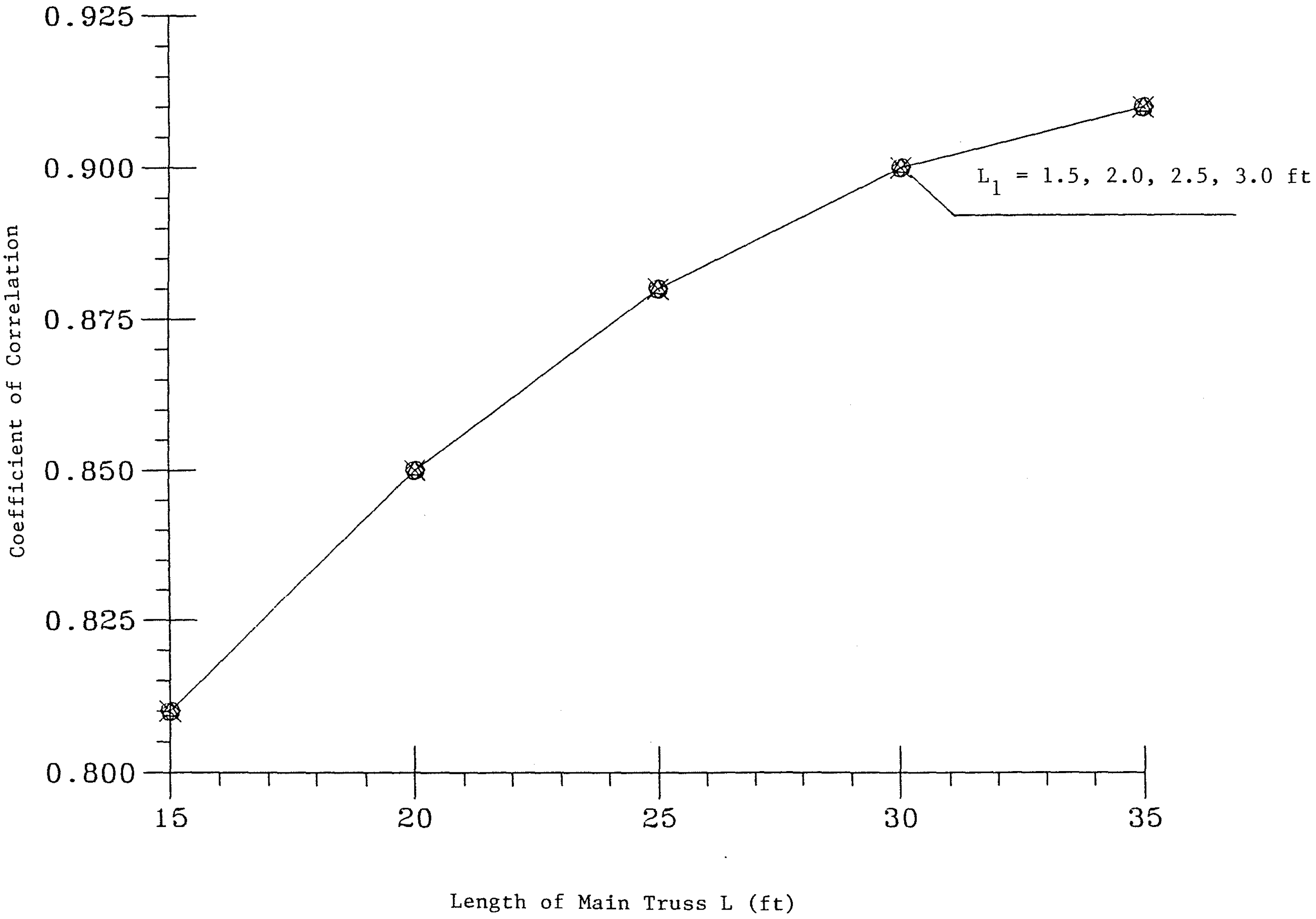


Figure 60. Effect of length of main truss, L, and spacing between supporting wheels, L_1, on correlation between actual and measured profiles for six-wheel profilograph.

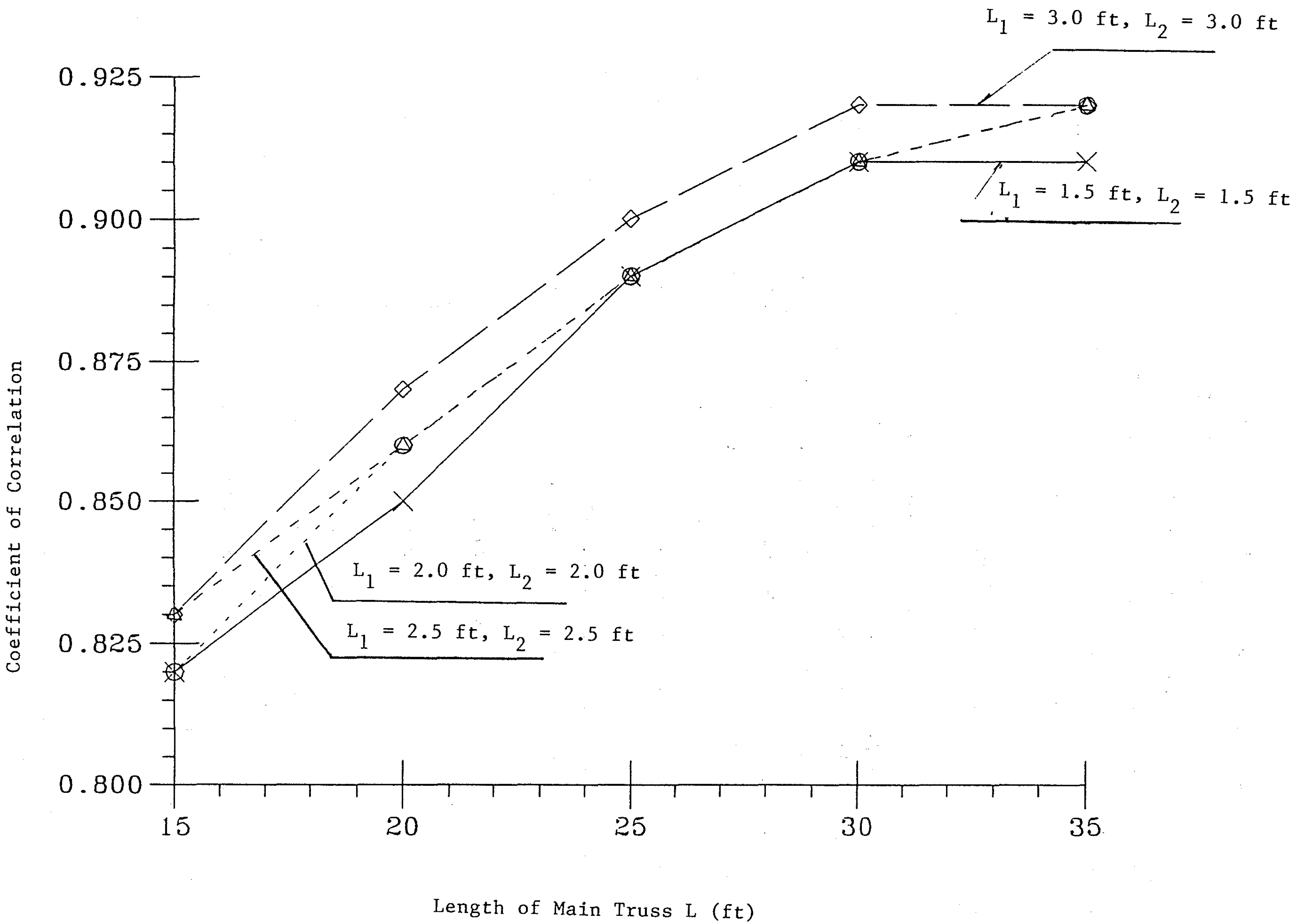


Figure 61. Effect of length of main truss, L, and spacing between supporting wheels, L_1, on correlation between actual and measured profiles for 12-wheel profilograph.

simulation that there is no lateral gradient of pavement profile. It is believed that this second condition may have a stronger impact on profilograph performance than the first one, favoring a greater number of supporting wheels if a significant lateral variation of pavement roughness does occur. No measurements of lateral profiles were conducted in this study; however, it is expected that the lateral variations on new pavements are insignificant.

EFFECT OF TIME WEAR AND WHEEL ECCENTRICITY

One of the objectives of this study was to determine the effect of tolerances and wear of profilograph components on performance. The design of the profilograph was first analyzed to identify those mechanical deficiencies that could affect the measurement of road profile. Backlash is one common deficiency that may seriously degrade the accuracy of a mechanical measuring device. However, no potential sources exist in profilograph design. The translational and rotational motions in a profilograph are transmitted by cables in tension and thus no dead motion, or backlash, occurs in this system.

Next, the effect of wear of the measuring wheel tire was considered. Although such wear does not affect the measurement of pavement profile directly, it introduces an error in measuring distance along the test site. This distance, D, is measured by a profilograph as

$$D(x) = k(x) 2\pi R \tag{32}$$

where D(x) is the distance measured by a profilograph at location x, k(x) is the number of revolutions of the measuring wheel from the beginning of the test site, and R is the radius of the measuring wheel. When the tire radius decreases due to wear by δ_w, the distance traveled for k revolutions of the measuring wheel is

$$D_m(x) = k(x) 2\pi (R - \delta_W) \tag{33}$$

The error in measuring distance will thus be

$$E_D(x) = D(x) - D_m(x) = k(x)2\pi\delta_w \tag{34}$$

As a result of the distance measuring error, the profilogram will be extended over a longer pavement distance than that actually traveled. The magnitude of this error increases with the length of the road site. The effects of the measuring wheel tire wear for $\delta_w = 0.05$ and 0.10 in are shown in figures 62 and 63. Clearly, these figures show that the error increases with distance.

To better evaluate the importance of tire wear, the values of roughness index were computed for magnitudes of wear equal to 0.05, 0.10, 0.15, and 0.20 in and compared with the roughness index obtained with no wear. The results, plotted in figure 64, indicate that the wear of the measuring wheel tire has no significant effect on the measurement of roughness.

Another potential cause of measuring error is an eccentricity of the measuring wheel, which occurs when the wheel is suspended at a point displaced from its geometrical center. Figure 65 shows the effect of the measuring wheel eccentricity when the point of the wheel suspension is displaced from the geometrical center by 0.05 in. In figure 66, the effect of the eccentricity on the measured roughness index for the range of displacements from 0 to 0.10 in is illustrated. The numerical results, given in table 18, prove that the eccentricity of the measuring wheel presents a serious problem in measuring pavement roughness. On the basis of these results, it is recommended that the measuring wheel eccentricity not exceed 0.02 in. As a minimum, the location of the point of the measuring wheel suspension should be measured periodically to determine if it is displaced with regard to the wheel's geometrical center. It should also be kept in mind that the measuring wheel eccentricity causes an overestimation of pavement roughness.

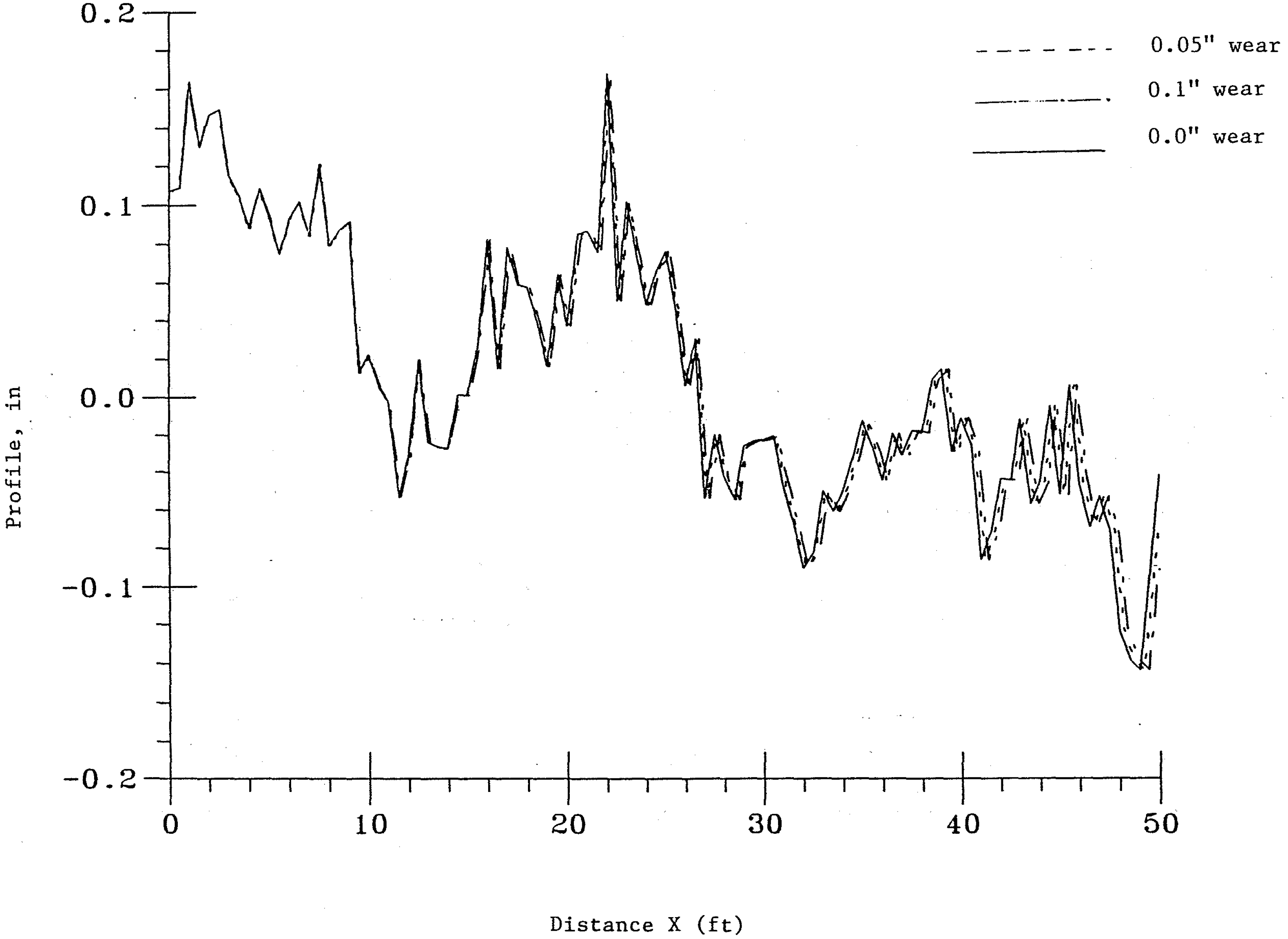


Figure 62. Effect of wear of measuring wheel tire on profile measurement over first 50 ft of test site.

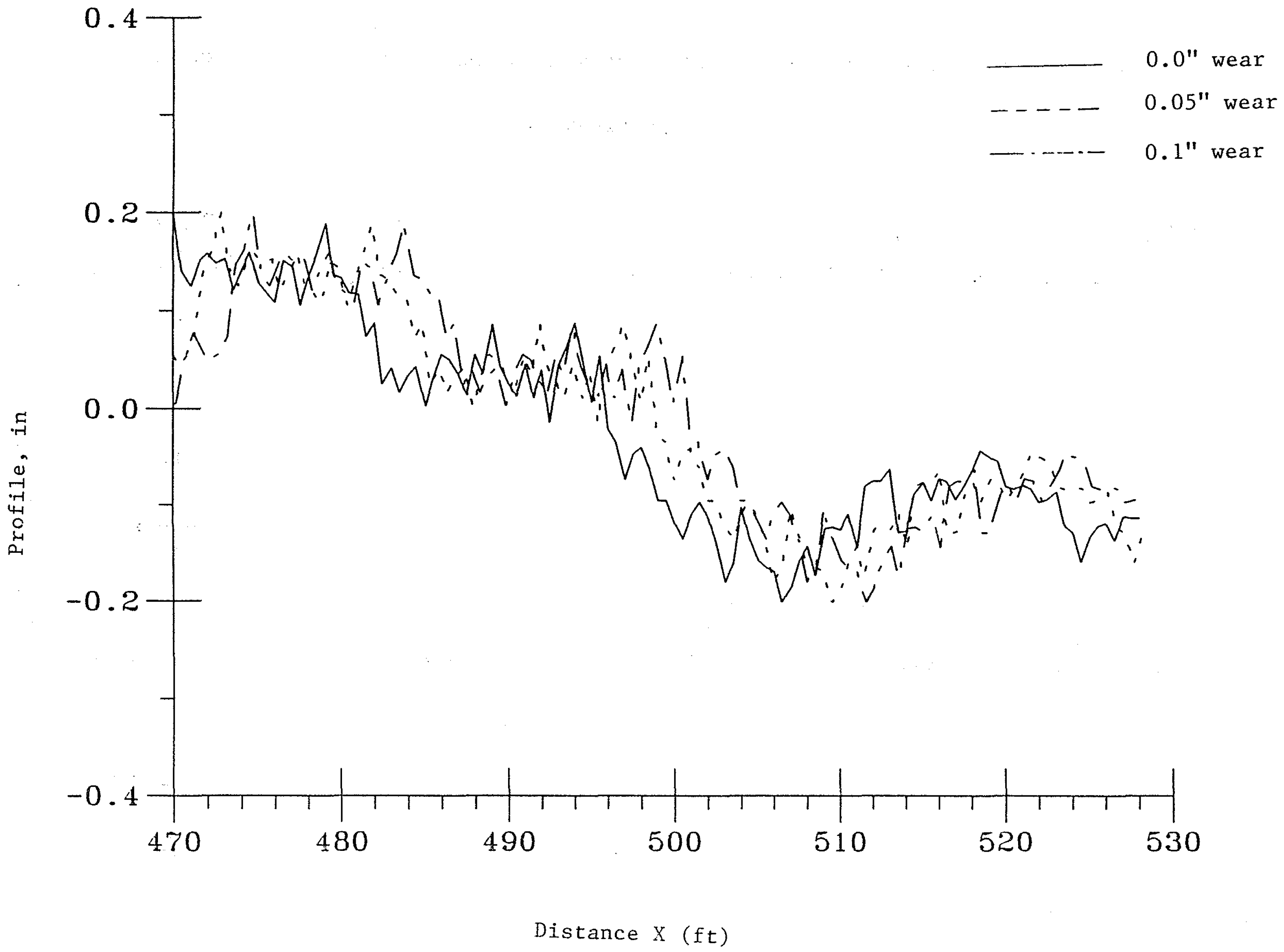


Figure 63. Effect of wear of measuring wheel tire on profile measurement over last 50 ft of test site.

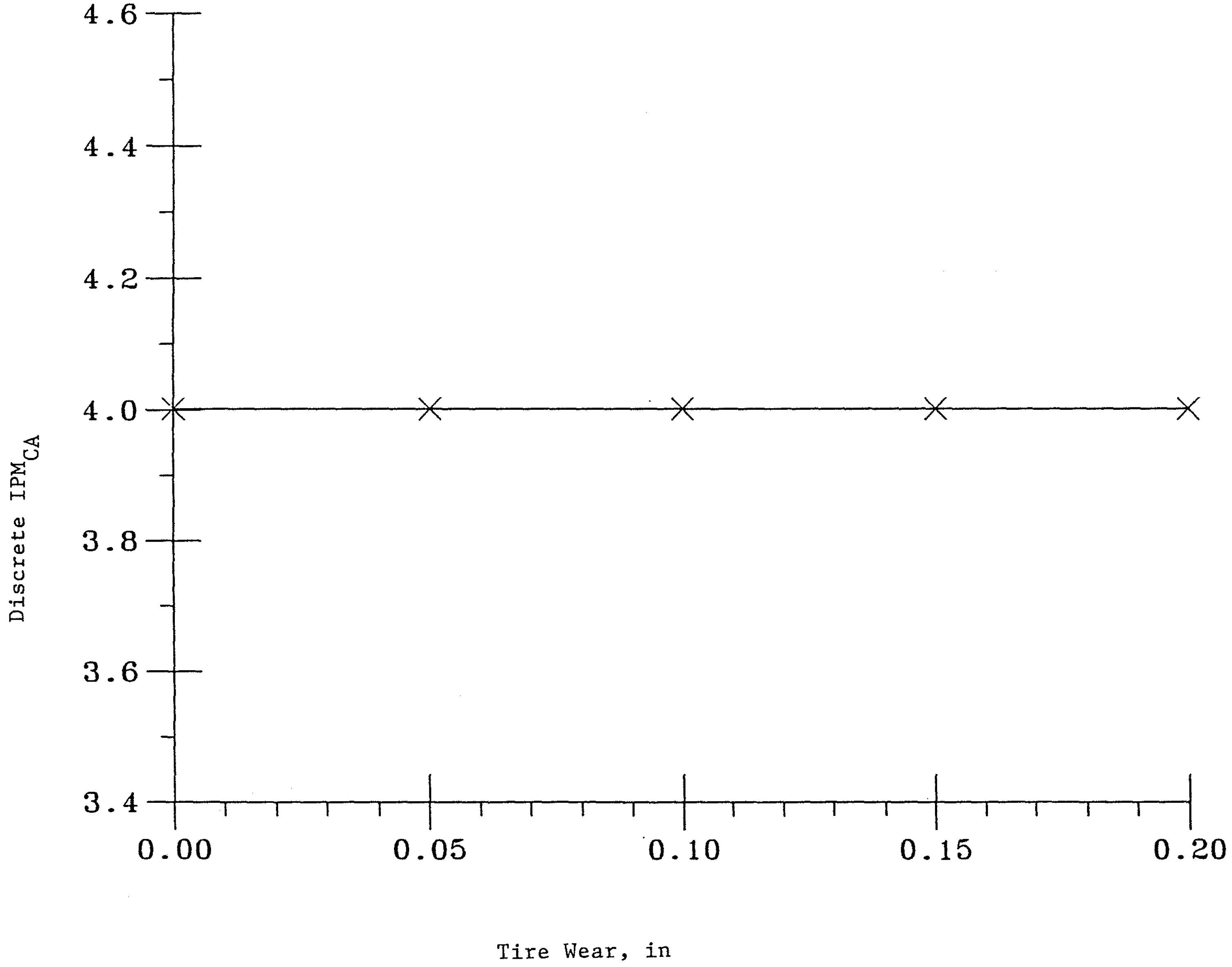


Figure 64. Effect of wear of measuring wheel tire on roughness measurement.

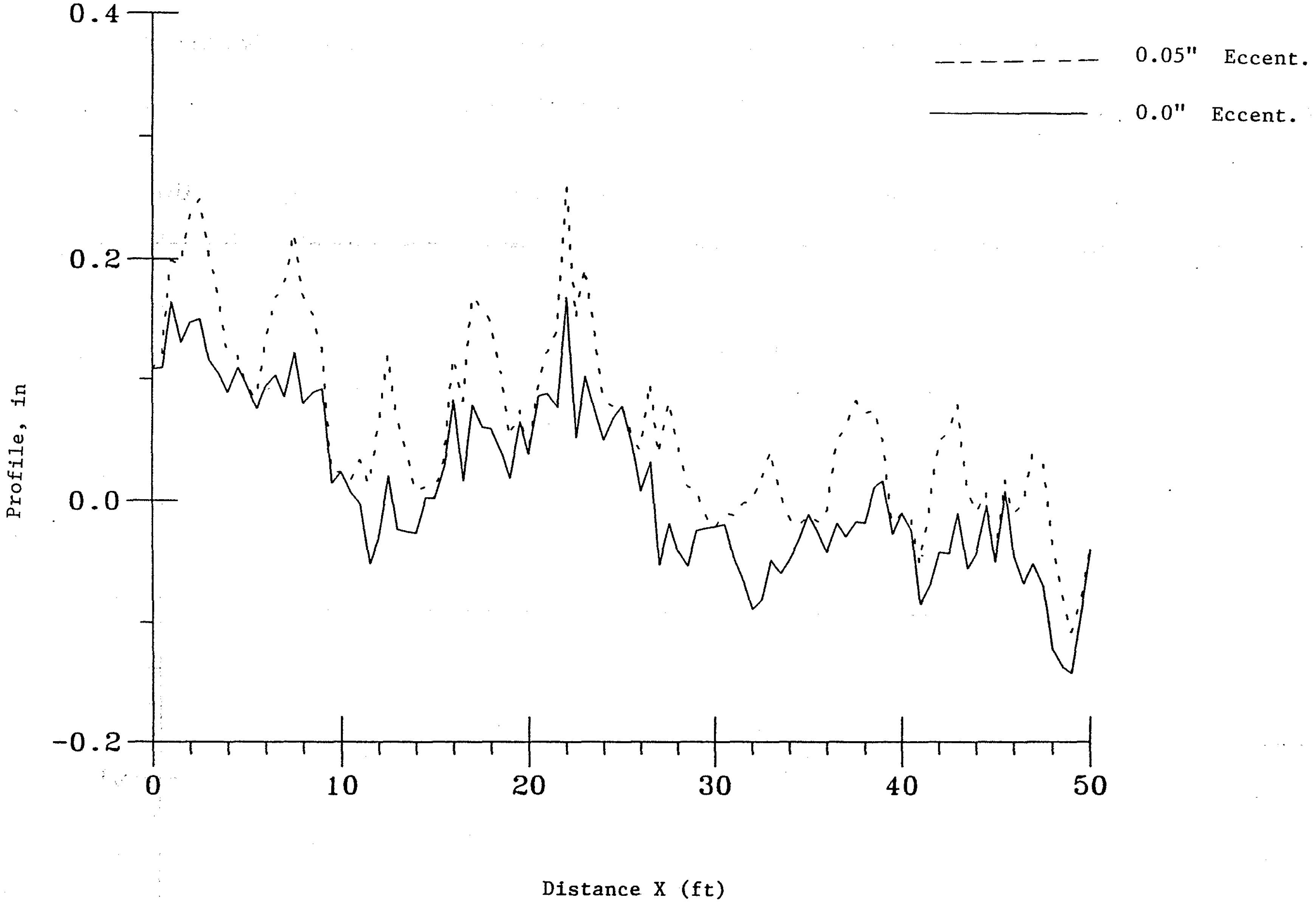


Figure 65. Effect of eccentricity of measuring wheel on profile measurement.

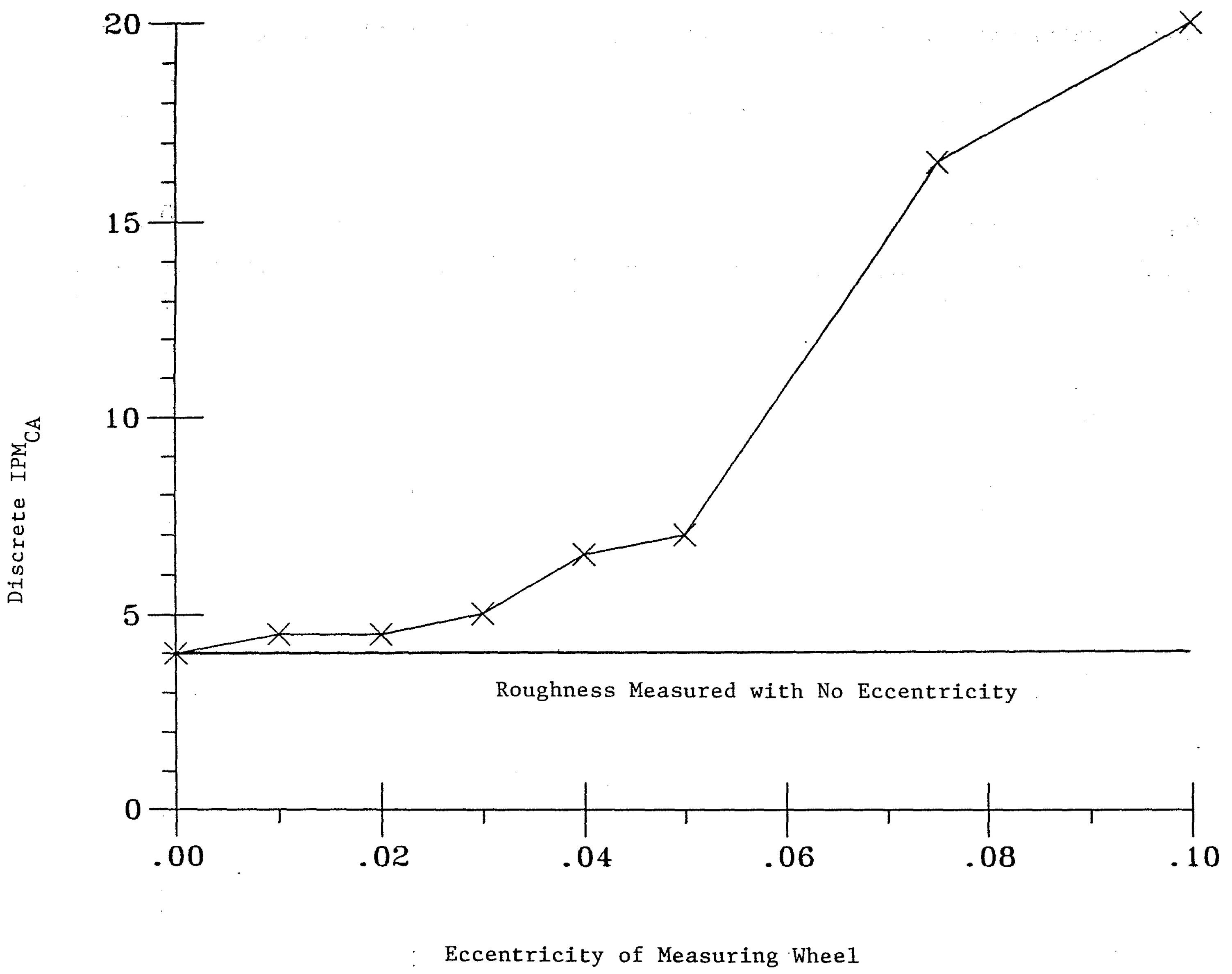


Figure 66. Effect of eccentricity of measuring wheel on roughness measurement.

Table 18. Effect of eccentricity of measuring wheel on roughness measurements.

Eccentricity, in	0.0	0.01	0.02	0.03	0.04	0.05	0.06	0.07
Roughness Index, continuous IPM_{CA}	3.75	4.13	4.34	5.00	6.50	7.83	14.70	20.94
Roughness Index, discrete IPM_{CA}	4.00	4.50	4.50	5.00	6.50	7.00	16.50	20.00

7. CALIBRATION OF PROFILOGRAPHS

The purpose of calibration of a measuring device is to develop a mathematical formula relating measurements produced by the calibrated device to an established calibration standard. A two-part procedure is proposed for calibration of profilographs. In the first part of this procedure, a relationship between a given profilograph and an ideal profilograph model, presented earlier in this study, will be derived. In the second part, a relationship between the ideal profilograph model and the calibration standard will be determined. The second part has to be performed only once for a specific type of profilograph. The two parts of the proposed calibration procedure are described in detail below.

Part 1: Developing a Profilograph Calibration Factor

The objective in this part of the calibration procedure is to develop a simple static relationship between a calibrated profilograph and an ideal kinematic model of a profilograph, described earlier in this report. Figure 67 shows a block diagram of the calibration process. The input to the process is a standard test surface. Due to the lack of dynamic effects in profilograph performance, a simple artificial test surface, such as sinusoidal with constant wavelength, can be built. Also, because there are no significant stochastic disturbances in this process, the test surface can be very short.

A single wavelength profile can be used because both the calibrated and model profilographs are expected to have essentially the same frequency response characteristics. The following profile is suggested for the test surface:

$$p^0(x) = 0.2 \sin 0.4 \pi x \qquad (35)$$

Equation 35 describes a sinusoidal function of 0.2-in amplitude and 5-ft wavelength. The amplitude of the test surface must exceed half of the

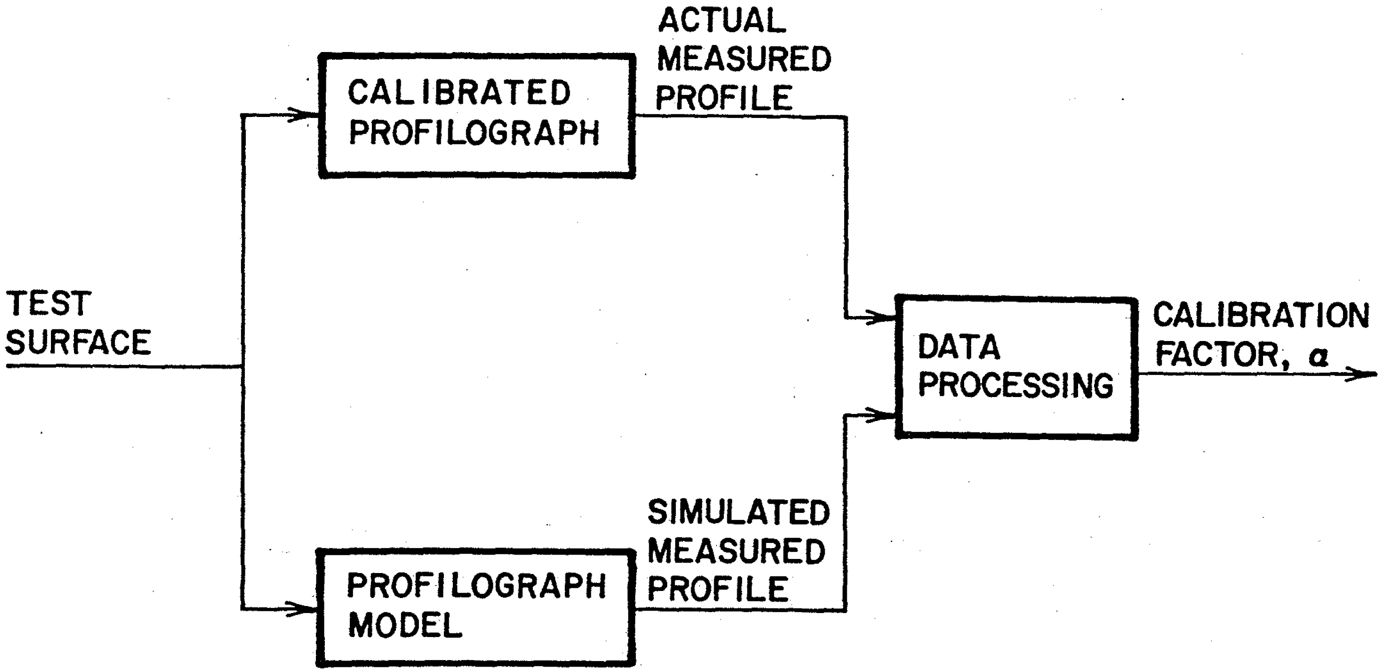


Figure 67. Block diagram of Part 1 of the calibration procedure.

profilograph blanking band. The wavelength of 5 ft is convenient because, as illustrated in figures 47 and 48, both the California and Rainhart profilographs have magnitudes of frequency response characteristics equal to or close to one at this wavelength.

If the artificial sinusoidal surface proves to be too difficult to manufacture, a surface consisting of a number of step bumps can also be considered. The profile of such a surface is described by the following equation:

$$p^0(x) = \sum_{i=0}^{m-1} \Delta p \cdot U_s(x-i\Delta x) - \sum_{i=m}^{2m} \Delta p U_s(x-i\Delta x) \tag{36}$$

where Δp is the magnitude of the step bump, Δx is the distance increment between the bumps, 2m is the total number of bumps, and $U_s(x-a)$ is a unit step function starting at $x=a$. The pattern shown in figure 68 is recommended for the calibration of profilographs. This surface starts with a flat section, 30 ft in length, which is followed by a rectangular bump, and ends with a 30 ft-long flat section. The height of the bump should be at least 0.4 in and less than 0.5 in. The roughness of this surface measured by an ideal profilograph is 14.67 IPM_{CA}. It should be noted that the bump height must be within the above range to ensure that the value of the roughness index will be 14.67 IPM_{CA}.

As illustrated in figure 67, the calibrated profilograph will be used to measure the roughness of the test surface. The set of profile data representing the test surface will be applied to the computer model of the profilograph, and the same type of roughness measure will be calculated for the profile data generated by the model. The profilograph calibration factor, α, is then calculated from the equation:

$$\alpha = \frac{\widehat{RI}}{RI} \tag{37}$$

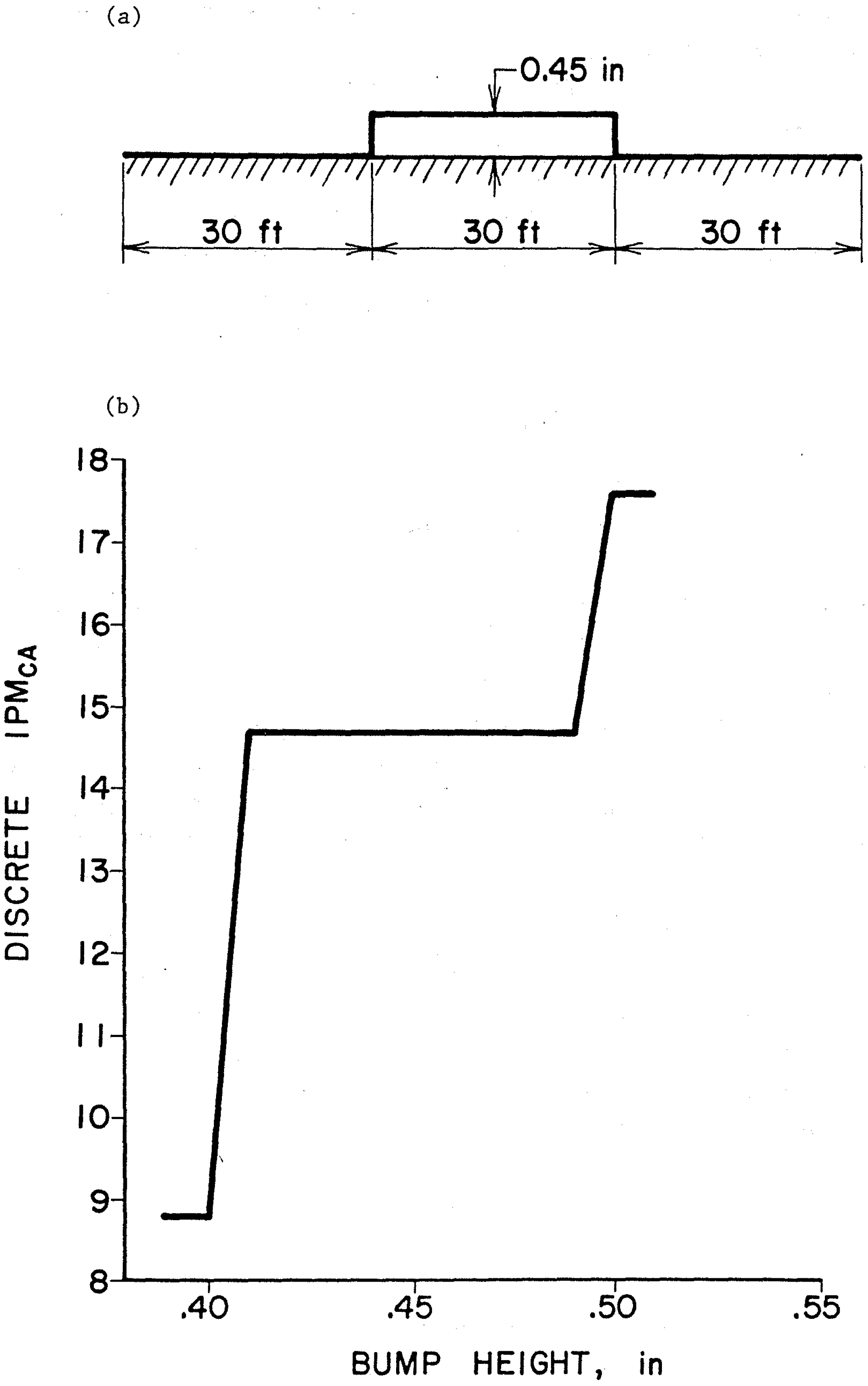


Figure 68. Recommended calibration surface (a), and the effect of the bump height on roughness of the calibration surface (b).

where $\hat{RI}$ is the roughness index obtained using the profilograph model, and RI is the roughness index obtained from the actual measurements.

Part 2: Comparison with Calibration Standard

It is proposed to use the International Roughness Index (IRI)[11,12] as the calibration standard. In Part 2 of the calibration procedure, regression models relating roughness measurements produced by the profilograph model and the IRI are derived. It should be noted that this part of the calibration procedure needs to be performed only once for a given type of profilograph. The details of the five-step procedure and the results obtained for the 12-wheel California and Rainhart profilographs are presented below.

Step 1. Generate 20 (or more) sets of profile data representing sections of new or newly surfaced pavements 0.1 mile in length, covering a range of roughness typical for new pavements, from 0 to approximately 20 IPM_{CA}.

Step 2. Compute values of IRI for each set of profile data generated in Step 1. The computer program for calculating IRI is described in "International Experiment to Establish Correlations and Standard Calibration Methods for Road Roughness Measurements."[11] The values of IRI obtained from the computation provide the calibration standard.

Step 3. Apply the sets of profile data generated in Step 1 to the profilograph simulation program. In response to each set of input data, the program will generate sets of profile data that would be measured by an ideal profilograph.

Step 4. Calculate a roughness index from each set of "measured" profile data obtained in Step 3.

Step 5. Develop calibration models relating roughness index values calculated in Step 4, representing measured profiles, and the IRI values obtained in Step 2, representing actual profiles.

The above five-step procedure was employed to develop calibration models for the California and Rainhart profilographs described in chapter 6. Each model was developed in three different forms. In the first form, the roughness index in Step 4 was calculated employing the methods commonly used in hand calculations of roughness from profilograph measurements. These methods involve the use of blanking bands of 0.2 in for the California profilograph and 0.1 in for the Rainhart profilograph. A linear regression model, given by the following equation, was used:

$$IRI^* = a_0 + a_1 \, IPM_{CA} \tag{38}$$

for the California profilograph, and

$$IRI^* = a_0 + a_1 \, IPM_{RH} \tag{39}$$

for the Rainhart profilograph. The symbol IRI^* represents the value of IRI predicted from the calibration equation.

The second form of the calibration model relates the same roughness indices as those used in equations 38 and 39, but the regression equation is quadratic. The quadratic calibration formulas for the California and Rainhart profilographs are:

$$IRI^* = b_0 + b_1 \, IPM_{CA} + b_2(IPM_{CA})^2 \tag{40}$$

$$IRI^* = b_0 + b_1 \, IPM_{RH} + b_2 \, (IPM_{RH})^2 \tag{41}$$

Finally, in developing the third form of the calibration models, the roughness of the profiles generated in Step 4 was expressed in terms of IRI instead of IPM. This form, therefore, eliminates the blanking bands from the profilograph data processing procedures. Linear regression models of the following forms were obtained:

$$IRI^* = a_0 + a_1 \, IRI_{CA} \tag{42}$$

$$IRI^* = a_0 + a_1 \, IRI_{RH} \tag{43}$$

Table 19 summarizes the calibration models developed using equations 38 through 43.

Table 19. Summary of the calibration models.

Calibration Equation	Coefficient of Correlation	Standard Deviation Around the Regression Line
$IRI^* = 36.4 + 3.11\ IPM_{CA}$	0.745	4.722
$IRI^* = 31.6 + 1.78\ IPM_{RH}$	0.798	4.200
$IRI^* = 30.3 + 6.67(IPM_{CA}) - 0.372(IPM_{CA})^2$	0.858	3.517
$IRI^* = 19.7 + 4.37(IPM_{RH}) - 0.117(IPM_{RH})^2$	0.983	1.235
$IRI^* = 0.107 + 0.773\ IRI_{CA}$	1.000	0.089
$IRI^* = 0.042 + 0.953\ IRI_{RH}$	1.000	0.1151

Several important observations can be made on the basis of the results presented in table 19. First of all, it can be seen that the quality of the linear calibration models is rather poor if blanking band is involved in processing profilograph data. This case is represented by the first two models in table 19. The nonlinear models, listed in the third and fourth lines of table 19, are much better in terms of the coefficient of correlation and standard deviation in this case. Also, the models developed for the Rainhart profilograph are considerably better than the models obtained for the California profilograph. The best models were obtained when IRI was used as the measure of roughness of the profiles measured by the profilographs. These models are listed in the last two lines of table 19. This final observation supports this study's recommendation to use IRI instead of the blanking band procedures in processing profilograph measurements.

8. SUMMARY AND RECOMMENDATIONS

ROUGHNESS CHARACTERISTICS OF NEW PAVEMENTS

Pavement roughness is described by two basic characteristics: its average magnitude over a given pavement length and its distribution with regard to the pavement profile wavelengths. The magnitude of roughness is commonly measured in inches per mile (IPM). However, the procedures employed in calculating the measure of roughness vary dramatically among the various roughness measuring devices. Table 14 lists the results obtained on 25 sites with four devices: the California profilograph, Rainhart profilograph, inertial profilometer, and Mays meter. The range of roughness obtained with the California profilograph is from 0 to 17.5 IPM_{CA}. The level of roughness varied with the test site locations, with the lowest values obtained on Interstate 83 and the highest values measured on Interstate 80 and Route 15.

To determine distribution of roughness versus profile wavelengths, PSD functions were found for seven sets of profile data measured with the laser beam. Five data sets were collected on bituminous pavements and two sets came from PCC pavements. No significant difference was observed between the PSD functions for bituminous and PCC pavements. The average PSD versus wavelength relationship was found to be similar to the relationships reported in the literature for other types of pavements. An analytical expression approximating the PSD of new pavements was derived in the following form:

$$S_{XX} = 6.66 \times 10^{-4} \lambda^2 \qquad (44)$$

Two computer programs were developed to generate sets of data with a desired PSD. Using the results of PSD calculations from the field test data, sets of data representing profiles of new pavements were generated.

ROUGHNESS MEASURING EQUIPMENT

There are two basic requirements for the devices used to measure roughness of new or newly surfaced pavements. The first requirement is that the frequency response characteristic should be uniform over the range of profile wavelengths from 1.6 to 32 ft. The second requirement specifies the minimum resolution of the device to be 0.5 IPM_{CA} (measured in the roughness scale of the California profilograph). The evaluations of the various roughness measuring devices used in the field tests are summarized below:

- An RTRRM device should be used to evaluate new pavement only if no other equipment is available, and then its frequency response must be determined at the speed it is used and time-consuming computer corrections are required.
- Profiling vehicles are the only type of equipment of those investigated in this study that have satisfactory frequency response and resolution.
- Profilographs have a varying response to wavelength. Some wavelengths are measured correctly, some hardly at all, and others are amplified. The 12-wheel California profilograph gives a poor measurement at 10- to 15-ft wavelengths and then amplifies those in the 20- to 50-ft range by as much as two times. The Rainhart profilograph has a better frequency response in the range of 1- to 20-ft wavelengths, nominally a one to one relation on the average. However, it attenuates wavelengths between 9 and 13 ft. Above 30-ft wavelengths, it attenuates the amplitude by at least 2, producing less than half of the actual amplitude in the road.

It was established that a 7-IPM_{CA} acceptance value is the most commonly used, but there is a desire to lower this value to 5 IPM_{CA}. These amplitude requirements are needed over a range of wavelengths from 1.6 to 32 ft. The use of profilographs to measure the roughness of new pavements where the acceptance criterion is below 7 in/mi is unacceptable unless the data acquisition is changed and the blanking is eliminated from the data processing procedure. If the height and distance are recorded so that these measurements can be used as input to a quarter-car model, then the International Roughness Index could be calculated and used as the acceptance criterion. However, this would still not account for the variable frequency response of the particular profilograph.

To determine the correlation among the various devices, linear regression models were developed relating the California and Rainhart profilographs, the profilometer, and Mays meter. Several different data processing methods were used with each raw data set. Forty-three models were found to be statistically significant on the basis of their coefficient of correlation greater than 0.75. In most cases, however, the accuracy of the regression models is not very high, mainly because of the relatively small range of the independent variables in these models. The best correlations were obtained from the data sets that originated from the profilometer measurements. The regression models involving profilographs developed in other studies and reported to have correlation coefficients higher than 0.9 were based on roughness data from a range exceeding the level of roughness typical for new pavements by a factor of 5 to 7.[5,6]

A profilograph computer simulation program was used to determine the effects of the length of the main truss and the number and location of the supporting wheels on the performance of profilographs. From the results of the computer simulation it was concluded that the optimum length of the profilograph main truss is 30 ft, which is somewhat longer than the 23-ft length recommended in the new ASTM standard (appendix B). It was also observed that the use of more than six supporting wheels did not improve profilograph performance significantly. The spacing of the supporting wheels in the range of 1.5 ft to 3.0 ft had a negligible effect on performance. On the basis of the computer simulation and field tests, it can also be concluded that the performance of profilographs would improve considerably if an electronic device were used to record and process profile measurements.

APPENDIX A. COMPUTER PROGRAMS

1. Data Acquisition for Profilometer

Function: Acquisition of height sensor and accelerometer signals from profilometer, sampling interval = 2 in.

Input: Acceleration signal, height signal, speed voltage

Output: Binary data of height, acceleration, and vehicle speed

Computer Requirements: IBM PC (or compatible) 640K, Hard Disk, Analog/Digital Interface Board DT2801A, Microsoft Fortran 4.0, PC-Lab Software

```
C     FORTRAN CODE TO OBTAIN ANALOG VOLTAGES THROUGH DT2801-A BOARD
C
C     This program acquires acceleration, height and vehicle speed signals
C
$LARGE : PROFILE
      INTEGER*2 SELECT_BOARD,SETUP_ADC,SET_CLOCK_DIVIDER,END_CHANNEL
      INTEGER*2 PROFILE(4,65000),BOARD_NUM,STATUS,GAIN,SCREEN_MODE
      INTEGER*2 START_CHANNEL,TIMING_SOURCE,NUMCHAN
      INTEGER*2 ROW,COL,BOARD_NUMBER,TEMP,I,IPP
      INTEGER*4 COUNTS,FREQ,NUMPTS,MAXPTS,INT
      REAL  DELTA,RTMP,SITELEN,MAXLEN,VELOCITY
      CHARACTER QUEST*1
      LOGICAL    DEFDAT
      EXTERNAL  SELECT_BOARD,SET_CLOCK_DIVIDER,SETUP_ADC,INITIALIZE
C
C     Clear screen
      SCREEN_MODE=2
      CALL MODE (SCREEN_MODE)
C     Use PCLSETUP to setup for board BOARD_NUM, single
C     ended input, and the start address factory is Hex 2EC
c
C     BOARD_NUM        Board selected in PCLSETUP.EXE
C
C     START_CHANNEL    First channel to scan
C
C     END_CHANNEL      Last channel to scan = START_CHANNEL+NUMCHAN
C
C     NUMCHAN          Number of channels to scan
C
C     STATUS           PCLAB returns an error status for any
C                      function call. If (STATUS <> 0) then
C                      there was an error.
C
C     TIMING_SOURCE    Specifies clock and trigger source
C                                          trigger     clock
C                      TIMING_SOURCE = 0   software   internal
C                      TIMING_SOURCE = 1   software   external
C                      TIMING_SOURCE = 2   external   internal
C                      TIMING_SOURCE = 3   external   external
C
C     GAIN             Specifies the voltage range for the channel
C                      GAIN = 1   (+/-) 10.00  volts
C                      GAIN = 2   (+/-)  5.00  volts
C                      GAIN = 4   (+/-)  2.50  volts
C                      GAIN = 8   (+/-)  1.25  volts
C
C     NUMPTS           Number of points for the acquisition
C     Initialize Variables
C
      BOARD_NUM=1
      TIMING_SOURCE=2
C
      INQUIRE (FILE='ACCHSDATA.SYS',EXIST=DEFDAT)
      OPEN (1,FILE='ACCHSDATA.SYS',FORM='BINARY')
```

```
      IF (DEFDAT) THEN
          READ (1) GAIN,NUMCHAN,START_CHANNEL,IPP,VELOCITY
      ELSE
         START_CHANNEL=1
         NUMCHAN=4
         GAIN=2
         VELOCITY=34.0
         IPP=6
      ENDIF
C
C     Clear screen and write information
C
      MAXPTS=65000
      DELTA=IPP
      MAXLEN=DELTA*MAXPTS/63360.0
      SITELEN=MAXLEN
1000  CONTINUE
      CALL MODE(SCREEN_MODE)
      WRITE (*,10)
      COL=0
      ROW=5
      CALL PUT (ROW,COL)
      WRITE (*,20) GAIN
      WRITE (*,*) '          '
      WRITE (*,30) NUMCHAN
      WRITE (*,*) '          '
      WRITE (*,40) START_CHANNEL
      WRITE (*,*) '          '
      END_CHANNEL=START_CHANNEL+NUMCHAN-1
      WRITE (*,50) END_CHANNEL
      WRITE (*,70) IPP
      WRITE (*,*) '          '
      WRITE (*,80) MAXLEN,SITELEN
      WRITE (*,*) '          '
      WRITE (*,60) VELOCITY
      WRITE (*,*) '          '
      QUEST='No'
      WRITE (*,90) QUEST
      READ (*,100) QUEST
C
C     If default informantion is not correct
C     then input correct information
C
      IF (QUEST.NE.'Q'.AND.QUEST.NE.'q')  THEN
         IF (QUEST.NE.'Y'.AND.QUEST.NE.'y')  THEN
C
C        While information is not correct loop
C
6000      CONTINUE
            CALL PUT (ROW,COL)
C
            WRITE (*,20) GAIN
            READ (*,110) TEMP
            IF (TEMP.EQ.1.OR.TEMP.EQ.2.OR.TEMP.EQ.4.OR.TEMP.EQ.8)
     &         GAIN=TEMP
C
            WRITE (*,30) NUMCHAN
            READ (*,110) TEMP
            IF (TEMP.GT.0.AND.TEMP.LT.5) NUMCHAN=TEMP
C
```

```
           WRITE (*,40) START_CHANNEL
           READ (*,110) TEMP
           IF (TEMP.GT.0.AND.TEMP.LT.10) START_CHANNEL=TEMP
           END_CHANNEL=START_CHANNEL+NUMCHAN-1
C
           WRITE (*,50) END_CHANNEL
           WRITE (*,70) IPP
           READ (*,110) TEMP
           IF (TEMP.GT.0) IPP=TEMP
           DELTA=IPP
           MAXLEN=DELTA*MAXPTS/63360.0
           IF (SITELEN.GT.MAXLEN) SITELEN=MAXLEN
           WRITE (*,80) MAXLEN,SITELEN
           READ (*,120) RTMP
           IF (RTMP.GT.0.01) THEN
                 IF (RTMP.LT.MAXLEN) THEN
                    SITELEN=RTMP
                 ELSE
                    SITELEN=MAXLEN
                 ENDIF
           ENDIF
           WRITE (*,60) VELOCITY
           READ (*,120) RTMP
           IF (RTMP.GT.0.01) VELOCITY=RTMP
C
           CALL PUT (ROW,COL)
           WRITE (*,20) GAIN
           WRITE (*,*) '          '
           WRITE (*,30) NUMCHAN
           WRITE (*,*) '          '
           WRITE (*,40) START_CHANNEL
           WRITE (*,*) '          '
           WRITE (*,50) END_CHANNEL
           WRITE (*,70) IPP
           WRITE (*,*) '          '
           WRITE (*,80) MAXLEN,SITELEN
           WRITE (*,*) '          '
           WRITE (*,60) VELOCITY
           WRITE (*,*) '          '
           QUEST='No'
           WRITE (*,90) QUEST
           READ (*,100) QUEST
        IF (QUEST.EQ.'Q'.OR.QUEST.EQ.'q') GOTO 5000
        IF (QUEST.NE.'Y'.AND.QUEST.NE.'y') GOTO 6000
      ENDIF
C
C
C     Initialize data translation board
C
      CALL INITIALIZE
C
C     Select data translation board BOARD_NUM
C
      STATUS=SELECT_BOARD (BOARD_NUM)
      IF (STATUS.NE.0) CALL ERROR (STATUS)
C
C     Setup A/D board to read a/d CHANNELS
C     and the clock speed = (number of channels * 1000 Hz)
C
      STATUS=SETUP_ADC (TIMING_SOURCE,START_CHANNEL,END_CHANNEL,GAIN)
```

```
      IF (STATUS.NE.0) CALL ERROR (STATUS)
      COUNTS=INT(800000.0/3000.0)
      STATUS=SET_CLOCK_DIVIDER (COUNTS)
      IF (STATUS.NE.0) CALL ERROR (STATUS)
      DELTA=IPP
      NUMPTS=INT(SITELEN/DELTA*63360.0+0.5)
      CALL A2D (PROFILE,NUMCHAN,NUMPTS,DELTA,VELOCITY,GAIN)
      GOTO  1000
      ENDIF
5000  CONTINUE
C
C     Update system file
C
      REWIND (1)
      WRITE (1) GAIN,NUMCHAN,START_CHANNEL,IPP,VELOCITY
      CLOSE (1)
      CALL MODE (SCREEN_MODE)
      STOP '**** PTI PROFILER TERMINATED ****'
C
10    FORMAT (//3X'*********** A/D CONFIGURATION ***********',
     & //3X,'INPUT CORRECT VALUE, PRESS ENTER IF VALUE IS CORRECT'$)
20    FORMAT (/3X,'A/D GAIN (1,2,4,8) [',I1,'] : '$)
30    FORMAT (/3X,'NUMBER OF CHANNELS TO SCAN (1-4) [',I3,'] : ',$)
40    FORMAT (/3X,'START CHANNEL (1-9) [',I2,'] : '$)
50    FORMAT (3X,'END CHANNEL [',I2,']'/)
70    FORMAT (/3X,'INCHES PER PULSE [',I2,'] : '$)
75    FORMAT (3X,'PULSE DIVIDER [',I2,'] : '$)
76    FORMAT (3X,'SAMPLE DISTANCE (Inches) [',F4.1,'] : ')
80    FORMAT (/3X,'SITE LENGTH (MAX ',F11.5,' Miles) [',F11.5,'] : '$)
60    FORMAT (/3X,'VELOCITY [',F5.2,'] MPH : '$)
90    FORMAT (/3X,'Is this correct (Y, N or Quit) (Default = ',
     & A3,') : '$)
100   FORMAT (A1)
110   FORMAT (I3)
120   FORMAT (F10.0)
      END
C
      SUBROUTINE A2D (PROFILE,NUMCHAN,NUMPTS,DELTA,VELOCITY,GAIN)
      INTEGER*2 ADC_SERIES,END_CHANNEL,BOARD_NUM,STATUS,GAIN
      INTEGER*2 START_CHANNEL,TIMING_SOURCE,NUMCHAN,SCREEN_MODE,FORM
      INTEGER*4 NUMPTS,COUNTS,FREQ,I,K
      INTEGER*2 PROFILE (4,65000)
      REAL      DELTA,VELOCITY
      CHARACTER QUEST*1,FILENAME*60,TEXT*80,CTMP*10,LANE*8
      LOGICAL   DEFDAT
      EXTERNAL  ADC_SERIES,ENABLE_SYSTEM_CLOCK
      EXTERNAL  DISABLE_SYSTEM_CLOCK
C
C     Clear screen
C
      SCREEN_MODE=2
      CALL MODE (SCREEN_MODE)
C
C     Wait for user to start test
C
      WRITE (*,10)
      READ (*,20) TEXT
      CALL MODE (SCREEN_MODE)
C
C
```

```
C     Disable system clock and start
C     data acquisition then restart system clock
C
      CALL DISABLE_SYSTEM_CLOCK
C      WRITE (*,*) 'press S to Stop A/D'
      WRITE (*,*) NUMPTS
C
      DO 1000 I=1,NUMPTS
            STATUS=ADC_SERIES (NUMCHAN,PROFILE(1,I))
1000  CONTINUE
C===
C            CALL GETKEY (QUEST)
C            IF (QUEST.EQ.'S'.OR.QUEST.EQ.'s') GOTO 2000
C===
C
2000  CONTINUE
C
      CALL ENABLE_SYSTEM_CLOCK
C
C     Testing finished
C
3000  CONTINUE
         CALL MODE (SCREEN_MODE)
C4000     CONTINUE
C         WRITE (*,30)
C         READ (*,40,ERR=4000) FORM
C      IF (FORM.LT.0.OR.FORM.GT.3) GOTO 3000
C      IF (FORM.NE.3) THEN
C
C     SAVE BINARY DATA
C
      FORM=2
      CALL SAVE (PROFILE,NUMCHAN,NUMPTS,DELTA,FORM,START_CHANNEL,
     &  VELOCITY,GAIN)
C      ENDIF
      RETURN
C
C     I/O Formats
C
10    FORMAT (//1X,'Press ENTER to start data acquisition'$)
20    FORMAT (A1)
30    FORMAT (//1X,'0 --> FORD FORMAT [default]',/1X,
     & '1 --> ASCII',/1X,'2 --> Binary',/1X,'3 --> Don''t save',
     & //1X,'Enter correct number : '$)
40    FORMAT (I1)
      END
C
C     Subroutine ERROR
C
C     STATUS <> 0 abort testing release brake and
C     stop program execution
C
      SUBROUTINE ERROR (STATUS)
      INTEGER*2 STATUS
      CHARACTER*1 QUEST
C
C     Issue error message and wait for user response
C
      WRITE (*,*) 'ERROR # ',STATUS
      WRITE (*,20)
```

```
      READ (*,10) QUEST
C
C     Subroutine ERROR finished
C
      STOP 'ERROR SKIDSUB'
C
C     I/O Formats
C
10    FORMAT (A1)
20    FORMAT (' Press ENTER and the program will abort'$)
      END
C
      SUBROUTINE SAVE (PROFILE,NUMCHAN,NUMPTS,DELTA,FORM,
     & START_CHANNEL,VELOCITY,GAIN)
      INTEGER*2 FORM,SCREEN_MODE,NUMCHAN,HOUR,MINUTE,SECOND,HUNDRED,GAIN
      INTEGER*2 ROW,COL,BOARD_NUMBER,TEMP,MONTH,YEAR,DAY,START_CHANNEL
      INTEGER*4 NUMPTS,I,J
      INTEGER*2 COUNT,PROFILE(4,65000)
      REAL DELTA,VELOCITY
      CHARACTER QUEST*1,FILENAME*15,TEXT*80,OUTPUT*9
      LOGICAL DEFDAT
      OUTPUT='FORMATTED'
      IF (FORM.EQ.2) OUTPUT='BINARY
      WRITE (*,*) NUMCHAN,NUMPTS
C
C     Get new filename and open
C
1000  CONTINUE
         WRITE (*,10)
         READ (*,20) FILENAME
         INQUIRE (FILE=FILENAME,EXIST=DEFDAT)
      IF (FILENAME.EQ.' ') GOTO 1000
      IF (DEFDAT) THEN
        WRITE(*,80)FILENAME
        READ(*,90) QUEST
        IF(QUEST.EQ.'N'.OR.QUEST.EQ.'n') GOTO 1000
      ENDIF
      OPEN (2,FILE=FILENAME,STATUS='UNKNOWN',FORM='BINARY')
C
C     Get header and save at top of data file
C
      WRITE (*,30)
      READ (*,50) TEXT
C
      CALL GETDAT (YEAR,MONTH,DAY)
      CALL GETTIM (HOUR,MINUTE,SECOND,HUNDRED)
      COUNT=START_CHANNEL
      WRITE (2) TEXT,YEAR,MONTH,DAY,HOUR,MINUTE,DELTA,VELOCITY,GAIN
      DO 3000 I=1,NUMPTS
         WRITE (2) (PROFILE (J,I),J=1,NUMCHAN)
3000  CONTINUE
      CLOSE (2)
      RETURN
10    FORMAT (1X,'Input NEW filename : '$)
20    FORMAT (A15)
30    FORMAT (//3X,'Location identification : ',$)
40    FORMAT ('DATE (',I2.2,'/',I2.2,'/',I4.4,') TIME (',I2.2,':',I2.2,
     & ')')
50      FORMAT(A80)
60    FORMAT (I4,3(1X,I4))
```

```
70    FORMAT (F11.5,' SAMPLE DISTANCE')
80      FORMAT(1X,'File : ',A15,' already exist..'/
     & 1X,'RETURN to overide..;N to reenter..',$)
90      FORMAT(A1)
      END
```

2. Processing of Profilometer Data

Function: Extract mean values for data stored by profile data acquisition program

Input: Binary data from data acquisition program

Output: List of file names, size, means of each signal

Computer Requirements: IBM PC (or compatible) 640K, hard disk, microsoft Fortran 4.0

```
c        STATISTICAL ANALYSIS OF PROFILE DATA
C        (SPEED COMPENSATED VERSION)
C        DATE     :     Sept 1, 1988
c        Developed by   Meau-Fuh Pong
C        This program reads a list of profile data, computes the
c        mean and standard deviation of the raw data, then writes
c        them in the control file for later profile computation.
         REAL           SIGMA(4),FMEAN(4),VAR(4),FLOAT,SQRT,FN,DX,SPEED
         INTEGER        INT,I,J,K,M,ICL,N
         INTEGER*2      MONTH,YEAR,DAY,HOUR,GAIN,MINUTE,SECOND
         INTEGER*2      IFILE,IEND,IX(4,36000),IV
         CHARACTER      TEXT*80,FILEIN*10
         CHARACTER*4    NAME,EXT
         CHARACTER*1    AGAIN
         EXT ='.BIN'
C    ICL= number of COLUMNS
         ICL=2
2        WRITE(*,6)
6        FORMAT(1X,'Enter 4-letter file name : ',$)
         READ(*,7) NAME
7        FORMAT(A4)
         WRITE(*,10)
10       FORMAT(1X,'Input start and end file numbers # ',$)
         READ(*,13) IFILE,IEND
13       FORMAT(I3,I3)
         WRITE(*,13) IFILE,IEND
         OPEN(UNIT=15,FILE='STATIS.SYS',STATUS='UNKNOWN')
1        CONTINUE
C      get filename for input data
            CALL FNAME(IFILE,FILEIN,NAME,EXT)
            WRITE(*,11) FILEIN
11          FORMAT(/1X,'Performing file: ',A10)
            OPEN(UNIT=11,FILE=FILEIN,STATUS='OLD',FORM='BINARY',ERR=400)
            READ(11) TEXT
            READ(11) MONTH,DAY,YEAR,HOUR,MINUTE
            READ(11) DX,SPEED,GAIN
            WRITE(*,79) TEXT
            WRITE(*,*) MONTH,DAY,YEAR,HOUR,MINUTE
            WRITE(*,*) DX,SPEED,GAIN
79          FORMAT(A79)
            DO 23 I=1,ICL
              FMEAN(I)=0.
              VAR(I)=0.
23            SIGMA(I)=0.
             J=1
18            READ(11,END=25) (IX(I,J),I=1,ICL),IV
             J=J+1
            GO TO 18
25          CONTINUE
            CLOSE(11)
            N=J-1
            WRITE(*,26) N
26          FORMAT(1X,'SIZE = ',I5)
            FN=FLOAT(N)
```

```
         DO 100 J=1,N
           DO 100 I=1,ICL
100          FMEAN(I)=FMEAN(I)+FLOAT(IX(I,J))/FN
         DO 150 J=1,N
           DO 150 I=1,ICL
150          VAR(I)=VAR(I)+((FLOAT(IX(I,J))-FMEAN(I))/FN)**2
         DO 300 I=1,ICL
300        SIGMA(I)=SQRT(VAR(I))
         WRITE(15,9) NAME,IFILE,N,(FMEAN(I),I=1,ICL),(SIGMA(J),J=1,ICL)
9        FORMAT(A4,I2,1X,I6,4(1X,F8.3))
400      CONTINUE
         IFILE=IFILE+1
         IF(IFILE.LE.IEND) GO TO 1
         WRITE(*,415)
415      FORMAT(1X,'Continue to process other file name ?(Y/N) ',$)
         READ(*,425) AGAIN
425      FORMAT(A1)
         IF(AGAIN.EQ.'Y'.OR.AGAIN.EQ.'y') GOTO 2
         CLOSE(15)
500      CONTINUE
         STOP
         END
C
         SUBROUTINE      FNAME(IFILE,FILEIN,FSTRING,GSTRING)
C        This subroutine  constructs the file name for main
c        program in an assigned name-pattern and sequential way.
c
         INTEGER*2       MOD,IFILE,JFILE,KFILE
         CHARACTER*4     FSTRING,GSTRING
         CHARACTER*10    FILEIN
         CHARACTER*1     CFILE(2),CHAR
           JFILE=MOD(IFILE,10)
           KFILE=(IFILE-JFILE)/10
           CFILE(1)=CHAR(KFILE+48)
           CFILE(2)=CHAR(JFILE+48)
         IF (CFILE(1).EQ.'0') THEN
           FILEIN=FSTRING//CFILE(2)//GSTRING
         ELSE
           FILEIN=FSTRING//CFILE(1)//CFILE(2)//GSTRING
         ENDIF
         RETURN
         END
```

3. PROFILE COMPUTATION FROM PROFILOMETER DATA

FUNCTION:	COMPUTATION OF ROAD PROFILE DATA FROM PROFILOMETER HEIGHT SENSOR AND ACCELEROMETER DATA. THE CALCULATED PROFILE SEQUENCE IS NUMERICALLY HIGH-PASS FILTERED TO ELIMINATE PROFILE WAVELENGTH COMPONENTS EXCEEDING 300 FT.
INPUT:	LIST OF FILES NAMES, SIZE, MEANS OF EACH SIGNAL; BINARY DATA; FILTER SPECIFICATION
OUTPUT:	PROFILE DATA
COMPUTER REQUIREMENTS:	IBM PC (OR COMPATIBLE) 640K, HARD DISK, MICROSOFT FORTRAN 4.0

```
C       A PROFILE COMPUTATION PROFGRAM (TIMEBASE PROFILING)
C       This program is to read acceleration and height data in
c       binary format produced by ACCHS program, then integrates
c       acceleration twice, added with height sensor output
c       to get profile.  This resultant profile has to be filtered
c       to get rid off long wavelength profile(more than 300 feet)
c       and square integration drifts.
c       *** NOTE ***
C       Before running this program, besure to run STATIS to
c       generate control batch file for those.data files you
c       want to process.
c               before running this program *****
$LARGE : X
        REAL    ACC,X(20000),ACCP,V,VPC
        REAL    DELTAT,CAL1,SIGMA(2),APROF,VP10MPH,WLF
        REAL    AMEAN,HMEAN,DX,SPEED,FN,FIPS,FLOAT
        REAL    CAL2R,VV,DELTAT2,VPG,VPIL,VPIR,DT
        INTEGER         I,J,K,N,NP,N2,ILOCK,IPATH,INT
        INTEGER*2       MONTH,YEAR,DAY,HOUR,GAIN,MINUTE,SECOND
        INTEGER*2       IACC,IHS,IV,IFILE,IEND
        CHARACTER*80    TEXT
        CHARACTER*10    FILEIN,FILEOUT
        CHARACTER*15    FILELST
        CHARACTER*4     NAME,EXT(3)
        NAME  ='    '
        EXT(1)='.BIN'
        EXT(2)='.PRF'
        EXT(3)='.160'
110     WRITE(*,111)
111     FORMAT(1X,'File list name : ',$)
        READ(*,115) FILELST
115     FORMAT(A15)
        OPEN(UNIT=15,FILE=FILELST,STATUS='OLD',ERR=120)
        GOTO 1
120     WRITE(*,121) FILELST
121     FORMAT(1X,'File : ',a15,' does not exist...')
        GOTO 110
C
1       CONTINUE
        READ(15,9,END=200) NAME,IFILE,N,AMEAN,HMEAN,(SIGMA(J),J=1,2)
9       FORMAT(A4,I2,1X,I6,4(1X,F8.3))
C     get filename for input data
        CALL FNAME(IFILE,FILEIN,NAME,EXT(1))
        WRITE(*,7) FILEIN
7       FORMAT(/1X,'Performing file : ',A10)
        OPEN(UNIT=11,FILE=FILEIN,STATUS='OLD',form='binary',ERR=200)
        READ(11) TEXT
        READ(11) MONTH,DAY,YEAR,HOUR,MINUTE
        READ(11) DX,SPEED,GAIN
        WRITE(*,31) TEXT
        WRITE(*,32) MONTH,DAY,YEAR,HOUR,MINUTE
        WRITE(*,33) DX,SPEED,GAIN
31      FORMAT(1x,A78)
32      FORMAT(5(1X,I4))
33      FORMAT(2(F8.5,1X),I2)
C
c ****   initialize variables    ****
C
C     speed in Real inch per second
        FIPS=SPEED*5280./3600.*12.
```

```
c     norminal time between samples
        DT =DX/FIPS
c     square of DT
C       DELTAT2=(DX/FIPS)**2
c     vole per one increment after A/D : 10 volts eq to 2048 increments
        VPC=10./2048.
C       Volt per one G
        VPG=3.77552
        CAL1=10./FLOAT(GAIN)/2048./VPG*32.2*12.
c       Volt per inch for each channel
C       VPIL=1.9433
        VPIR=1.73495
C       CAL2L=VPC/FLOAT(GAIN)/VPIL
        CAL2R=VPC/FLOAT(GAIN)/VPIR
C       write(*,11)
11      format(3x,'pass 1')
C
C       define voltage per 10 Mile per hore
        VP10MPH = 0.949
C
C  read input data; Acceleations and Height Sensors
C   This section computes profiles
C    Because acceleration profile is one sample ahead, I delay it
c    and add it to height sensor profile.
        J=1
18      READ(11,ERR=25) IACC,IHS,IV
        V = FLOAT(IV-2048)*VPC
        IF(V.GT.0.) DELTAT = DT*VP10MPH/V
        IF(J.EQ.1) THEN
          VV= (FLOAT(IACC)-AMEAN)*CAL1*DELTAT
          APROF=VV*DELTAT
          X(J)=APROF
        ELSE
          DELTAT2=DELTAT**2
          X(J)= (FLOAT(IHS)-HMEAN)*CAL2R+APROF
          ACC = (FLOAT(IACC)-AMEAN)*CAL1
          VV  = VV+ACC*DELTAT
          APROF= APROF+VV*DELTAT+ACC*DELTAT2
        ENDIF
        J=J+1
        GO TO 18
25      CONTINUE
        N=J-1
        CLOSE(11)
C       write(*,26)
26      format(3x,'pass 2')
C
C       Following section performs filtering long wave legnth
c       more than 300 feet.
C
C       long wavelength to be more than 300 feet
        WLF = 300.
C
C       Filtering :
c       First get rid of integration drift and DC offset
c
        CALL REGRFILT (N,DX,FIPS,WLF,X)
        CALL REGRFILT (N,DX,FIPS,WLF,X)
C
c       Second, filter away long wave length part
```

```
c
C       CALL HPFILT   (N,DX,FIPS,WLF,X)
        CALL HPFILT   (N,DX,FIPS,WLF,X)
c
C   Output profiles results
        CALL FNAME(IFILE,FILEOUT,NAME,EXT(2))
        OPEN(UNIT=12,FILE=FILEOUT,STATUS='UNKNOWN')
        DO 155 J=1,N
        WRITE(12,160) X(J)
155     CONTINUE
        CLOSE(12)
160     FORMAT(2(E10.4,1X))
        GO TO 1
200     CONTINUE
        STOP
        END
C
C
        SUBROUTINE      FNAME(IFILE,FILEIN,FSTRING,GSTRING)
C       This subroutine  constructs the file name for main
c       program in an assigned name-pattern and sequential numbering.
c
        INTEGER*2       MOD,IFILE,JFILE,KFILE
        CHARACTER*4     FSTRING,GSTRING
        CHARACTER*10    FILEIN
        CHARACTER*1     CFILE(2),CHAR
          JFILE=MOD(IFILE,10)
          KFILE=(IFILE-JFILE)/10
          CFILE(1)=CHAR(KFILE+48)
          CFILE(2)=CHAR(JFILE+48)
        IF (CFILE(1).EQ.'0') THEN
          FILEIN=FSTRING//CFILE(2)//GSTRING
        ELSE
          FILEIN=FSTRING//CFILE(1)//CFILE(2)//GSTRING
        ENDIF
        RETURN
        END
C
C
        SUBROUTINE HPFILT(N,DX,FIPS,WLF,X)
c       A HIGH PASS FILTER VERSION 3.1
C       This subroutine contains two parts:
c           A regresion filter to eliminate Integration drift
c
c           A Highpass filter to eliminate long wavelength (300 ft)
c           a impulse response functuion is to be generated in
c           program and a time domain convolution between imp.
c           function H(n) and input function X(n) to produce
c           the output function Y(n).
C
c       DEVELOPED by :  Meau-Fuh Pong
c       Date (2.0)   :  Dec. 30, 1987
c       Revise 3.0   :  Feb. 24, 1988
C       Revise 3.1   :  Sept. 1, 1988
C
C
$LARGE : X,Y,H
        REAL    X(20000),Y(20000),STEP,DIF
        REAL    H(2000),FLOAT,XSUM,WLF,DX,SPEED
        INTEGER I,INT,J,N,NH,NT,NH2,K,JMK,MOD,NHOLD
```

```
C       dummy operation..
        FIPS=FIPS
c
C   remove some DC
          STEP=X(1)
          DIF =(X(N)-X(1))/FLOAT(N-1)
          DO 160 J=1,N
160         X(J)= X(J) - STEP - FLOAT(J-1) * DIF
C
C
c   Digital (Convolution) filter
C
C       First, generate filter impulse response function
C       NH      number of data in Impulse function
c       for 300 feet wavelength;
        NH=INT(WLF*12./DX+.5)
C       Make NH to be odd number
        IF(MOD(NH,2).EQ.0) NH=NH+1
C
C       Check if it was the same filter function,
c       If Yes, no need to generate the same one.
        IF(NH.EQ.NHOLD) GOTO 180
C
C         generates Impulse Response Function
          CALL FILTWIN2(NH,H)
C         Save the old NH
          NHOLD=NH
c         half of the filter samples
          NH2=NH/2
C
180     CONTINUE
C
C       Total number to perform convolution
        NT=N
C
        WRITE(*,190)
190     FORMAT(1X,' Performing convolution filter ...')
        DO 200 J=1,NT
          Y(J)=0.
          DO 200 K=1,NH
            JMK=J-K+1+NH2
            IF ((JMK.GE.1).AND.(JMK.LE.N)) THEN
              Y(J)=Y(J) + H(K) * X(JMK)
C           ELSEIF(JMK.LT.1) THEN
C             Y(J)=Y(J)+H(K)*X(1)
C           ELSE
C             Y(J)=Y(J)+H(K)*X(N)
            ENDIF
200     CONTINUE
C       DO J=1,N
C         WRITE(22,*) Y(J)
C       ENDDO
C   get high frequency parts
        DO 300 J=1,N
            X(J)=X(J)-Y(J)
300     CONTINUE
c   average by 2; smoothing by 2
C       DO 400 J=1,N
C           IF (J.EQ.1) THEN
C             Y(J)=X(J)
```

```
C           ELSE
C             Y(J)=(X(J)+X(J-1))/2.
C           ENDIF
400     CONTINUE
        IF(N.GT.2*NH) THEN
          XSUM = 0.0
          DO 450 J = NH2+1,N-NH2
            XSUM = XSUM + Y(J)
450       CONTINUE
          XSUM = XSUM/FLOAT(N-NH)
        ENDIF
c   move the signal arround zero
        DO 500 J=1,N
500         X(J) = Y(J) - XSUM
C
        RETURN
        END
c
        SUBROUTINE FILTWIN2(NH,H)
C
C       This is a routine to generate filter impulse response
c       function by using SYNC function whose extented version
c       is the inverse Fourier transform of BOX filter in frequency
c       domain.  The output array will be used as the weighted
c       function in converlution with original signal to produce
c       lowpassed version of the signal.
C       NH      number of data in Impulse function
c       H       the impulse response function array
        REAL    H(2000),AMIN1,ANG,SPAN,LOW,ASUM
        REAL    FNH,DX,FLOAT,W,PI,ACOS,SIN
        INTEGER I,NH,K
        DX=12.0
        FNH=FLOAT(NH+1)
        PI=2.*ACOS(0.0)
        W=2.*PI/FNH
        DO 10 K=1,NH
          ANG = FLOAT(K-1)*W-PI
          H(K)=SIN(ANG)/ANG
10      CONTINUE
C
        LOW=1.
        DO 20 K=1,NH
          LOW=AMIN1(LOW,H(K))
20      CONTINUE
        ASUM=0.
        DO 30 K=1,NH
          H(K)=H(K)-LOW
          ASUM = ASUM + H(K)
30      CONTINUE
C
        DO 40 K=1,NH
          H(K)=H(K)/ASUM
40      CONTINUE
C
        RETURN
        END
c
C
        SUBROUTINE REGRFILT(N,DX,FIPS,WLF,X)
c       A HIGH PASS FILTER VERSION 3.01
```

```
C       This subroutine performs regresion filter to eliminate
c       Integration drift.
C
c       DEVELOPED by :  Meau-Fuh Pong
c       Date (2.0)   :  Dec. 30, 1987
c       Revise 3.0   :  Feb. 24, 1988
C
        REAL    X(20000),STEP,DIF,FLOAT,FN
        REAL    DT,DT2,SX,SX2,SX3,SX4,SY,SYX,SYX2,DELTA
        REAL    A0,A1,A2,T,FIPS,DX
        INTEGER I,J,K,N,NT
C       null operation
        WLF=WLF
        WRITE(*,5)
5       FORMAT(3X,'Performing regresion filtering...')
c
c
C     Remove integration drift by REGRESSION
c
C       DO J=1,N
C         WRITE(20,*) X(1,J)
C       ENDDO
C   Vehicle speed : inch per second
C       FIPS=SPEED*5280./3600*12.
C    Pick time history to be variable and the profile to be
c    dependent variable
c    Time between samples
        DT=DX/FIPS
        write(*,10) N,DX
10      format(1x,' Regression filter: N= ',I6,'  DX=',F8.3)
        FN=FLOAT(N)
c
c   Preparing Auto-products up to 4th power
        SX=0.
        SX2=0.
        SX3=0.
        SX4=0.
        DO 90 J=1,N
            T=FLOAT(J-1)*DT
            SX=SX+T
            SX2=SX2+T**2
            SX3=SX3+T**3
90          SX4=SX4+T**4
C  Denominator :
        DELTA=FN*SX2*SX4+2*SX*SX3*SX2-SX2**3-SX**2*SX4-FN*SX3**2
        WRITE(*,95) DELTA,FIPS,DT
95      FORMAT(1X,'DELTA= ',F16.0,' SPEED=',F7.2,
     &  'inches/sec  DT=',F8.6)
C
C   Generating Cross products
c   vertical (dependent)  : profile
c   variable (horizontal) : time index
          SY=0.
          SYX=0.
          SYX2=0.
          DO 100 J=1,N
            T=FLOAT(J-1)*DT
            SY=SY+X(J)
            SYX=SYX+X(J)*T
100         SYX2=SYX2+X(J)*T**2
```

```
c       WRITE(*,*)' PASS 2'
C
C       The coefficients of each power
        A0=(SY*SX2*SX4+SX3*SX*SYX2+SYX*SX3*SX2-SX2**2*SYX2
     &     -SX*SX4*SYX-SX3**2*SY)/DELTA
        A1=(FN*SYX*SX4+SX*SX2*SYX2+SX2*SX3*SY-SX2**2*SYX
     &     -SX*SX4*SY-FN*SX3*SYX2)/DELTA
        A2=(FN*SX2*SYX2+SX*SX2*SYX+SY*SX*SX3-SY*SX2**2
     &     -SX**2*SYX2-FN*SX3*SYX)/DELTA
c       WRITE(*,*) ' PASS 3'
c       WRITE(*,103) A0,A1,A2
103     FORMAT(1X,'A0= ',E15.8,' A1= ',E15.8,' A2= ',E15.8)
        DO 120 J=1,N
          T=FLOAT(J-1)*DT
120       X(J)=X(J)-A0-A1*T-A2*T**2
C
C       DO J=1,N
C         WRITE(21,*) X(J)
C       ENDDO
150     CONTINUE
C
C   remove some DC
          STEP=X(1)
          DIF =(X(N)-X(1))/FLOAT(N-1)
          DO 160 J=1,N
160         X(J)= X(J) - STEP - FLOAT(J-1) * DIF
C
        RETURN
        END
```

4. PROFILOGRAPH DATA ACQUISITION

FUNCTION:	ACQUISITION OF ANALOG VOLTAGE SIGNAL FROM A POTENTIOMETER INSTALLED ON PROFILOGRAPH MEASURING SYSTEM VIA METRABYTE DASH-8 INTERFACE BOARD
INPUT:	ANALOG SIGNAL FROM POTENTIOMETER
OUTPUT:	SET OF DISCRETE PROFILE DATA
COMPUTER REQUIREMENTS:	IBM PC (OR COMPATIBLE) PORTABLE, HARD DISK, DASH-8 ANALOG/DIGITAL INTERFACE BOARD, DASH-8, SUBROUTINES

```
10 REM
20 '  CALIFORNIA PROFILOGRAPH DATA ACQUISITION PROGRAM
30 '       Pennsylvania Transportation Institute
40 '
50 '  Developed by      : Meau-Fuh Pong
60 '  Date        : Aug. 10, 1988
70 '  Revised           : Aug. 22, 1988
80 '  This program is designed to acquire analog voltage signals
90 ' from a hardware device which converts the measurements of inches
100 'from California Profilograph through a MetraByte DASH8 A/D board.
110 ' A few pre-required processes have to be checked :
120 ' * Channel 1 of DASH8 connects to voltage measured
130 ' * INT IN    of DASH8 connects to trigger pulse train
140 '   * Variable IPP has to be calibrated as Inches per Pulse
150 ' * DASH8 must be configured differential input +- 5 volts
160 ' * Acquired voltage is assumed to be 1 volt/inch
170 ' * IPP should be less than RECDX
180 '   *** This program will be compiled and linked with DASH8*.OBJ
200 DIM DIO%(4),AR%(20000)
210 HEADER1$="DATA saved for California Profilograph pavement measurement"
220 HEADER2$="Saved values are in INCHES"
230 OPEN "I",#2,"CALIPP.SYS"
240 INPUT #2,IPP
250 CLOSE #2
260 'IPP = .8711811/764.24*524!    'Inch per pulse calibration
270 '                   this constant should be calibrated with
280 '                   real equipment enviroment.  If profilograph
290 '                         run too short, decrease IPP
300 RECDX=2!                  'The required recording sampling distance
310 AVGDX=10!                 'smoothing moving average distance
320 MD%=0               'Mode for initialization for DASH8
330 DIO%(0)=&H300               'Base address of DASH8 board setup
340 CALL DASH8 (MD%, DIO%(0), FLAG%)
350 IF FLAG%<>0 THEN PRINT "Initialization error"
370 'SET MULTIPLEXER SCAN LIMITS
380 MD% = 1             'Mode for set upper and lower scan limits
390 DIO%(0)=1                  'Lower channel limit
400 DIO%(1)=1                  'Upper channel limit
410 CALL DASH8(MD%, DIO%(0), FLAG%)
420 IF FLAG% <> 0 THEN PRINT"Multiplexer scan limit setting error"
440 MD%=2               'Mode for one channel A/D
450 CH% =1
460 CALL DASH8 (MD%,CH%,FLAG%)
470 IF FLAG%<>0 THEN PRINT"Multiplexer address setting error"
490 'Loop start for every data set
510 CLS:LOCATE 5,1
520 INPUT "Desired distance in feet (528) ";DIST
530 IF DIST = 0! THEN DIST=528!
540 PRINT "  accepted distance = ";DIST
550 N% = DIST*12!/IPP         'figure out the required number of A/D
560 PRINT "  Number of points sampled will be = ";N%
570 INPUT "  Hit RETURN to start...";K$         'Wait for start
580 BEEP:BEEP
600 PRINT "   Hit .. T .. to terminate the process....."
```

```
610 PRINT ""
620 PRINT "     .................GETTING DATA................."
630 MD% = 5                       'Mode for trigger A/D
640 DIO%(1) = 1                   'One conversion only
650 I% = 0
660 '
670 'Loop for every data point
680 A$=INKEY$                     'Check keyboard
690 IF A$="T" OR A$="t" THEN 770     'S mean stop acquition process
700 DIO%(0) = VARPTR(AR%(I%))  'Sets pointer to i_th elem. of array
710 CALL DASH8 (MD%, DIO%(0), FLAG%)
720 IF FLAG <> 0 THEN PRINT "Mode 5 error":STOP
730 I% = I% +1
740 IF I% < N% THEN 680
750 PRINT "Program terminates normally."
760 GOTO 780
770 PRINT "....... Terminated by user ........."
780 BEEP
790 'Acknowledge user the results
800 NEWN% = I%                    'If terminated by user, new N is NEWN%
810 PRINT "Number of data points acquired = ";NEWN%
820 NDIST = NEWN%*IPP/12!
830 PRINT "Terminated at distance = " ;NDIST
840 PRINT ""
850 PRINT "Type Q to restart,A to auto compensate, or S to stop program..."
860 INPUT "Fileneame to save :";FILE$   'ask for filename
870 IF FILE$=""  THEN 860
880 IF FILE$="Q" THEN 500               'User might wish to quit this data set
890 IF FILE$="S" THEN 1220
900 IF FILE$="q" THEN 500               'User might wish to quit this data set
910 IF FILE$="s" THEN 1220
920 IF FILE$="A" THEN GOTO 1370
930 IF FILE$="a" THEN GOTO 1370
940 INPUT "Comments or notes:";COMMENT$
950 '
960 'write headers to stored data file
970 OPEN "O",#1,FILE$
980 WRITE #1, HEADER1$
990 WRITE #1, HEADER2$," Sampling distance (inches)= ", RECDX
1000 WRITE #1, COMMENT$
1010 WRITE #1, NDIST, "feet    ",NEWN%,"samples"
1020 '
1030 'store data in disk
1040 INCH=AR%(0)*5!/2048!
1050 PRINT #1, USING "##.###"; INCH
1060 J=RECDX
1070 SIDE%=(AVGDX/IPP+.25)             'figure out # of samples
1080 '                                  to be sum on two sides
1090 CONV=5/2048!/(2!*SIDE%+1!)
1100 '
1110 'Start to find the sample near the desired recording distance
1120 FOR I%=2 TO NEWN%
1130 EVEN = IPP * I%                   'find the appropriate sample by
1140 IF EVEN >= J THEN GOSUB 1270      'comparing with accumulated distance
1150 NEXT I%
1160 CLOSE #1
1170 NDATA%=J/RECDX
1180 PRINT NDATA%;" DATA were saved....."
1190 INPUT "Perform another run Y/N ?";AGAIN$
1200 IF AGAIN$="y" THEN 500
```

```
1210 IF AGAIN$="Y" THEN 500
1220 STOP
1230 END
1240 '
1250 ' SUBroutine to save data in disk
1260 '
1270 IF I% < SIDE% OR I% > (NEWN%-SIDE%) THEN INCH=5!/2048!*AR%(I%):GOTO 1330
1280    ARSUM% = 0
1290    FOR K% = (I%-SIDE%) TO (I%+SIDE%)
1300      ARSUM% = ARSUM% + AR%(K%)
1310    NEXT K%
1320    INCH=CONV*ARSUM%
1330    PRINT #1,USING "##.###"; INCH
1340    J = J + RECDX
1350    RETURN
1360 '
1370 ' SUBroutine to compensate the pulses/distance variation
1380 '
1390    IPP=IPP*DIST/NDIST
1400    NNDIST=IPP*NEWN%/12!
1410    PRINT "After compensated, new total distance= ",NNDIST;"feet"
1420    OPEN "O",#3,"CALIPP.SAV"
1430    WRITE #3,"IPP = ",IPP
1440    CLOSE #3
1450    GOTO 840
1460 NDATA%=J/RECDX
```

5. Laser Beam Data Acquisition

Function: Acquisition of analog voltage signal from a SELCOM laser sensor via Metrabyte DASH-8 interface board

Input: Analog laser beam signal

Output: Discrete laser beam data

Computer Requirements: IBM PC (or compatible) portable, hard disk, DASH-8 analog/digital interface board, DASH-8 subroutines

```
10 '  ROLLING STRAIGHT EDGE (BEAM) DATA ACQUISITION PROGRAM
20 '       Pennsylvania Transportation Institute
30 '         Date : July 20th, 1988
40 '  This program is designed to acquire analog voltage signals
50 '  from a Selcom laser sensor installed on
60 '  rolling straight edge, through a MetraByte DASH8 A/D board.
70 '
80 '  A few pre-required processes have to be checked :
90 '
100 ' * Channel 1 of DASH8 connects to voltage measured
110 ' * INT IN    of DASH8 connects to trigger pulse train
120 '    * Varible IPP has to be calibrated as Inches per Pulse
130 ' * DASH8 must be configured differential input +- 5 volts
140 '
150 DIM DIO%(4),AR%(1600),ELEV(5,1600),DIFF(5)
160 HEADER1$="DATA saved for Rolling straight edge pavement measurement"
170 IPP = .72000000     'Inch per pulse calibration
180 '             this constant should be calibrated with
190 '             real equipment enviroment.  If profilograph
200 '                   run too short, decrease IPP
205 RECDX=2!
210 MD%=0               'Mode for initialization
220 DIO%(0)=&H300               'Base address of DASH8 board setup
230 CALL DASH8 (MD%, DIO%(0), FLAG%)
240 IF FLAG%<>0 THEN PRINT "Initialization error"
250 '
260 'SET MULTIPLEXER SCAN LIMITS
270 MD% = 1             'Mode for set upper and lower scan limits
280 DIO%(0)=1                 'Lower channel limit
290 DIO%(1)=1                 'Upper channel limit
300 CALL DASH8(MD%, DIO%(0), FLAG%)
310 IF FLAG% <> 0 THEN PRINT"Multiplexer scan limit setting error"
320 '
330 MD%=2               'Mode for one channel A/D
340 CH% =1
350 CALL DASH8 (MD%,CH%,FLAG%)
360 IF FLAG%<>0 THEN PRINT"Multiplexer address setting error"
370 '
380 'Loop start for every data set
390 '
400 CLS:LOCATE 5,1:S%=0
410 INPUT "Desired distance in feet (528) ";DIST
420 IF DIST = 0! THEN DIST=528!
430 PRINT "  accepted distance = ";DIST
440 N% = DIST*12!/IPP        'figure out the required number of A/D
450 PRINT "  Total number of points sampled will be = ";N%
460 INPUT "Length of section (12 feet) = ",LENGTH
470 IF LENGTH= 0! THEN LENGTH=12!
480 PRINT "  accepted section length = ";LENGTH
490 NS% = 12!*LENGTH/IPP       'figure out the required number of A/D
500 LEN12=12!*LENGTH+2!
510 NS1% = NS% + 1
520 PRINT "  Number of samples for section = ";NS%
530 TSEC% = (DIST+3!)/LENGTH                   'figuring out how many sections
```

```
540 PRINT "  Total number of section = ",TSEC%
550 INPUT "How many repeated run for one section ?(5 or less) ",NREP%
560 IF NREP% = 0 THEN NREP% = 5
570 PRINT " Number of repeated run is ",NREP%
580 IF NREP% > 5 THEN BEEP:PRINT "Repeated number should be less than 5, Try
again!":GOTO 520
590 '
600 INPUT "Fileneame to save (Q to reset):";FILE$     'ask for filename
610 IF FILE$=""  THEN 600
620 IF FILE$="Q" OR FILE$ = "q" THEN 390 'User might wish to quit this data set
630 INPUT "Comments or notes:";COMMENT$   '
640 '
650 '
660 'write headers in disk
670 OPEN "O",#1,FILE$
680 WRITE #1, HEADER1$
690 WRITE #1, "All values are in inches, Sampling distance = 2 inches"
700 WRITE #1, COMMENT$
710 '
720 'set some constants
730 CONV= -5!/2048!/3!          'Negative conversion
735 NSEC%=1
737 JLAST%=LEN12/RECDX
740 MD% = 5                'Mode for trigger A/D
750 DIO%(1) = 1                 'One conversion only
760 '
770 FOR NRUN% = 1 TO NREP%
780   I% = 1
790 '
800 'Data acquisition loop start here
805   PRINT " "
810   PRINT "  SECTION : ",NSEC%," RUN : ",NRUN%
820 '
830   NDIST= LENGTH * (NSEC%-1)
840   PRINT "  Move-to/stay-on distance = " ;NDIST
841   INPUT "    Hit RETURN to start...(or S to terminate)";K$  'Wait for start
842   IF K$ ="S" OR K$="s" THEN S% =1: GOTO  1010
843   BEEP
850   PRINT "      Hit  T  to terminate the process......"
860 'Loop for every data point
870   A$=INKEY$                 'Check keyboard
880   IF A$="T" OR A$="t" THEN NS% = I%: GOTO 940     'T to stop data acquition
890   DIO%(0) = VARPTR(AR%(I%))  'Sets pointer to i_th elem. of array
900   CALL DASH8 (MD%, DIO%(0), FLAG%)
910   IF FLAG <> 0 THEN PRINT "Mode 5 error":STOP
920   I% = I% +1
930   IF I% < NS1% THEN 860
940   BEEP:PRINT "    Number of samples = ",I%
950 '
960 '
970 ' Acknowledge user the results
980 ' PRINT ""
990   INPUT "  Was this section good ?(N to re-run) ",GOOD$
1000   IF GOOD$ = "N" OR GOOD$ = "n" THEN 780
```

```
1010 '
1050   PRINT "....Computing and Saving data file, please WAIT...."
1060 '
1070 ' Convert data to real values and stroe in memory for late processing
1080   J%=1:J2=0!
1090   FOR I%=1 TO NS%
1100     EVEN = IPP * (I%-1)  'converting sample to longitudinal location
1110 '
1120     IF EVEN >= J2 THEN GOSUB 1430    'meet a even location -->save data
1130     IF EVEN > LEN12 THEN 1150
1140   NEXT I%
1145   IF S%=1 GOTO 1180
1150 NEXT NRUN%
1160 '
1170 '
1180 'Store data in the disk
1190 FOR I%=1 TO J%
1200  IF NREP% = 1 THEN PRINT #1,USING "##.###";ELEV(1,I%)
1210  IF NREP% = 2 THEN PRINT #1,USING "###.###";ELEV(1,I%);ELEV(2,I%)
1220 IF NREP% = 3 THEN PRINT #1,USING "###.###";ELEV(1,I%);ELEV(2,I%);ELEV(3,I%)
1230 IF NREP% = 4 THEN PRINT #1,USING
"###.###";ELEV(1,I%);ELEV(2,I%);ELEV(3,I%);ELEV(4,I%)
1240 IF NREP% = 5 THEN PRINT #1,USING
"###.###";ELEV(1,I%);ELEV(2,I%);ELEV(3,I%);ELEV(4,I%);ELEV(5,I%)
1250 NEXT I%
1260 '
1270 WRITE #1,"END OF SECTION";NSEC%
1280 PRINT "SECTION NUMBER ",NSEC%," ACCOMPLISHED !!"
1290 NSEC%=NSEC%+1
1300 '
1310 IF S%=1 THEN GOTO 1400
1320 IF NSEC% < TSEC% THEN 740
1330 IF NSEC% = TSEC% THEN BEEP:PRINT "Next will be last section..":GOTO 740
1340 '
1350 'Test and saving data finished..
1360 CLOSE #1
1370 INPUT "Perform another run Y/N ?";AGAIN$
1380 IF AGAIN$="y" THEN S%=0 : GOTO 390
1390 IF AGAIN$="Y" THEN S%=0 : GOTO 390
1400 STOP
1410 END
1420 '
1430 'Subroutine to convert/reduce raw data and save
1440 IF I% = 1 OR I >= JLAST% THEN ELEV(NRUN%,J%)=-5!/2048!*AR%(I%):GOTO 1470
1450    ELEV(NRUN%,J%)=CONV*(AR%(I%-1)+AR%(I%)+AR%(I%+1))
1470  J%=J%+1
1480  J2=J%*2!
1490    RETURN
```

6. PROCESSING OF LASER BEAM DATA

FUNCTION: A) CORRECTION OF LASER BEAM DATA FOR THE BEAM ANGLE WITH RESPECT TO HORIZONTAL USING ROD AND LEVEL DATA

B) FILTERING LASER BEAM DATA TO ELIMINATE 12-FT COMPONENT INDUCED BY THE BEAM DEFLECTION

INPUT: LASER BEAM DATA; ROD AND LEVEL MEASUREMENTS

OUTPUT: ROAD PROFILE

COMPUTER REQUIREMENTS: IBM PC (OR COMPATIBLE) PORTABLE, HARD DISK, DASH-8 ANALOG/DIGITAL INTERFACE BOARD, DASH-8 SUBROUTINES

```
c       This program was to process the data obtained from
c       a 12-foot Rolling Straightegde (Leser beam).
c
c       Because it was 12 feet long, data is only good for
c       12 foot as long as wavelength is concerned.
c
c       The beam had deflection (bending) like an U-shape.
c       This program is also prepared to correct it.
c
c       If Rod and Level data is associated with the R.S.E.
c       measurement, the program will look for the rod-level
c       data to make correction, After this kind of process,
c       data is good for long wavelength.
c
c       Developed by    Meau-Fuh Pong
c       For project     USDT 7375
c       finishedf date  Oct. 4, 1988
c
$LARGE
        REAL     PROFL(5500),PROFC(5500)
        REAL     ABS,FLOAT,WLF,DX,FIPS
        REAL     BEGIN(100),ENDS(100),CHS
        REAL     BOUND,DIFF,DIFFL,DIFFP,TEMP,DENO,PROFP,CENTER
        REAL     B0,B1,TRA0,TRA1,MSE,X(100),Y(100),LEVEL(100)
        REAL     DEFL(100),A(3),TRA(3),SSE,DM,BEND(100)
        REAL     LEVR(100),LEVD(100),DL,FN,PGLEN,SITELEN
        INTEGER          NFILT,NREG
        INTEGER          I,J,K,L,M,N,NS,ISEC,NSEC,NMISS,NJUMP,NS1
        INTEGER          JSTART(100),JEND(100),IFRESH,NP,NP2,ND,NL,NT
        INTEGER*2        IFILE
        CHARACTER        FILEIN*10,FILEOUT*10,FILELST*15,DEFLDATA*15
        CHARACTER*4      NAME,EXT(5)
        CHARACTER        TEXT(3)*78,QUEST*1,JUNK*15
        LOGICAL*1        THERE
        EXT(1)='.DAT'
        EXT(2)='.RSE'
        EXT(3)='.LEV'
        EXT(4)='.DFL'
        EXT(5)='.BEN'
C
        DEFLDATA='DEFL.DAT'
C
        DIFF = 0.1
        BOUND = 1.0
        DM = 6.0
        DX = 2.0
        IFRESH=1
C
        OPEN(UNIT=14,FILE='PROCESS.RSE',STATUS='UNKNOWN')
1       CONTINUE
6       WRITE(*,15)
        READ(*,35) FILELST
C
        OPEN(UNIT=15,FILE=FILELST,STATUS='OLD',ERR=7)
        GOTO 10
7       WRITE(*,5) FILELST
        GOTO 1
10      CONTINUE
        READ(15,65,END=1000) NAME,IFILE
        CALL FNAME(IFILE,NAME,EXT(1),FILEIN)
```

```
        WRITE(*,85) FILEIN
        WRITE(14,85) FILEIN
        OPEN(UNIT=11,FILE=FILEIN,STATUS='OLD',ERR=11)
        GOTO 12
11      WRITE(*,5) FILEIN
        GOTO 10
12      CONTINUE
C----------------------------------------------------------------
C       READING DATA FILE
C................................................................
        DO 16 I=1,3
16        READ(11,80) TEXT(I)
C
        ISEC=1
        J=1
14      FORMAT(F7.3)
20      CONTINUE
          READ(11,14,ERR=100,END=110) PROFL(J)
          IF(IFRESH.EQ.1) THEN
            JSTART(ISEC) = J
            IFRESH = 0
          ENDIF
          J=J+1
          GOTO 20
100     CONTINUE
        JEND(ISEC)=J-1
        ISEC= ISEC +1
        IFRESH = 1
        READ(11,17) JUNK
        GOTO 20
17      FORMAT(A15)
C
110     CONTINUE
        CLOSE(11)
        JEND(ISEC)=J-1
        N= J-1
        NSEC = ISEC -1
C
        WRITE(*,95) NSEC,N
        WRITE(14,95) NSEC,N
C
        DO 119 ISEC=1,NSEC
119     WRITE(14,165) ISEC,JSTART(ISEC),JEND(ISEC)
C
c------------------------------------------------------------
C       REMOVING THE EFFECT OF BEAM DEFLECTION
C............................................................
C
        DO 120 ISEC = 1, NSEC
          DO 118 J = JSTART(ISEC), JEND(ISEC)
            K = J - JSTART(ISEC) + 1
            BEND(K) = BEND(K) + PROFL(J)
118       CONTINUE
120     CONTINUE
C
        L =  JEND(1)-JSTART(1)+1
        FN = FLOAT(NSEC)
        CALL FNAME(IFILE,NAME,EXT(4),FILEIN)
        OPEN(UNIT=21,FILE=FILEIN,STATUS='UNKNOWN')
        DO 130 K=1,L
```

```
          DEFL(K)= BEND(K)/FN
          WRITE(21,205) DEFL(K)
130     CONTINUE
        CLOSE(21)
C
C
        NT = 8
        CALL SECFIT(L,NT,DEFL,BEND)
C
C
c       CALL FNAME(IFILE,NAME,EXT(5),FILEIN)
c       OPEN(UNIT=22,FILE=FILEIN,STATUS='UNKNOWN')
c       DO 140 K=1,L
c         WRITE(22,205) BEND(K)
140     CONTINUE
c       CLOSE(22)
C
C
        DO 170 ISEC = 1, NSEC
          DO 168 J = JSTART(ISEC), JEND(ISEC)
            K = J - JSTART(ISEC) + 1
            PROFL(J) = PROFL(J) - BEND(K)
168       CONTINUE
170     CONTINUE
c--------------------------------------------------------------
C       EXAMINE THE DATA    I : ABSOLUTE VALUES
C..............................................................
        DO 210 ISEC = 1, NSEC
          NP = 1
          DO 200 J = JSTART(ISEC), JEND(ISEC)
            IF(ABS(PROFL(J)).GT.BOUND) THEN
              IF(ABS(J-JSTART(ISEC)).LE.6) THEN
                PROFL(J) = PROFL(J+1)
              ELSE
                IF(ABS(J-JEND(ISEC)).LE.6) THEN
                  PROFL(J) = PROFL(J-1)
                ENDIF
              ENDIF
            ENDIF
200       CONTINUE
210     CONTINUE
C-------------------------------------------------------------
C       EXAMINE THE DATA    II : DIFF BETWEEN SAMPLES
C.............................................................
        DO 310 ISEC = 1, NSEC
          NMISS = 0
          DO 300 J = JSTART(ISEC), JEND(ISEC)
            IF(J.EQ.JSTART(ISEC)) THEN
              IF(ABS(PROFL(J)-PROFL(J+1)).GT.DIFF) THEN
               CHS=(PROFL(J)-PROFL(J+1))*(PROFL(J+1)-PROFL(J+2))
               IF(CHS.LT.0..AND.ABS(PROFL(J+1)-PROFL(J+2)).GT.DIFF) THEN
                  PROFL(J) = PROFL(J+2)
                  NMISS = NMISS + 1
                ELSE
                  PROFL(J) = PROFL(J+1)
                  NMISS = NMISS + 1
                ENDIF
              ENDIF
            ELSEIF(J.EQ.JEND(ISEC)) THEN
              IF(ABS(PROFL(J)-PROFL(J-1)).GT.DIFF) THEN
```

```
               CHS=(PROFL(J)-PROFL(J-1))*(PROFL(J+1)-PROFL(J-2))
               IF(CHS.LT.0..AND.ABS(PROFL(J-1)-PROFL(J-2)).GT.DIFF) THEN
                  PROFL(J) = PROFL(J-2)
                  NMISS = NMISS + 1
               ELSE
                  PROFL(J) = PROFL(J-1)
                  NMISS = NMISS + 1
               ENDIF
              ENDIF
            ELSE
              CENTER = (PROFL(J-1)+PROFL(J+1))/2.
              IF(ABS(PROFL(J)-CENTER).GT.DIFF) THEN
                PROFL(J) = CENTER
                NMISS = NMISS + 1
              ENDIF
            ENDIF
300       CONTINUE
          IF(NMISS.NE.0) THEN
            WRITE(*,115) NMISS,ISEC
            WRITE(14,115) NMISS,ISEC
          ENDIF
310     CONTINUE
C
C-----------------------------------------------------------
c       check the inter-computation results
c       OPEN(UNIT=13,FILE='INTER.PRO',STATUS='UNKNOWN')
c       DO 320 I=1,3
c320      WRITE(13,80) TEXT(I)
c       DO 330 J=1,N
c330      WRITE(13,*) PROFL(J)
c       CLOSE(13)
C-------------------------------------------------------------
C       SLOPE REMOVAL (DUE TO UNEVEN HEIGHT OF R.S.E. SUPPORTS)
C.............................................................
c       prepare an array for dependent variables
c       DO 350 K=1,80
c350      X(K) = FLOAT(K-1)*DX
C
c       DO 410 ISEC = 1, NSEC
c         put one section data in a short array
c         DO 360 J = JSTART(ISEC), JEND(ISEC)
c           K = J -JSTART(ISEC) + 1
c360        Y(K) = PROFL(J)
C
c       CALL LINREG (K,B0,B1,TRA0,TRA1,MSE,X,Y)
C
c       put back to the long array
c         DO 400 L = 1,K
c           TEMP= Y(L) - B0 - B1*X(L)
c           PROFC(JSTART(ISEC)+L-1) = TEMP
c           IF(L.EQ.1) BEGIN(ISEC)= TEMP
c           IF(L.EQ.K) ENDS(ISEC)= TEMP
400       CONTINUE
c         WRITE(*,125) ISEC,B0,TRA0,B1,TRA1
c         WRITE(14,125) ISEC,B0,TRA0,B1,TRA1
410     CONTINUE
c
C-----------------------------------------------------------
C       PREPARE LEVEL TABLE FOR RECONFIGURING THE DATA
C...........................................................
```

```
C
        CALL FNAME(IFILE,NAME,EXT(3),FILEIN)
        INQUIRE(FILE=FILEIN,EXIST=THERE)
c.......................................................
        IF(THERE) THEN
c
          WRITE(*,175) FILEIN
C
C         Associated rod and level exists !!
C
          OPEN(UNIT=18,FILE=FILEIN,STATUS='OLD')
          I = 1
416       CONTINUE
            READ(18,*,END=420) LEVR(I)
            I=I+1
            GOTO 416
420       CONTINUE
          NL = I - 1
          CLOSE(18)
C
C       find out the change between two level point
c       if it is too much, it must be an another set of measurement.
c       record the changes in LEVD
          I = 1
          K = 0
430       CONTINUE
            DL = LEVR(I+1) - LEVR(I)
            IF(ABS(DL).LE.2.0) THEN
                K = K + 1
                LEVD(K) = DL
            ELSE
                I = I + 1
                GOTO 430
            ENDIF
            I = I + 1
          IF(I.LE.NL) GOTO 430
          NL = K
C
          WRITE(*,185) NL
          IF(NL.NE.NSEC+1) THEN
            WRITE(*,195)
            WRITE(14,195)
          ENDIF
c
c       assemble the level table
          LEVEL(1) = 0.0
          DO 440 I = 1,NL
440         LEVEL(I+1) = LEVEL(I) + LEVD(I)*12.0
          DO 442 I = 1, NL+1
442         X(I) = FLOAT(I-1)
C
          NP = NL +1
C
c       find the slope and initial vertical shift
c
          CALL LINREG(NP,B0,B1,TRA0,TRA1,MSE,X,LEVEL)
C
c       put them near zero
c
          DO 446 I = 1,NP
```

```
446         LEVEL(I) = LEVEL(I) - B0 - B1 * X(I)
C
      ELSE
C
        LEVEL(1) = 0.0
        NJUMP=0
C       fix the level value for each end of section
        DO 450 ISEC = 2,NSEC
          IF(ABS(BEGIN(ISEC)-ENDS(ISEC-1)).GT.DIFF) NJUMP=NJUMP+1
C
          IF(ABS(BEGIN(ISEC)).LE.ABS(ENDS(ISEC-1))) THEN
            LEVEL(ISEC) = BEGIN(ISEC)
          ELSE
            LEVEL(ISEC) = ENDS(ISEC-1)
          ENDIF
450     CONTINUE
        LEVEL(NSEC+1) = 0.0
        WRITE(*,135) NJUMP
        WRITE(14,135) NJUMP
c
      ENDIF
C............................................................
c
c     remove the long wavelength of rod & level data
c
      PGLEN = 16.
      SITELEN = 12.*12.
      NS1=NSEC+1
C
C     obtaing long wavelength by moving average
c
      CALL MOVAVG(NS1,SITELEN,PGLEN,LEVEL,LEVR)
C
C     subtraction to remove long wavelength
      DO 480 I=1,NS1
        LEVEL(I)=LEVEL(I)-LEVR(I)
480   CONTINUE
c
C------------------------------------------------------------
C     RECONFIGURE THE DATA
C............................................................
      DO 510 ISEC = 1, NSEC
        DO 500 J = JSTART(ISEC), JEND(ISEC)
          K = J - JSTART(ISEC)
          DENO = FLOAT(K) / FLOAT(JEND(ISEC)-JSTART(ISEC))
          DIFFP = PROFC(JEND(ISEC)) - PROFC(JSTART(ISEC))
          DIFFL = LEVEL(ISEC+1) - LEVEL(ISEC)
          PROFL(J) = PROFC(J) + (DIFFL-DIFFP) * DENO
     &               + LEVEL(ISEC) - PROFC(JSTART(ISEC))
500     CONTINUE
510   CONTINUE
C
c-----------------------------------------------------------
c     DIGITAL FILTER
C
C
      OPEN(UNIT=19,FILE='FILTER.SYS',STATUS='OLD')
      READ(19,515) NREG,NFILT,WLF,DX
515   FORMAT(2I2,2F6.2)
      CLOSE(19)
```

```
        IF (NREG.GT.0) THEN
          DO 520 I = 1,NREG
            CALL REGRFILT(N,DX,FIPS,WLF,PROFL)
520       CONTINUE
        ENDIF
C
        IF(NFILT.GT.0) THEN
          DO 530 I=1,NFILT
            CALL HPFILT(N,DX,FIPS,WLF,PROFL)
530       CONTINUE
        ENDIF
C
C--------------------------------------------------------------
C       OUTPUT DATA
C..............................................................
        CALL FNAME (IFILE,NAME,EXT(2),FILEIN)
        OPEN (UNIT=12,FILE=FILEIN,STATUS='UNKNOWN')
        DO 580 I= 1,3
580       WRITE(12,80) TEXT(I)
        DO 600 J = 1,N
           WRITE(12,590) PROFL(J)
590     FORMAT(F6.3)
600     CONTINUE
        CLOSE(12)
        GOTO 10
1000    CONTINUE
        CLOSE(14)
        CLOSE(15)
C--------------------------------------------------------------
C       FORMAT SECTION
C..............................................................
5       FORMAT(1x,'Expected data file: ',a10,' does not exit !!'/
     $  2x,'please check file list...')
15      FORMAT(1X,'Input file list to be processed: ',$)
25      FORMAT(I3)
35      FORMAT(A15)
45      FORMAT(1X,'More than ',I3,' data in the beginning of',
     &  ' section are invalid.',/,5X,' YES to overide ? ',$)
55      FORMAT(A1)
65      FORMAT(A4,I2)
75      FORMAT(/5X,'FILE : ',A10/)
80      FORMAT(A78)
85      FORMAT(1X,'....Processing file : ',A10,'.....')
95      FORMAT(1X,'Number of sections= ',I3,' Number of points= ',I4)
105     FORMAT(A10)
115     FORMAT(1X,I3,' data in section ',I3,' were out of bound.')
125     FORMAT(1X,'The regression of section ',I3,' has:',/
     &  10x,'vertical shift = ',f8.3,' t * = ',f10.2,/
     &  10x,'slope = ',f7.4,' t * = ',f10.2)
135     FORMAT(1X,'Number of jump between sections = ',i3)
145     FORMAT(1X,'File : ',a15,' does not exist, another one : ',$)
155     FORMAT(1X,'ND='I3,' COEFFICIENTS=',3(E10.4,1X))
165     FORMAT(1X,'SECTION ',I3,' START=',I4,' END=',I4)
175     FORMAT(6X,'Associated rod-level file : ',a10,' exists!')
185     FORMAT(6X,'Number of level data = ',I3)
195     FORMAT(3X,' **** ROD-LEVEL DATA DOES NOT MATCH ****')
205     FORMAT(F7.3)
1200    CONTINUE
        STOP
        END
```

```
c
c
      SUBROUTINE      FNAME(IFILE,FSTRING,GSTRING,FILEIN)
C     This subroutine  constructs the file name for main
c     program in an assigned name-pattern and sequential way.
      INTEGER*2       IFILE,JFILE,KFILE,MOD
      CHARACTER*4     FSTRING
      CHARACTER*4     GSTRING
      CHARACTER*10    FILEIN
      CHARACTER*1     CFILE(2),CHAR
        JFILE=MOD(IFILE,10)
        KFILE=(IFILE-JFILE)/10
        CFILE(1)=CHAR(KFILE+48)
        CFILE(2)=CHAR(JFILE+48)
      IF(CFILE(1).NE.'0'.AND.CFILE(2).NE.'0') THEN
        FILEIN=FSTRING//CFILE(1)//CFILE(2)//GSTRING
      ELSEIF(CFILE(2).NE.'0') THEN
        FILEIN=FSTRING//CFILE(2)//GSTRING
      ELSE
        FILEIN=FSTRING//GSTRING
      ENDIF
      RETURN
      END
C
C
      SUBROUTINE LINREG (N,B0,B1,TRA0,TRA1,MSE,X,Y)
C
C     This subroutine does linear regression :
c
C     Y(I) =  B0 + B1 * X(I)
c
c     TRA0    t ratio for B0
c     TRA1    t ratio for B1
C     MSE     Mean square error or Standard deviation
C
C     Written by      Meau-Fuh Pong
c     Date            Aug. 29, 1988
c
      REAL    B0,B1,TRA0,TRA1,FLOAT,XSUM,YSUM,XMEAN,YMEAN
      REAL    FN,VFN,SSE,MSE,SX2,SXYC,SXC2,SB0,SB1,SQRT,TEMP
      REAL    X(100),Y(100)
      INTEGER I,N
      FN = FLOAT(N)
      VFN = 1./FN
      XSUM = 0.
      YSUM = 0.
C
      DO 10 I=1,N
        XSUM = XSUM + X(I)
        YSUM = YSUM + Y(I)
10    CONTINUE
      XMEAN = XSUM* VFN
      YMEAN = YSUM* VFN
      SXYC = 0.
      SXC2 = 0.
      SX2 = 0.
      DO 20 I = 1,N
        TEMP = X(I) - XMEAN
        SXYC = SXYC + TEMP * (Y(I) - YMEAN )
        SXC2 = SXC2 + TEMP**2
```

```
          SX2  = SX2  + X(I)**2
20      CONTINUE
C
C
        B1 = SXYC/SXC2
        B0 = YMEAN - B1 * XMEAN
C
C
C       SSE = 0.
C       DO 30 I=1,N
C         SSE = SSE + (Y(I) - B0 - B1 * X(I))**2
30      CONTINUE
C       MSE = SSE/(FN-2.)
C       SB1 = SQRT(MSE/SXC2)
C       IF (SB1.NE.0.) THEN
C         TRA1 = B1/SB1
C       ENDIF
C
C       SB0 = SQRT(MSE*(VFN + XMEAN**2/SXC2))
C       IF(SB0.NE.0.) THEN
C         TRA0 = B0/SB0
C       ENDIF
C
        RETURN
        END
C
C
        SUBROUTINE SECFIT(N,NTHROW,X,Y)
C
C       This subroutine is to fit the entry to a second order curve
C
        REAL    X(100),Y(100),A(3),DT,T,Z(100)
        INTEGER N,I,J,NTHROW,NKEEP
        DT=2.0
C       NTHROW=7
        NKEEP = N - NTHROW
C
        DO 50 J=1,NKEEP
          Z(J)=X(J+NTHROW)
50      CONTINUE
C
        CALL SECREG(NKEEP,DT,A,Z)
C
        DO 100 I=1,N
          T = FLOAT(I-NTHROW-1) * DT
          Y(I) = A(1) + A(2)*T + A(3)*T**2
100     CONTINUE
        RETURN
        END
C
C
        SUBROUTINE SECREG(N,DT,A,X)
C       This subroutine performs 2nd order regresion to extrate
c       parabolic fuction
C
c       DEVELOPED by :  Meau-Fuh Pong
c       Date (2.0)   :  Dec. 30, 1987
c       Revise 3.0   :  Feb. 24, 1988
C
        REAL    X(100),STEP,DIF,FLOAT,FN
```

```
        REAL    DT,DT2,SX,SX2,SX3,SX4,SY,SYX,SYX2,DELTA
        REAL    A(3),TRA(3),T,FIPS,DX
        INTEGER I,J,K,N,NT
        WRITE(*,5)
5       FORMAT(3X,'Performing QUODRATIC regresion ...')
c
C       DO J=1,N
C         WRITE(20,*) X(1,J)
C       ENDDO
C    Pick time history to be variable and the profile to be
c    dependent variable
c    Time between samples
        write(*,10) N,DT
10      format(1x,' Regression filter: N= ',I6,'  DT=',F8.3)
        FN=FLOAT(N)
c
c   Preparing Auto-products up to 4th power
        SX=0.
        SX2=0.
        SX3=0.
        SX4=0.
        DO 90 J=1,N
            T=FLOAT(J-1)*DT
            SX=SX+T
            SX2=SX2+T**2
            SX3=SX3+T**3
90          SX4=SX4+T**4
C  Denominator :
        DELTA=FN*SX2*SX4+2*SX*SX3*SX2-SX2**3-SX**2*SX4-FN*SX3**2
        WRITE(*,95) DELTA
95      FORMAT(1X,'DELTA= ',E16.9)
C
C   Computing Cross products
c   vertical (dependent)   : profile
c   variable (horizontal) : time index
          SY=0.
          SYX=0.
          SYX2=0.
          DO 100 J=1,N
            T=FLOAT(J-1)*DT
            SY=SY+X(J)
            SYX=SYX+X(J)*T
100         SYX2=SYX2+X(J)*T**2
C
C       The coefficients of each power
c       CONSTANT:
        A(1)=(SY*SX2*SX4+SX3*SX*SYX2+SYX*SX3*SX2-SX2**2*SYX2
     &     -SX*SX4*SYX-SX3**2*SY)/DELTA
C       1ST ORDER
        A(2)=(FN*SYX*SX4+SX*SX2*SYX2+SX2*SX3*SY-SX2**2*SYX
     &     -SX*SX4*SY-FN*SX3*SYX2)/DELTA
C       2ND ORDER
        A(3)=(FN*SX2*SYX2+SX*SX2*SYX+SY*SX*SX3-SY*SX2**2
     &     -SX**2*SYX2-FN*SX3*SYX)/DELTA
C
        RETURN
        END
c
        SUBROUTINE MOVAVG(N,DX,PGLEN,X,Y)
C
```

```
C       This is a subrouting to perform moving average with specified
C       averaging length.  The output of this sub is the array of
c       after-smoothing.  It show the long-wave length part of the
c       original profilogram.  You may subtracted this by original
c       to get short wavelength part.
c       Developed by    Meau-Fuh Pong
c       Date            Aug. 12, 1988
C
C       N       number of samples
C       DX      sampling distamce of profilogram (INCH)
C       PGLEN   length of the main struss of profilograph (FEET)
C               (or half of the wavelength to be removed)
$LARGE : X,Y
        REAL    X(100),Y(100),DX,PGLEN,FNAVG,FLOAT,SUM
        INTEGER I,J,K,NINT,INT,MOD,JLEFT,JRIGHT,JREM,JADD,N,NAVG,NAVG2
c
        NAVG = NINT(PGLEN*2./DX*12.)
C    make it odd number
        IF( MOD(NAVG,2).EQ.0) NAVG=NAVG+1
        NAVG2= NAVG/2
        FNAVG=FLOAT(NAVG)
C
        SUM=0.
        DO 100 K=2,NAVG2+1
100       SUM=SUM+X(K)
C
        Y(1)= ( FLOAT(NAVG2+1)*X(1) + SUM )/FNAVG
C
        DO 200 J=2,N
          JLEFT  = J-NAVG2
          IF(JLEFT.LE.1) JLEFT = 1
          JRIGHT = J+NAVG2
          IF(JRIGHT.GE.N) JRIGHT = N
          Y(J) = Y(J-1) + ( X(JRIGHT) - X(JLEFT) )/FNAVG
200     CONTINUE
        RETURN
        END
c

C
        SUBROUTINE HPFILT(N,DX,FIPS,WLF,X)
c
c       A HIGH PASS FILTER VERSION 3.1
c
c       A Highpass filter to eliminate long wavelength (300 ft)
c       a impulse response functuion is to be generated in
c       program and a time domain convolution between imp.
c       function H(n) and input function X(n) to produce
c       the output function Y(n).
C
c       Developed by :  Meau-Fuh Pong
c       Date (2.0)   :  Dec. 30, 1987
c       Revise 3.0   :  Feb. 24, 1988
C       Revise 3.1   :  Sept. 1, 1988
C
C
$LARGE : X,Y,H
        REAL    X(5500),Y(5500),STEP,DIF
        REAL    H(1000),FLOAT,XSUM,WLF,DX
        INTEGER I,INT,J,N,NH,NT,NH2,K,JMK,MOD,NHOLD
```

```
c       Now Y(I) contains the low frequency or long wavelength part
c       of original function
C       to get high frequency parts is to subtract
c
        DO 300 J=1,N
            X(J)=X(J)-Y(J)
300     CONTINUE
c
c       remove the vertical shift
        IF(N.GT.2*NH) THEN
          XSUM = 0.0
          DO 450 J = NH2+1,N-NH2
            XSUM = XSUM + X(J)
450       CONTINUE
          XSUM = XSUM/FLOAT(N-NH)
        ENDIF
c   move the signal arround zero
        DO 500 J=1,N
500         X(J) = X(J) - XSUM
C
        RETURN
        END
c
c
        SUBROUTINE FILTWIN2(NH,H)
C
C       This is a routine to generate filter impulse response
c       function by using SYNC function whose extented version
c       is the inverse Fourier transform of BOX filter in frequency
c       domain.  The output array will be used as the weighted
c       function in converlution with original signal to produce
c       lowpassed version of the signal.
c
C       NH       number of data in Impulse function
c       H        the impulse response function array
C
c       Developed by :  Meau-Fuh Pong
c
        REAL    H(1000),AMIN1,ANG,SPAN,LOW,ASUM
        REAL    FNH,DX,FLOAT,W,PI,ACOS,SIN
        INTEGER I,NH,K
        DX=12.0
        FNH=FLOAT(NH+1)
        PI=2.*ACOS(0.0)
        W=2.*PI/FNH
        DO 10 K=1,NH
          ANG = FLOAT(K-1)*W-PI
          H(K)= SIN(ANG)/ANG
10      CONTINUE
C
        LOW=1.
        DO 20 K=1,NH
          LOW = AMIN1(LOW,H(K))
20      CONTINUE
        ASUM=0.
        DO 30 K=1,NH
          H(K) = H(K) - LOW
          ASUM = ASUM + H(K)
30      CONTINUE
C       normalize the array to make unit sum
```

```
      DO 40 K=1,NH
        H(K)= H(K)/ASUM
40    CONTINUE
C
      RETURN
      END
cC
      SUBROUTINE REGRFILT(N,DX,FIPS,WLF,X)
c     A HIGH PASS FILTER VERSION 3.01
C     This subroutine performs 2nd order regresion to extrate
c     parabolic drift of fuction due to double integration.
c     Original function will be subtrated by the fitted parabolic
c     function to get rid of the integration drift.
C
c     DEVELOPED by :  Meau-Fuh Pong
c     Date (2.0)   :  Dec. 30, 1987
c     Revise 3.0   :  Feb. 24, 1988
C
      REAL    X(5500),STEP,DIF,FLOAT,FN
      REAL    DT,DT2,SX,SX2,SX3,SX4,SY,SYX,SYX2,DELTA
      REAL    A0,A1,A2,T,FIPS,DX
      INTEGER I,J,K,N,NT
C     null operation
      WLF=WLF
      WRITE(*,5)
5     FORMAT(3X,'Performing regresion filtering...')
c
c
C    Remove integration drift by REGRESSION
c
C     DO J=1,N
C       WRITE(20,*) X(1,J)
C     ENDDO
C  Vehicle speed : inch per second
C     FIPS=SPEED*5280./3600*12.
C   Pick time history to be variable and the profile to be
c   dependent variable
c   Time between samples
      IF (FIPS.EQ.0) THEN
        FIPS = 73.33333
      ENDIF
C
      DT=DX/FIPS
      write(*,10) N,DX
10    format(1x,' Regression filter: N= ',I6,'  DX=',F8.3)
      FN=FLOAT(N)
c
c  Preparing Auto-products up to 4th power
      SX=0.
      SX2=0.
      SX3=0.
      SX4=0.
      DO 90 J=1,N
          T=FLOAT(J-1)*DT
          SX=SX+T
          SX2=SX2+T**2
          SX3=SX3+T**3
90        SX4=SX4+T**4
C Denominator :
      DELTA=FN*SX2*SX4+2*SX*SX3*SX2-SX2**3-SX**2*SX4-FN*SX3**2
```

```
        WRITE(*,95) DELTA,FIPS,DT
95      FORMAT(1X,'DELTA= ',E16.9,' SPEED=',F7.2,
     & 'inches/sec  DT=',F8.6)
C
C   Computing Cross products
c   vertical (dependent)  : profile
c   variable (horizontal) : time index
          SY=0.
          SYX=0.
          SYX2=0.
C
          DO 100 J=1,N
            T=FLOAT(J-1)*DT
            SY=SY+X(J)
            SYX=SYX+X(J)*T
100         SYX2=SYX2+X(J)*T**2
c       WRITE(*,*)' PASS 2'
C
C       The coefficients of each power
c       CONSTANT:
        A0=(SY*SX2*SX4+SX3*SX*SYX2+SYX*SX3*SX2-SX2**2*SYX2
     &     -SX*SX4*SYX-SX3**2*SY)/DELTA
C       1ST ORDER
        A1=(FN*SYX*SX4+SX*SX2*SYX2+SX2*SX3*SY-SX2**2*SYX
     &     -SX*SX4*SY-FN*SX3*SYX2)/DELTA
C       2ND ORDER
        A2=(FN*SX2*SYX2+SX*SX2*SYX+SY*SX*SX3-SY*SX2**2
     &     -SX**2*SYX2-FN*SX3*SYX)/DELTA
c       WRITE(*,*) ' PASS 3'
c       WRITE(*,103) A0,A1,A2
103     FORMAT(1X,'A0= ',E15.8,' A1= ',E15.8,' A2= ',E15.8)
        DO 120 J=1,N
          T=FLOAT(J-1)*DT
120       X(J)=X(J)-A0-A1*T-A2*T**2
C
C       DO 150 J=1,N
C         WRITE(21,*) X(J)
C       ENDDO
150     CONTINUE
C
C   remove some DC
          STEP=X(1)
          DIF =(X(N)-X(1))/FLOAT(N-1)
          DO 160 J=1,N
160         X(J)= X(J) - STEP - FLOAT(J-1) * DIF
C
        RETURN
        END
```

7. COMPUTATION OF PROFILOGRAPH ROUGHNESS INDEX

FUNCTION:	CALCULATION OF ROUGHNESS INDEX FOR A GIVEN SET OF PROFILE DATA USING CALIFORNIA OR RAINHART PROCEDURE
INPUT:	PROFILOGRAPH DATA PRODUCED BY DATA ACQUISITION PROGRAM
OUTPUT:	ROUGHNESS INDEX, IPM_{CA} OR IMP_{RH}
COMPUTER REQUIREMENTS:	IBM PC OR COMPATIBLE

```
C       This is a program to count the profile index from
c       profilogragh, road measurement device.
C       This program calls propriate subroutines to obtain
c       profile index Inches per Mile
$LARGE : PROFL,PROFC,PROFD
        REAL    PROFL(5500),PROFC(5500),PROFD(5500)
        REAL    WL,DIST,DX,DT,PGLEN,BLANK,YL,YT,DENO
        REAL    REIPM,DSIPM,FLOAT,SUM,FN,YMEAN
        INTEGER         I,J,K,L,M,N,ICL
        INTEGER*2       IFILE
        CHARACTER       FILEIN*10,FILEOUT*10,FILELST*15
        CHARACTER       NAME*6,EXT(3)*4
        CHARACTER*80    TEXT
        EXT(1)='.DAT'
C
        DX=2.0
C    FOR CALIFORNIA PROFILOGRAPH, PGLEN=25 feet, BLANK=0.2 inches
C    FOR RAINHART PROFILOGRAPH, PGLEN=12.5 feet, BLANK=0.1 inches
        PGLEN=25.
        BLANK=0.2
        YT=BLANK/2.
        YL=-YT
C
C
1       CONTINUE
6       WRITE(*,15)
        READ(*,35) FILELST
C
        OPEN(UNIT=15,FILE=FILELST,STATUS='OLD',ERR=7)
        GOTO 13
7       WRITE(*,5) FILELST
        GOTO 1
13      CONTINUE
        WRITE(*,8)
        READ(*,35) FILELST
        OPEN(UNIT=14,FILE=FILELST,STATUS='UNKNOWN')
8       FORMAT(1X,'File name for counting history : ',$)
9       FORMAT(1X,'filename for IPM listings : ',$)
        WRITE(*,9)
        READ(*,35) FILELST
        OPEN(UNIT=12,FILE=FILELST,STATUS='UNKNOWN')
        WRITE(14,70)
        WRITE(12,70)
c
10      CONTINUE
        READ(15,65,ERR=1000) NAME
        CALL FNAME(NAME,EXT(1),FILEIN)
        WRITE(*,85) FILEIN
        OPEN(UNIT=11,FILE=FILEIN,STATUS='OLD',ERR=11)
        GOTO 12
11      WRITE(*,5) FILEIN
        GOTO 10
12      WRITE(14,75) FILEIN
C
        DO 16 I=1,4
16        READ(11,80) TEXT
C
        J=1
20        CONTINUE
            READ(11,*,END=100,ERR=100) PROFL(J)
```

```
          J=J+1
          GOTO 20
100     CONTINUE
        N=J-1
        WRITE(*,95) N
        FN=FLOAT(N)
        DIST=DX*FN/12.
c
        CALL MOVAVG (N,DX,PGLEN,PROFL,PROFC)
        SUM=0.0
C       DO 150 I=,4
C150      WRITE(13,*) SUM
        DENO=0.
        DO 200 J=1,N
          PROFD(J)=PROFL(J)-PROFC(J)
C         IF(PROFD(J).GT.YT.OR.PROFD(J).LT.YL) THEN
            SUM=SUM+PROFD(J)
C           DENO=DENO+1
C         ENDIF
200     CONTINUE
        YMEAN=SUM/FN
        DO 300 J=1,N
          PROFC(J)=PROFD(J)-YMEAN
C         WRITE(13,*) PROFC(J)
300     CONTINUE
C
C       WRITE(14,155)
        CALL COUNTIPM (N,DX,BLANK,REIPM,DSIPM,PROFC)
C
        WRITE(12,55) NAME,REIPM,DSIPM
        CLOSE(11)
        GOTO 10
1000    CONTINUE
        CLOSE(12)
        CLOSE(14)
        CLOSE(15)
5       FORMAT(lx,'Expected data file: ',a10,' does not exit !!'/
     $  2x,'please check file list...')
15      FORMAT(1X,'Input filename to be processed: ',$)
25      FORMAT(I3)
35      FORMAT(A15)
45      FORMAT(2(F6.3,1X))
55      FORMAT(/1X,A6,5X,'CONTINUOUS IPM =',f6.2,5X,
     &  'DISCRETE IPM =',F6.2/)
65      FORMAT(A6)
70      FORMAT(5X,'CALIFORNIA INCHES PER MILE FROM COMPUTER RESULTS'/)
75      FORMAT(/5X,'FILE : ',A10/)
80      FORMAT(A80)
85      FORMAT(1X,'....Processing file : ',A10,'.....')
95      FORMAT(1X,'Number of points = ',I5)
105     FORMAT(A10)
115     FORMAT(1X,'Number of columns :(1/2) : ',$)
125     FORMAT(1X,'Number should be 1 or 2, Try again..')
135     format(/lx,'LEFT TRACK '/)
145     format(/lx,'RIGHT TRACK '/)
1200    CONTINUE
        STOP
        END
c
c
```

```
      SUBROUTINE MOVAVG(N,DX,PGLEN,X,Y)
C
C     This is a subrouting to perform moving average with specified
C     averaging length.  The output of this sub is the array of
c     after-smoothing.  It show the long-wave length part of the
c     original profilogram.  You may subtracted this by original
c     to get short wavelength part.
c     Developed by    Meau-Fuh Pong
c     Date            Aug. 12, 1988
C
C     N       number of samples
C     DX      sampling distamce of profilogram
C     PGLEN   length of the main struss of profilograph
C
$LARGE : X,Y
      REAL    X(5500),Y(5500),DX,PGLEN,FNAVG,FLOAT,SUM
      INTEGER I,J,K,NINT,INT,MOD,JLEFT,JRIGHT,JREM,JADD,N,NAVG,NAVG2
c
      NAVG = NINT(PGLEN*2./DX*12.)
C   make it odd number
      IF( MOD(NAVG,2).EQ.0) NAVG=NAVG+1
      NAVG2= NAVG/2
      FNAVG=FLOAT(NAVG)
C
      SUM=0.
      DO 100 K=2,NAVG2+1
100     SUM=SUM+X(K)
C
      Y(1)= ( FLOAT(NAVG2+1)*X(1) + SUM )/FNAVG
C
      DO 200 J=2,N
        JLEFT  = J-NAVG2
        IF(JLEFT.LE.1) JLEFT = 1
        JRIGHT = J+NAVG2
        IF(JRIGHT.GE.N) JRIGHT = N
        Y(J) = Y(J-1) + ( X(JRIGHT) - X(JLEFT) )/FNAVG
200   CONTINUE
      RETURN
      END
c
c
      SUBROUTINE COUNTIPM (N,DX,BLANK,FIPM,GIPM,X)
C     This subroutine is design for counting the Inches per Mile
c     Index for a provided road profilogram.  Profilogram may be
c     obtained by either California or Rainhart Profilograph.
c     The Inches per Mile index is used to judge the degree of
c     roughness/smothness of a new constructed road pavement.
c
$LARGE : X
      REAL X(5500),DIST,DX,SUM,YT,YL,DISTM,ACROUND,ROUND
      REAL ACUINCH,SCALOP,GIPM,FIPM,FLOAT,LEFT,RIGHT,TEMP
      REAL    FOUND,FOUNDR,HORDIST,LEFTP
      INTEGER I,J,N
c
      DIST=FLOAT(N)*DX/12.
C   correspondent sample size for minimum scalop width (2 feet)
      HORDIST=2./DX*12
      YT=BLANK/2.
      YL=-YT
      ACUINCH=0.0
```

```
      ACROUND=0.0
      I=2
      LEFTP=0.0
20    CONTINUE
      IF(X(I).GE.0.) THEN
C       Find a positive slope cross upper blanking line
c        using linear interpolation computation.
21      CONTINUE
        IF (X(I).GT.YT.AND.X(I-1).LE.YT) THEN
          LEFT=FLOAT(I-1)+(YT-X(I-1))/(X(I)-X(I-1))
          IF(LEFT.LE.LEFTP) GOTO 27
          LEFTP=LEFT
c         Locate next negative cross upper blanking line
22        CONTINUE
          IF (X(I-1).GE.YT.AND.X(I).LT.YT) THEN
            RIGHT=FLOAT(I-1)+(YT-X(I-1))/(X(I)-X(I-1))
C
24          CALL UPPER(LEFT,RIGHT,BLANK,HORDIST,SCALOP,ROUND,X)
            IF(SCALOP.GE.0.01) THEN
              FOUND=LEFT*DX/12.
              FOUNDR=RIGHT*DX/12.
              WRITE(14,55) FOUND,FOUNDR,SCALOP,ROUND
              ACUINCH=ACUINCH+SCALOP
              ACROUND=ACROUND+ROUND
            ENDIF
          ELSE
            I=I+1
            IF (I.GT.N) THEN
              RIGHT=FLOAT(N)
              GOTO 24
            ENDIF
            GOTO 22
          ENDIF
        ENDIF
C
      ELSEIF(X(I).LT.0.) THEN
C       Find a negative slope cross lower blanking line
23      CONTINUE
        IF (X(I).LT.YL.AND.X(I-1).GE.YL) THEN
          LEFT=FLOAT(I-1)+(YL-X(I-1))/(X(I)-X(I-1))
          IF(LEFT.LE.LEFTP) GOTO 27
          LEFTP=LEFT
c         Locate next positive cross lower blanking line
25        CONTINUE
          IF (X(I).GT.YL.AND.X(I-1).LE.YL) THEN
            RIGHT=FLOAT(I-1)+(YL-X(I-1))/(X(I)-X(I-1))
C
26          CALL LOWER(LEFT,RIGHT,BLANK,HORDIST,SCALOP,ROUND,X)
            IF(SCALOP.GE.0.01) THEN
              FOUND=LEFT*DX/12.
              FOUNDR=RIGHT*DX/12.
              WRITE(14,56) FOUND,FOUNDR,SCALOP,ROUND
              ACUINCH=ACUINCH+SCALOP
              ACROUND=ACROUND+ROUND
            ENDIF
          ELSE
            I=I+1
            IF (I.GT.N) THEN
              RIGHT=FLOAT(N)
              GOTO 26
```

```
              ENDIF
              GOTO  25
            ENDIF
          ENDIF
        ENDIF
27      CONTINUE
        I=I+1
        IF (I.LT.N) GOTO 20
C
30      CONTINUE
        DISTM=DIST/5280.
        FIPM=ACUINCH/DISTM
        GIPM=ACROUND/DISTM
        WRITE(14,65) ACUINCH,ACROUND
        WRITE(14,75) DIST,DISTM,GIPM,FIPM
55      FORMAT(5X,f6.0,' to',f6.0,' found + ',f6.4,
     $  ' Rounded to ',f6.2)
56      FORMAT(5X,f6.0,' to ',f6.0,' found - ',f6.4,
     $  ' Rounded to ',f6.2)
65      FORMAT(/5X,'Accumulated continuous Index :',2x,f6.3//
     $  5X,'Accumulated roundoff Index :',2x,f6.3//)
75      FORMAT(5x,'Overall distance = ',f6.1,' feet or ',f6.3,
     $  ' miles'//5x,'Therefore, continuous Inches per Mile = ',f6.3/
     $  5X,'And Discrete Inches per Mile = ',f6.3// )
        RETURN
        END
C
        SUBROUTINE UPPER(LEFT,RIGHT,BLANK,HORDIST,SCALOP,ROUND,X)
c       This sub-subroutine is to judge the found scalop is wide
c       enough to be counted as roughness contribution.
c       The lease longitudinal requireement is 20 feet.
$LARGE : X
        REAL    X(5500),SCALOP,TOPSCALOP,ABS
        REAL    LEFT,RIGHT,HORDIST,AMAX1,FLOAT
        REAL    ROUND,LEVEL,BLANK,BLANK2,BLANK4
        INTEGER I,J,L,M,N,NINT,INT
C
        ROUND=0.0
        SCALOP=0.0
        IF ( (RIGHT-LEFT).LT.HORDIST) GOTO 30
        BLANK2=BLANK/2.
        BLANK4=BLANK2/2.
        TOPSCALOP=BLANK2
        L=INT(LEFT)
        M=NINT(RIGHT)
C    Find top level of scalop
        DO 10 I=L,M
10        TOPSCALOP=AMAX1(TOPSCALOP,X(I))
c    Taking away of the blanking band 0.1 inch
        SCALOP=TOPSCALOP-BLANK2
C
C  To round-off the scalop into descrete levels in the increment of 0.05
        ROUND=FLOAT(NINT(SCALOP/BLANK4))/(BLANK*100.)
30      CONTINUE
        RETURN
        END
C
      SUBROUTINE LOWER(LEFT,RIGHT,BLANK,HORDIST,SCALOP,ROUND,X)
c       This sub-subroutine is to judge the found scalop is wide
c       enough to be counted as roughness contribution.
```

```
c       The lease longitudinal requireement is 20 feet.
$LARGE : X
        REAL    X(5500),LOWSCALOP,SCALOP,ABS,FLOAT
        REAL    LEFT,RIGHT,HORDIST,AMIN1
        REAL    ROUND,LEVEL,BLANK,BLANK2,BLANK4
        INTEGER M,N,I,L,NINT,INT
C
        ROUND=0.0
        SCALOP=0.0
        IF ((RIGHT-LEFT).LT.HORDIST) GOTO 30
        BLANK2=BLANK/2.
        BLANK4=BLANK2/2.
        LOWSCALOP=-BLANK2
        L=INT(LEFT)
        M=NINT(RIGHT)
        DO 10 I=L,M
10      LOWSCALOP=AMIN1(LOWSCALOP,X(I))
        SCALOP=ABS(LOWSCALOP)-BLANK2
C
C  To round-off the scalop into descrete levels in the increment of 0.05
        ROUND=FLOAT(NINT(SCALOP/BLANK4))/(BLANK*100.)
30      CONTINUE
        RETURN
        END
c
        SUBROUTINE      FNAME(FSTRING,GSTRING,FILEIN)
C       This subroutine  constructs the file name for main
c       program in an assigned name-pattern and sequential way.
C       INTEGER*2       IFILE,JFILE,KFILE
        CHARACTER*6     FSTRING
        CHARACTER*4     GSTRING
        CHARACTER*10    FILEIN
C       CHARACTER*1     CFILE(2)
C       FSTRING='FORD'
C       GSTRING='.BIN'
C         JFILE=MOD(IFILE,10)
C         KFILE=(IFILE-JFILE)/10
C         CFILE(1)=CHAR(KFILE+48)
C         CFILE(2)=CHAR(JFILE+48)
C       IF(CFILE(1).EQ.'0') THEN
C         FILEIN=FSTRING//CFILE(2)//GSTRING
C       ELSE
C         FILEIN=FSTRING//CFILE(1)//CFILE(2)//GSTRING
C       ENDIF
          FILEIN=FSTRING//GSTRING
        RETURN
        END
```

8. COMPUTATION OF PSD FUNCTION

FUNCTION:	CALCULATION OF POWER SPECTRAL DISTRIBUTION FUNCTION FOR A GIVEN SET OF ROAD PROFILE DATA
INPUT:	ROAD PROFILE DATA IN FILE FILE.LST
OUTPUT:	POWER SPECTRAL DENSITY IN FILE FILE.PSD
COMPUTER REQUIREMENTS:	VAX 780 OR HIGHER

```
C
C     Program for calculating the PSD function for given profile data.
C
C       This program requires that the names of data files to be
C         processed be listed in file [FILE.LST].
C
C       The PSD output is assigned the same name as the profile data
C         file but with an extention [.PSD].
C
      DIMENSION DAT(5001),DATA(5001),R(501),PSD(501),F(501)
      CHARACTER*15 FILEIN,FILEOUT
C
      B=1.0/6.0
      OPEN(UNIT=8,FILE='FILE.LST',STATUS='OLD')
20    READ(8,25,ERR=90)FILEIN
      OPEN(UNIT=9,FILE=FILEIN,STATUS='OLD')
      WRITE(6,35) FILEIN
      I=1
45    IF (FILEIN(I:I).EQ.'.') GO TO 55
      I=I+1
      GO TO 45
55    FILEOUT=FILEIN(1:I-1)//'.PSD'
      OPEN(UNIT=10,FILE=FILEOUT,STATUS='NEW')
25    FORMAT(A15)
35    FORMAT(1X,'Processing file ',A10,'....')
C
      I=1
110   READ(9,*,ERR=10) DATA(I)
      I=I+1
      GO TO 110
10    CONTINUE
      CLOSE(9)
C
      M=I-1
      IMAX=JINT(FLOAT(M)/1000.)*100
      DO 40 J=1,IMAX+1
      SR=0.
      DO 100 I=1,M-J+1
100   SR=SR+DATA(I)*DATA(I+J-1)
40    R(J)=SR/FLOAT(M-J+1)
      SPSD=0.
      DO 60 I=2,IMAX
60    SPSD=SPSD+R(I)
      PSD(1)=2.*B*(R(1)+2.*SPSD+R(IMAX+1))
      F(1)=1E-3
      DO 30 K=2,IMAX+1
      SPSD=0.
      DO 50 J=2,IMAX
50    SPSD=SPSD+R(J)*COS(3.14159*FLOAT(K-1)/FLOAT(IMAX)*FLOAT(J-1))
      PSD(K)=2.*B*(R(1)+2.*SPSD+(-1.0)**(K-1)*R(IMAX+1))
30    F(K)=.5*FLOAT(K-1)/FLOAT(IMAX)/B
```

```
C
C     Compute smoothed values of PSD.
      X=PSD(1)
      PSD(1)=.5*(X+PSD(2))
      DO 70 I=2,IMAX
      SUM=X+2.*PSD(I)+PSD(I+1)
      X=PSD(I)
70    PSD(I)=.25*SUM
      PSD(IMAX+1)=.5*(X+PSD(IMAX+1))
C
      DO 80 I=1,IMAX+1
      F(I)=ALOG10(F(I))
      PSD(I)=20.*ALOG10(ABS(PSD(I))+1E-6)
80    WRITE(10,*) F(I),PSD(I)
      CLOSE(10)

      GO TO 20
90    CLOSE(8)
      STOP
      END
```

9. GENERATION OF ROAD PROFILE -- DIRECT PROCEDURE

FUNCTION:	GENERATION OF A SEQUENCE OF ROAD PROFILE DATA WITH A DESIRED PSD FUNCTION
INPUT:	PSD FUNCTION DATA FILE
OUTPUT:	ROAD PROFILE DATA FILE
COMPUTER REQUIREMENTS:	VAX 780 OR HIGHER

```
C
C     Program for generating a profile with desired PSD function.
C
      DIMENSION DIST(5001),PRO(5001),F(501),PSD(501),PHI(501)
      CHARACTER*15 FILEIN,FILEOUT
C
      WRITE(6,35)
      READ(5,55)FILEIN
      OPEN(UNIT=7,FILE=FILEIN,STATUS='OLD')
      DO 5 I=1,3
5     READ(7,*) AF(I),APSD(I)
      DO 8 I=1,5
      F(I)=AF(1)+FLOAT(I)*(AF(2)-AF(1))/5.0
      F(I)=10.0**F(I)
      PSD(I)=APSD(1)+FLOAT(I)*(APSD(2)-APSD(1))/5.0
8     PSD(I)=10.0**(PSD(I)/20.0)
      DO 15 I=1,5
      F(5+I)=AF(2)+FLOAT(I)*(AF(3)-AF(2))/5.0
      F(5+I)=10.0**F(5+I)
      PSD(5+I)=APSD(2)+FLOAT(I)*(APSD(3)-APSD(2))/5.0
15    PSD(5+I)=10.0**(PSD(5+I)/20.0)
      I=11
10    READ(7,*,ERR=20) F(I),PSD(I)
      F(I)=10.0**F(I)
      PSD(I)=10.0**(PSD(I)/20.0)
      I=I+1
      GO TO 10
20    CLOSE(7)
      B=1.0/6.0
      IMAX=I-1
      WRITE(6,45)
      READ(5,55)FILEOUT
C
      OPEN(UNIT=8,FILE=FILEOUT,STATUS='NEW')
C
      L=999999999
      DO 25 I=1,IMAX
25    PHI(I)=RAN(L)
      DO 30 J=1,10*IMAX
      PRO(J)=0.
      DO 40 I=1,IMAX
40    PRO(J)=PRO(J)+SQRT(2.0*ABS(PSD(I))/FLOAT(IMAX))*SIN(2.*3.14159
     1*(F(I)*B*FLOAT(J)+PHI(I)))
      DIST(J)=B*FLOAT(J)
30    WRITE(8,*) PRO(J)
      CLOSE(8)
C
35    FORMAT(1X,'Enter name of PSD data file:')
45    FORMAT(1X,'Give a name for profile data output:')
55    FORMAT(A15)
      STOP
      END
```

10. GENERATION OF ROAD PROFILE--ITERATIVE PROCEDURE

FUNCTION:	GENERATION OF A SEQUENCE OF ROAD PROFILE DATA WITH A DESIRED PSD FUNCTION
INPUT:	DESIRED PSD FUNCTION AND INITIAL VALUES OF MODEL PARAMETERS, EQUATION (7)
OUTPUT:	ROAD PROFILE DATA FILE
COMPUTER REQUIREMENTS:	VAX 780 OR HIGHER

```
C     PROGRAM TO GENERATE ROAD PROFILE WITH DESIRED
C     POWER  SPECTRAL DENSITY
      external f
      dimension wi(3), c(24), w(3,9),a(4,4),wk(3)
      common j. zheta(500).alpha1,alpha2.beta
     1        v, sigma1, sigma2, a0, a1, a2, b0. b2. b4
      open(unit=10.file='profile.dat',status='new')
      write(6,12)
12    format(1x.'input the value of alpha1')
      read(6,*)alpha1
      write(6.14)
14    format(1X,'input vehicle velocity)
      read(6.*) v
      alpha2=0.2
      beta=2.0
      sigma1=2.55e-4
      sigma2=4.5e-3
      a1=alpha1*v
      a2=2.0*(alpha2**2-beta**2)*(v**2)
      a0=sqrt((alpha2**2+beta**2)*(v**2)+
     1          4.0*(alpha2*beta*(v**2))**2)
      b4=(sigma1*alpha1+sigma2*alpha2)*v
      b2=(2.0*sigma1*alpha1*(alpha2**2-beta**2)
     2    +sigma2*alpha2*(alpha1**2+alpha2**2
     3    +beta**2))*v**3/b4
      b0=sqrt((sigma1*alpha1*(alpha2**2+beta**2)**2
     4          +sigma2*alpha2*(alpha2*(alpha2**2+beta**2)
     5          *alpha1**2))*v**5/b4)
      n=3
      nw=3
      tol=0.00001
      pi=acos(-1.00)
      do 10 l=1.24
10    c(l)=0.0
      ind=1
      t=0.0
      tfinal=1.0
      do 20 i=1, 500
      j=i  -
      call dverk(n,f,t,wi,tfinal.tol,ind,c,nw,w.ier)
      tfinal=tfinal+1.0
20    continue
      close(unit=10)
      stop
      end
      subroutine f(n,t,wi,widot)
      dimension widot(3).wi(4)
      common j, zheta(500), alpha1, alpha2, beta, v,
     1        v, sigma1, sigma2, a0, a1, a2, b0, b2, b4
      wdot(1)=w(2) + d1*zheta(i)
      wdot(2)=w(3) + d2*zheta(i)
      wdot(3)=-a0*a1*w(1)-(a0+a1*a3)*w(2)
     1         -(a1+a3)*w(3) + d3*zheta(i)
      end
```

```
C      A gaussian white noise generating program for EE560 HW #5
C      by calling IMSL routine GGNSM with provided variance.
c      Prepared by          Meau-Fuh Fong
c      Date                 Oct. 28, 1987
C
       REAL     R(501,1),WKVEC,SIGMA(1)
       INTEGER NR,K,I,J,IR,IER
       REAL*8    DSEED(6)
       NR=501
       K=1
       IR=501
       DSEED(1)=6781919.D0
       DSEED(2)=3468920.D0
       DSEED(3)=5647996.D0
       DSEED(4)=2314561.D0
       DSEED(5)=1989027.D0
       DSEED(6)=7329755.D0
       DO 100 I=1,6
         IF(I.LE.5) THEN
         SIGMA(1)=1.
         CALL GGNSM(DSEED(I),NR,K,SIGMA(1),IR,R,WKVEC,IER)
         IF(IER.NE.0) PRINT *,'IER= ',IER,'I= ',I
         OPEN (UNIT=11,FILE='WNOISE.DAT',STATUS='NEW')
         DO 14 J=1, NR
         WRITE (11,*) J,R(J,1)
14       CONTINUE
         CLOSE(11)
         ELSE
         SIGMA(1)=.25
         CALL GGNSM(DSEED(I),NR,K,SIGMA(1),IR,R,WKVEC,IER)
         IF(IER.NE.0) PRINT *,'IER= ',IER,'I= ',I
         OPEN (UNIT=11,FILE='VNOISE.DAT',STATUS='NEW')
         DO 13 J=1, NR
         WRITE (11,*) J, R(J,1)
13       CONTINUE
         CLOSE(11)
         ENDIF
100    CONTINUE
       STOP
       END
```

11. SIMULATION OF CALIFORNIA PROFILOGRAPH

FUNCTION:	CALCULATION OF PROFILE MEASURED BY THE CALIFORNIA-TYPE PROFILOGRAPH WITH 2, 4, 6, 8, 10, OR 12 SUPPORTING WHEELS. MEASURING WHEEL TIRE WEAR AND ECCENTRICITY CAN BE INCORPORATED.
INPUT:	PROFILE DATA FILE, NUMBER OF SUPPORTING WHEELS ON EACH SIDE, LENGTH OF MAIN TRUSS, SPACING BETWEEN SUPPORTING WHEELS
OUTPUT:	SEQUENCE OF PROFILE DATA MEASURED BY THE PROFILOGRAPH
COMPUTER REQUIREMENTS:	VAX 780 OR HIGHER

```
C
C THE PROGRAM IS TO CALCULATE THE RESPONSE OF THE CALIFORNIA PROFILOGRAPH
C OF 2, 4, 6, 8, 10, 12 WHEELS.
C -----------------------------------------------------------------------
C
        REAL RDELTA(100),LDELTA(100),D(3000),Y(3000)
        INTEGER I,J,K,L,M,N
        CHARACTER FOUT*16,FILST*16
C
1       TYPE *,' INPUT THE FILENAME TO STORE THE OUTPUT DATA:'
        READ (*,2)FOUT
2       FORMAT(A16)
        OPEN (UNIT=8, FILE=FOUT, STATUS='NEW')
C
        TYPE *
9       TYPE *,' INPUT THE TOTAL NUMBERS OF R.H.S WHEELS:'
        READ (*,10)KR
10      FORMAT(I4)
C
        TYPE *
        TYPE *,' INPUT THE TOTAL NUMBERS OF L.H.S WHEELS:'
        READ (*,20)IL
20      FORMAT(I4)
        KK=(KR/2)
        II=(IL/2)
        CN1=(KR/2.)-KK
        CN2=(IL/2.)-II
        IF(CN1.NE.0.0.OR.CN2.NE.0.0) THEN
         PRINT *,' INPUT THE EVEN NUMBERS OF WHEELS ONLY !!'
         GO TO 9
        ENDIF
C
C       INITIALIZATION OF CALIFORNIA PROFILOGRAPH
c        SAMPLING DISTANCE DX =6.0 in(0.5 ft).
        DX=0.5
        TYPE *
        TYPE *,' INPUT THE LENGTH OF MAIN TRUSS L (FT):'
        READ(*,30)XL
        TYPE *
        PRINT *,' INPUT THE DISTANCE BETWEEN TWO WHEELS X1(FT) AT R.H.S'
         READ(*,30)X1
30      FORMAT(F6.2)
        PRINT *
        PRINT *,' INPUT THE DISTANCE BETWEEN TWO WHEELS X2(FT) AT L.H.S'
        READ (*,30)X2
```

```
C   CALCULATING THE WHEEL DISTANCE BETWEEN EACH WHEEL AND THE CENTER WHEEL
        IF(KK.EQ.0)GO TO 110
        RDELTA(1)=XL/2.0-((KK-1)*X1/2.)
         PRINT *
         PRINT *
        TYPE *,' RDELTA(1)=',RDELTA(1)
        DO 100 I=2,KK
          RDELTA(I)=RDELTA(1)+(I-1)*X1
        TYPE *,' RDELTA(',I,')=',RDELTA(I)
100     CONTINUE
110     IF (II.EQ.0) GO TO 210
         LDELTA(1)=XL/2.0-((II-1)*X2/2.)
         PRINT *
        TYPE *,' LDELTA(1)=',LDELTA(1)
        DO 200 J=2,II
          LDELTA(J)=LDELTA(1)+(J-1)*X2
        TYPE *,' LDELTA(',J,')=',LDELTA(J)
200     CONTINUE
210     TYPE *
C  INPUT THE DATA FILE FOR 0.1 MILES PROFILE
        TYPE *,' INPUT THE FILELIST TO BE PROCESSED:'
        READ(*,222)FILST
222     FORMAT(A16)
        OPEN(UNIT=11,FILE=FILST,STATUS='OLD')
C  THE STATNDARD CIRCUMFERENCE OF THE MEASURED WHEEL = 5 FT.
        PI=3.14159
        RSTD=5.0*12.0/(2.*PI)
        TYPE *,' INPUT THE WEAR QTY. OF RADIUS OF MEASURED WHEEL(in.):'
        READ *,DR
        RW=RSTD-DR
        MP=NINT((528.*RW/RSTD)/0.5+1.)
C
C INPUT THE ECCENTRICITY OF THE MEASURED WHEEL EC(in.)
        TYPE *
        TYPE *,' INPUT THE ECCENTRICITY OF THE MEASURE WHEEL (in.):'
        READ *,EC
        DO 300 L=1,MP
C  Y(L) : PROFILE DATA
         READ(11,*)Y(L)
300      CONTINUE
         CLOSE(11)
         X=200.0
         DO 400 N=1,MP
          S1=0.0
          S2=0.0
          SUM1=0.0
          SUM2=0.0
          IF(KK.EQ.0) GO TO 120
```

```
          DO 500 I=1,KK
            PX1=X+RDELTA(I)
            PX2=X-RDELTA(I)
          IF(PX2.LT.0.0) PX2=0.0
            MX=NINT(PX1/DX)+1
            NX=NINT(PX2/DX)+1
           S1=S1+Y(MX)+Y(NX)
500       CONTINUE
           SUM1=S1/(KK*2.)
120       IF(II.EQ.0)GO TO 220
           DO 600 J=1,II
             PY1=X+LDELTA(J)
             PY2=X-LDELTA(J)
            IF(PY2.LT.0.0) PY2=0.0
             MY=NINT(PY1/DX)+1
             NY=NINT(PY2/DX)+1
            S2=S2+Y(MY)+Y(NY)
600        CONTINUE
           SUM2=S2/(II*2.)
            THETA=(X*12.0)/RW
            D(N)=Y(N)+EC*(1-COS(THETA))-(SUM1+SUM2)/2.0
            GO TO 330
220         THETA=(X*12.0)/RW
            D(N)=Y(N)+EC*(1-COS(THETA))-(SUM1+SUM2)
330          WRITE(8,77)D(N)
77          FORMAT(F15.7)
           X=X+DX
400        CONTINUE
C
           TYPE *,' DO YOU WANT TO TRY AGAIN ?(YES=1)'
            READ(*,499)LL
499         FORMAT(I6)
            IF(LL.EQ.1) GO TO 1
           STOP
           END
```

12. SIMULATION OF RAINHART PROFILOGRAPH

FUNCTION:	CALCULATION OF PROFILE MEASURED BY THE RAINHART-TYPE PROFILOGRAPH WITH 2, 4, 6, 8, OR 12 SUPPORTING WHEELS
INPUT:	PROFILE DATA FILE, NUMBER OF SUPPORTING WHEELS, LENGTH OF MAIN TRUSS, SPACING BETWEEN SUPPORTING WHEELS
OUTPUT:	SEQUENCE OF PROFILE DATA MEASURED BY THE PROFILOGRAPH
COMPUTER REQUIREMENT:	VAX 780

```
C
C THE PROGRAM IS TO CALCULATE THE RESPONSE OF THE RAINHART PROFILOGRAPH
C OF 2, 4, 6, 8, 10, 12 WHEELS.
C ---------------------------------------------------------------------
C
      REAL DELTA(100),D(3000),Y(3000)
      INTEGER I,J,K,L,M,N
      CHARACTER FOUT*16,FILST*16
C
1     TYPE *,' INPUT THE FILENAME TO STORE THE OUTPUT DATA:'
      READ (*,2)FOUT
2     FORMAT(A16)
      OPEN (UNIT=8, FILE=FOUT, STATUS='NEW')
C
9     TYPE *,' INPUT THE TOTAL NUMBERS OF WHEELS:'
      READ (*,10)KR
10    FORMAT(I4)
C
      KK=(KR/2)
      CN1=(KR/2.)-KK
      IF(CN1.NE.0.0) THEN
       PRINT *,' INPUT THE EVEN NUMBERS OF WHEELS ONLY !!'
       GO TO 9
      ENDIF
C
C     INITIALIZATION OF CALIFORNIA PROFILOGRAPH
      TYPE *
      TYPE *,' INPUT THE LENGTH OF MAIN TRUSS L (FT):'
      READ(*,30)XL
      PRINT *,' INPUT THE DISTANCE BETWEEN TWO WHEELS X1(FT)'
       READ(*,30)X1
30    FORMAT(F6.2)
       DELTA(1)=XL/2.0-((KK-1)*X1/2.)
       PRINT *
      TYPE *,' DELTA(1)=',DELTA(1)
      DO 100 I=2,KK
        DELTA(I)=DELTA(1)+(I-1)*X1
      TYPE *,' DELTA(',I,')=',DELTA(I)
100   CONTINUE
       TYPE *
C  INPUT THE DATA FILE FOR 0.1 MILES PROFILE
      TYPE *,' INPUT THE FILE TO BE PROCESSED'
      READ(*,222)FILST
222   FORMAT(A16)
      TYPE *
      OPEN(UNIT=11,FILE=FILST,STATUS='OLD')
      DO 300 L=1,1057
C  Y(L) : PROFILE DATA
       READ(11,*)Y(L)
300    CONTINUE
       CLOSE(11)
```

```
         X=200.0
         DO 400 N=1,1057
          S1=0.0
          SUM1=0.0
          DO 500 I=1,KK
            PX1=X+DELTA(I)
            PX2=X-DELTA(I)
          IF(PX2.LT.0.0) PX2=0.0
            MX=NINT(PX1/0.5)+1
            NX=NINT(PX2/0.5)+1
           S1=S1+Y(MX)+Y(NX)
500       CONTINUE
           SUM1=S1/(KK*2.)
            D(N)=Y(N)-SUM1
            WRITE(8,77)D(N)
77          FORMAT(F15.7)
           X=X+0.5
400        CONTINUE
C
           TYPE *,' DO YOU WANT TO TRY AGAIN ?(YES=1)'
            READ(*,499)LL
499         FORMAT(I6)
            IF(LL.EQ.1) GO TO 1
           STOP
           END
```

13. FREQUENCY RESPONSE OF CALIFORNIA PROFILOGRAPH

FUNCTION:	CALCULATION OF MAGNITUDE OF FREQUENCY RESPONSE TRANSFER FUNCTION FOR A CALIFORNIA-TYPE PROFILOGRAPH. THE RANGE OF WAVELENGTHS SET IN THE PROGRAM IS 0 TO 37.5 FT WITH 0.25-FT INTERVALS
INPUT:	NUMBER OF SUPPORTING WHEELS, LENGTH OF MAIN TRUSS, SPACING BETWEEN SUPPORTING WHEELS
OUTPUT:	MAGNITUDE OF FREQUENCY RESPONSE TRANSFER FUNCTION
COMPUTER REQUIREMENTS:	IBM PC

```
10 '***********************************************************************
20 ' A program for calculating the [G(jw)] of California Profilographs.  *
30 ' **********************************************************************
40 CLEAR:CLS
50 '
60 DIM RDELTA(100),LDELTA(100)
70 OPEN"cal.dat" FOR OUTPUT AS #1
80 LOCATE 5,10:INPUT" Input the total no. of wheels at the R.H.S:";K%
90 LOCATE 8,10:INPUT" Input the total no. of wheels at the L.H.S:";I%
100 CN1=(K%/2)-INT(K%/2):CN2=(I%/2)-INT(I%/2)
110 IF CN1<>0 OR CN2<>0 THEN PRINT" input the even no. of wheels only !!":CLS:GO
TO 80
120 LOCATE 10,10: INPUT" Input the length of main truss L";L
130 LOCATE 15,10 : INPUT" Input the distance between two wheels L1 at R.H.S";L1
140 LOCATE 18,10 : INPUT" Input the distance between two wheels L2 at L.H.S";L2
150 ' calculating the summation of Cosine terms
160 N%=K%/2:M%=I%/2
170 RDELTA(1)=L/2-((N%-1)*L1/2)
180 LDELTA(1)=L/2-((M%-1)*L2/2)
190 IF RDELTA(1)>=0! AND LDELTA(1) >=0! THEN GOTO 230
200 PRINT" Waring!! The distance of delta(1) is too small"
210 'PRINT" Readjust the length of main truss L of the wheel distance L1"
220 'GOTO 120
230 '
240 FOR I=2 TO N%
250 RDELTA(I)= RDELTA(1)+(I-1)*L1
260 NEXT I
270 FOR I=2 TO M%
280 LDELTA(I)= LDELTA(1)+(I-1)*L2
290 NEXT I
300 FOR M=1 TO N%
310 PRINT "RDELTA(";M;")=";RDELTA(M)
320 NEXT M
330 FOR J=1 TO M%
340 PRINT "LDELTA(";J;")=";LDELTA(J)
350 NEXT J
360 LAMDA =.05
370 S1=0 : S2=0 : PI=3.14159
380 FOR I=1 TO N%
390 S1=S1+COS(2!*PI*RDELTA(I)/LAMDA)
400 NEXT I
410 SUM1=S1/(2*N%)
420 FOR I=1 TO M%
430 S2=S2+COS(2!*PI*LDELTA(I)/LAMDA)
440 NEXT I
450 SUM2=S2/(2*M%)
460 ' Calculating the [G(jw)]
470 G=1!-SUM1-SUM2
480 WRITE #1,LAMDA,G
490 LAMDA=LAMDA+.25
500 IF LAMDA < 37.5 THEN GOTO 370
510 END
```

14. FREQUENCY RESPONSE OF RAINHART PROFILOGRAPH

FUNCTION:	CALCULATION OF MAGNITUDE OF FREQUENCY RESPONSE TRANSFER FUNCTION FOR A RAINHART-TYPE PROFILOGRAPH. THE RANGE OF WAVELENGTHS SET IN THE PROGRAM IS FROM 0 TO 35 FT WITH 0.25-FT INTERVALS
INPUT:	NUMBER OF SUPPORTING WHEELS, LENGTH OF MAIN TRUSS, SPACING BETWEEN SUPPORTING WHEELS
OUTPUT:	MAGNITUDE OF FREQUENCY RESPONSE TRANSFER FUNCTION
COMPUTER REQUIREMENTS:	IBM PC

```
10 '*********************************************************************
20 ' A program for calculating the [G(jw)] of Rainhart Profilographs.  *
30 ' *******************************************************************
40 CLEAR:CLS
50 '
60 DIM DELTA(200)
70 OPEN"rainhart.dat" FOR OUTPUT AS #1
80 LOCATE 5,10:INPUT" Input the total no. of wheels:";K%
90 CN=(K%/2)-INT(K%/2)
100 IF CN <>0 THEN PRINT" input the even no. of wheels only !!":CLS:GOTO 80
110 LOCATE 10,10: INPUT" Input the length of main truss L";L
120 LOCATE 15,10 : INPUT" Input the distance between two wheels L1";L1
130 ' calculating the summation of Cosine terms
140 N%=K%/2
150 DELTA(1)=L/2-((N%-1)*L1/2)
160 IF DELTA(1)>= L1 THEN GOTO 200
170 PRINT" Waring!! The distance of delta(1) is too small"
180 'PRINT" Readjust the length of main truss L of the wheel distance L1"
190 'GOTO 120
200 '
210 FOR I=2 TO N%
220 DELTA(I)= DELTA(1)+(I-1)*L1
230 NEXT I
240 FOR M=1 TO N%
250 PRINT DELTA(M)
260 NEXT M
270 LAMDA =.05
280 S=0 : PI=3.14159
290 FOR I=1 TO N%
300 S=S+COS(2!*PI*DELTA(I)/LAMDA)
310 NEXT I
320 SUM=S/N%
330 ' Calculating the [G(jw)]
340 G=1!-SUM
350 WRITE #1,LAMDA,G
360 LAMDA=LAMDA+.25
370 IF LAMDA < 35! THEN GOTO 280
380 END
```

APPENDIX B: ASTM STANDARD E1274-88

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ASTM Designation: E0000-00

Standard Test Method for
MEASURING PAVEMENT ROUGHNESS USING A PROFILOGRAPH[1]

1. Scope

1.1 This test method covers the measurement of pavement roughness using an articulated multi-wheeled profilograph at least 23 ft (7 m) long (see Fig.1).

1.2 This test method utilizes a surface record made by moving the profilograph longitudinally over the pavement at less than 3 mi/hr (5 km/hr). The record is analyzed to determine rate of roughness and to identify bumps that are excessively high.

1.3 The values stated in inch-pound units are to be regarded as the standard. The values in parentheses are SI units and are not exact equivalents; therefore, each system must be used independently of the other, without combining values in any way.

1.4 *This standard may involve hazardous materials, operations and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.* A precautionary statement is contained in Section 6.

2. Referenced Document

2.1 Drawings of California Profilograph.[2]

3. Terminology (see Fig.2)

3.1 *Blanking band*- A band of uniform height with its longitudinal center positioned optimally between the highs and lows of the surface record depicting at least 100 ft(30 m) of pavement.

3.2 *Scallops*- Excursions of the surface record above and below the blanking band.

3.3 *Roughness*- Height of each continuous scallop rounded to nearest 0.05 in. (1 mm), except those less than 0.03 in. (0.8 mm) vertically and 2 ft (0.6 m) longitudinally.

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[1] This test method is under the jurisdiction of ASTM Committee E-17 on Traveled Surface Characteristics and is the direct responsibility of Subcommittee E17.32 on Measurement and Control of Roughness in Construction and Rehabilitation.

[2] Adjunct available from ASTM, 1916 Race St., Philadelphia, PA 19103.

3.4 *Rate of roughness-* The sum of the roughness divided by the longitudinal distance between the farthest points of the beginning and ending scallops or absence thereof to nearest 0.1 in/mi (1 mm/km).

3.5 *Cutoff height-* Maximum permissible distance of a high on the surface record from a chord representing 25 ft (7.5 m) on the longitudinal scale. The chord may represent less than 25 ft (7.5 m) if it is from the lows on each side of the high.

4. Significance and Use

4.1 This test method provides a means of measuring the roughness of new or rehabilitated pavement. Results probably will differ between profilographs designed differently; therefore, reliance on profilographs of a particular manufacture must be understood.

4.2 When this standard is referenced, the referencing person or authority must stipulate:

4.2.1 Height of blanking band to nearest 0.05 in. (1 mm), e.g. 0.1 or 0.2 in.

4.2.2 Cutoff height to nearest 0.05 in. (1 mm), e.g. 0.3 in.

4.2.3 Profilograph with or without uniformly spaced reference platform wheels.

4.2.4 Optimum length of each segment for which rate of roughness is calculated.

5. Apparatus

5.1 *Profilograph*:

5.1.1 *With uniformly spaced wheels-* The reference platform is comprised of dollies articulated by rigid members or trusses such that all wheels are supporting the profilograph. There must be at least twelve reference platform wheels, and the axes of these wheels must be uniformly spaced throughout the effective length of the profilograph.[3] This length must be at least 23 ft (7 m) long. At least a 6 in. (150 mm) diameter surface sensing wheel and recorder are located at the center of the reference platform. If the recorder is graphic, its scales shall be 1:1 vertically and 1:300 longitudinally (1 in. = 25 ft). If the recorder is digital (optional analog display must have same scales as graphic recorder), it must sample 5 times per longitudinal inch and record the relative height of the surface to at least the nearest 0.01 in. (0.25 mm).

5.1.2 *Without uniformly spaced wheels-* The same as with (above) except the axes of the reference platform wheels are not uniformly spaced but are at least 1 ft (0.3 m) apart so no two wheels cross the same bump at the same time. The recorder can be located elsewhere, but surface sensing must occur at the center of the reference platform. A common apparatus without uniformly spaced wheels is the California

---

[3] Hankins, Kenneth D., "Construction Control Profilograph Principles," *Research Report 49-1*, Texas Highway Department, June 1967.

Profilograph (see Referenced Document 2.1).

5.1.3 There are differences in frequency responses between profilographs with uniformly spaced wheels and profilographs without uniformly spaced wheels (see Fig.3).

5.2 *Blanking band template* (optional)- Approximately 2 in. (50 mm) wide clear plastic strip at least 4 in. (100 mm) long. 21.12 in. length is common. The center of the template is marked with an opaque strip the width of the stipulated blanking band throughout its length and with lines every 0.1 in. (2 mm) above and below the blanking band.

5.3 *Excessive height template* (optional)- Clear plastic piece marked with a 1.00 ± 0.02 in. (25.0 ± 0.5 mm) line that is the stipulated cutoff height distance from a straight edge on the template. Two small holes may be drilled to fix the ends of the line.

6. Hazards

6.1 Since profilographs in the testing mode are moved no faster than 3 mi/hr (5 km/hr), they should not be operated near traffic without proper traffic control devices and procedures such that the safety of testing personnel and the public is assured.

7. Sampling

7.1 Profilograph recordings shall be taken 3.5 ± 0.5 ft (1.0 ± 0.2 m) from and parallel to both edges of the pavement and to both sides of each planned longitudinal joint or in each planned wheel path.

7.2 Exemptions to these sampling requirements (e.g. 25 ft from each bridge) must be stipulated.

8. Standardization

8.1 *Height recording*:

8.1.1 Alternately push 0.5 in. (10 mm) and 1.5 in. (60 mm) platforms with wedge ramps under the surface sensing wheel. The record must indicate the actual height of each platform within ± 0.02 in. (0.5 mm).

8.1.2 Standardization of the height recording shall be verified once before any week of use, whenever the profilograph is re-assembled and whenever there is evidence of possible inaccuracy.

8.2 *Distance recording*:

8.2.1 Mark a distance of 100.00 ft (30.00 m) on reasonably even pavement. Move the profilograph forward until a particular point is at the first mark and cause the recorder to mark the event on the record. Resume until the point is at the second mark and cause the recorder to mark this event, too. The record must indicate 100 ± 1 ft (30.0 ± 0.3 m) between the two events (4.00 ± 0.04 in. on graphic record).

8.2.2 Standardization of the distance recording shall be verified once before any month of use and whenever there is evidence of possible inaccuracy.

9. Procedure

9.1 Clear the intended profilograph path of all loose material and foreign objects.

9.2 If possible, move the profilograph about 30 ft (10 m) forward to the starting point. Once there, initialize the recorder and make beginning notations.

9.3 Move the profilograph forward no faster than 3 mi/hr (5 km/hr), steering it to stay within that prescribed sampling path. Pertinent observation about surveyed location or unusual conditions may be made on the record only as they occur. Observe the recorder for any unusual operation.

9.4 Upon completion of a sampling path, make ending notations and review the recording for reasonableness. Repeat the procedure for successive sampling paths.

10. Calculations

NOTE 1- Calculations can be done physically with the blanking band and excessive height templates or electronically with routines in a computer.

10.1 Apply the blanking band to successive sections of the surface record. Determine roughness from each scallop. Add all roughness for each stipulated segment. From the surface record determine the longitudinal distance between the farthest points of the beginning and ending scallops or absence thereof. Divide the result of the addition by the corresponding longitudinal distance to calculate the rate of roughness for that segment of that path.

10.2 Apply the excessive height chord to the top of each wave on the surface record. Identify all bumps that are excessively high by their locations.

11. Precision and Bias

11.1 The precision and bias of the procedure and calculations in Test Method E0000 for measuring pavement roughness are being determined.

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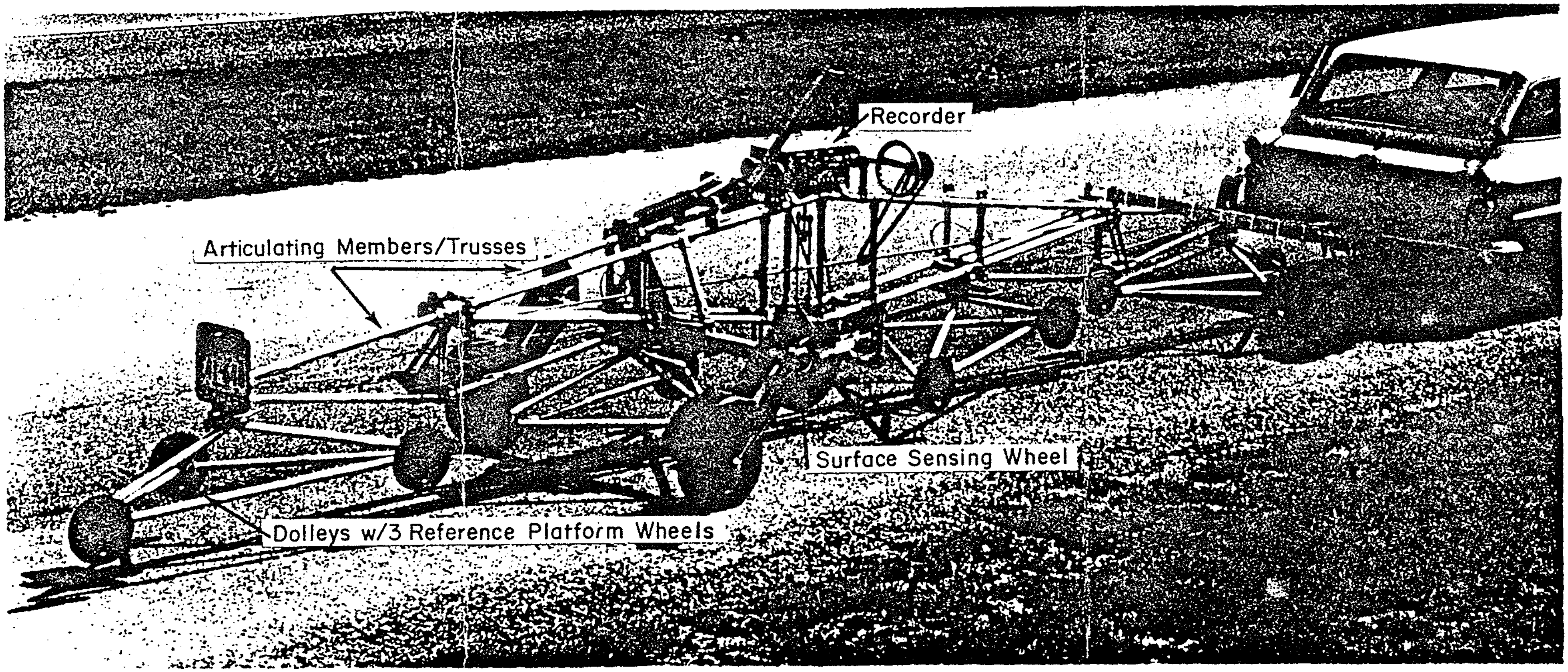

FIG. 1 Profilograph

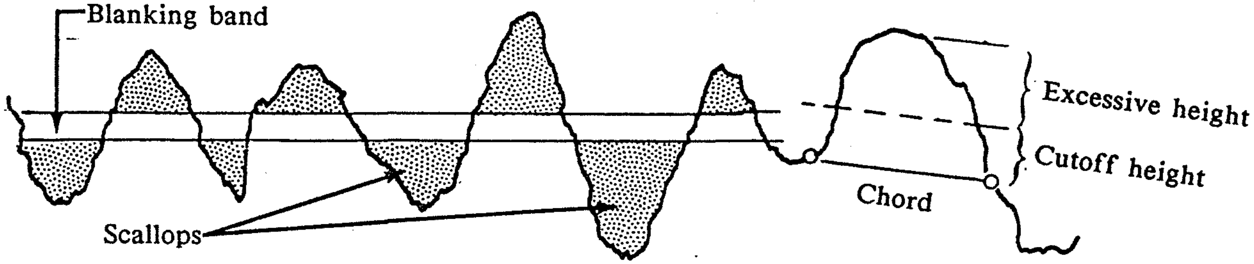

FIG. 2 Surface Record

NOTE 2: Fig. 2 is graphic for visual reading. It can be digital for computer input.

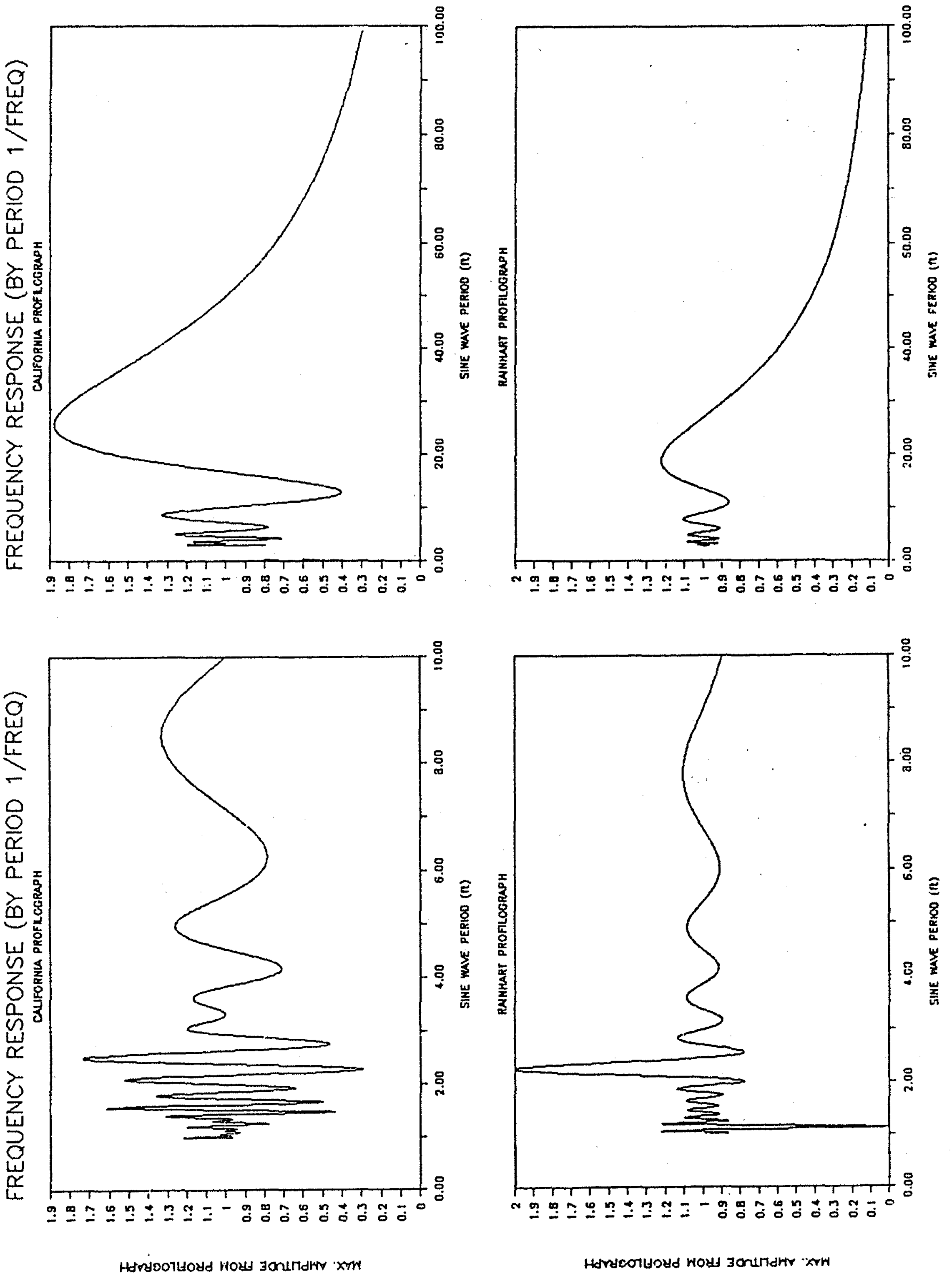

Figure 3[4]

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[4] Walker, Roger S., and H.-T. Lin, The University of Texas at Arlington, Research Project 8-10-87-569, "Correlation of California and Rainhart Profilographs with PSI," conducted for Texas State Department of Highways and Public Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

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