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ANALYSIS OF CHARACTERISTIC ROUGHNESS PATTERNS IN PAVEMENTS AND THE RELATIONSHIP BETWEEN ROUGHNESS AND PAVEMENT DISTRESS

by

Hugh J. Williamson
W. Ronald Hudson

Research Report 156-3

Surface Dynamics Road Profilometer Applications
Research Project 3-8-71-156

conducted for

The Texas Highway Department

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

February 1974

PREFACE

This is the third report presenting results from Research Project 1-8-71-156, "Surface Dynamics Road Profilometer Applications," which was initiated to carry out the implementation and operation of the Surface Dynamics Road Profilometer (SDP) in field and research applications.

Although operations efforts will continue to be made to improve measurement accuracy and efficiency, the SDP is now an effective measurement system, as is evidenced by the numerous successful research results obtained in the last few years, such as the empirical development of a model to predict human panel serviceability ratings of roads from roughness amplitudes computed from SDP measurements.

The purpose of this report is to present results from pilot studies done with the purpose of analyzing certain pavement distress problems with the aid of the SDP.

The authors appreciate the many helpful suggestions made by the Texas Highway Department representative James L. Brown. The engineering consultations and SDP measurements by Mr. H. H. Dalrymple and Mr. Noel Wolf and the programming support by Mr. Jack O'Quin are also greatly appreciated.

Hugh J. Williamson
W. Ronald Hudson

LIST OF REPORTS

Report No. 156-1, " Correlation Study of the Mays Road Meter with the Surface Dynamics Profilometer," by Roger S. Walker and W. Ronald Hudson, discusses a study of the correlation between measurements made with the Mays Road Meter and the Surface Dynamics Profilometer and, based on this study, provides a set of calibration, operation, and control procedures for operation of the Mays Road Meter using serviceability index values from the profilometer as a measurement standard.

Report No. 156-2, "The Use of Spectral Estimates for Pavement Characterization," by Roger S. Walker and W. Ronald Hudson, discusses the general uses of road profile spectral estimates for pavement characterization. A model for predicting serviceability index based on road profile amplitude estimates is also described.

Report No. 156-3, "Analysis of Characteristic Roughness Patterns in Pavements and the Relationship Between Roughness and Pavement Distress," by Hugh J. Williamson and W. Ronald Hudson, discusses the characterization and comparison of the roughness on pavements of differing types and ages. The application of digital filtering is treated, and pilot-study results are presented.

ABSTRACT

A pilot study of certain pavement distress problems is discussed in this report. Road roughness measurements made with the Surface Dynamics Road Profilometer (SDP) and pavement condition survey data have been analyzed by statistical methods to demonstrate approaches to these problems, and, within the scope of a pilot study, to obtain results.

The particular problems addressed are

(1) comparisons of characteristic roughness types (as to wavelength, transverse vs. longitudinal effects, etc.) in pavements of different types and ages and

(2) investigation of relationships among various roughness and distress types.

KEY WORDS: Surface Dynamics Road Profilometer, roughness, distress, digital filtering.

SUMMARY

A pilot study of certain pavement distress problems is discussed in this report. Road roughness measurements made with the Surface Dynamics Road Profilometer (SDP) and pavement condition survey data have been analyzed by statistical methods to demonstrate approaches to these problems and, within the scope of the pilot study, to obtain results. The particular problems addressed are

(1) Comparisons of the types of roughness in different types of pavements. Samples of new versus old (scheduled for maintenance) flexible pavements and new surface-treated versus new hot-mix asphalt-concrete pavements are compared. In broad terms, the following observations were made.

For new versus deteriorated pavements.

(a) The old pavements have greater roughness amplitudes (more severe roughness) than the new pavements. The difference in the severity is greater for isolated extreme roughness than for measures of overall roughness.

(b) The sample of old pavements has more road-section to road-section diversity than the sample of new pavements has. Both samples are more diverse with respect to isolated extreme roughness than with respect to overall roughness.

(c) For short wavelengths (0-1 feet) the amplitudes of the vertical motion of one wheel relative to the other (i.e., the vehicle roll) is greater than the roughness amplitudes for longitudinal waves in either wheelpath. The opposite is true for longer waves.

For surface-treated (ST) versus hot-mix aspahlt-concrete (HMAC) roads

(a) As expected, the less expensive ST roads have more severe roughness and are more diverse than the HMAC roads. Each sample is more diverse with respect to isolated extreme roughness than with respect to overall roughness.

(b) The differences between the HMAC and ST roads are most pronounced for roughness with wavelengths less than nine feet. As the wavelength increased beyond nine feet, the two samples become increasingly similar.

(c) The transverse waves have greater amplitudes than the longitudinal waves for short wavelengths, but the reverse is true for long wavelengths.

(2) Prediction of other distress measures (areas of cracking, cracking plus patching, rutting, and total distress) from roughness measures. The point here is that the roughness measures, which are obtainable from road profiles measured by the SDP, are much less time-comsuming than condition surveys done visually. Thus, it is of interest to know whether it is feasible to predict the other distress measures with sufficient accuracy from the roughness measures.

The results indicated that a high percentage, from 72 to 91 percent, of the road-to-road variation in the other types of distress can be explained in terms of roughness. Thus, it has been shown that there is a close relationship between the progression of roughness and the progression of other types of distress. The possibilities of using roughness measurements as a supplement to or even possibly in place of visual condition surveys in future distress-to-performance studies appears very promising.

To obtain reliable, widely applicable predicting equations, further analysis with a larger pavement sample would be required. The sample used in this study contained 20 road sections, all of which were scheduled for maintenance.

In connection with the pilot study for predicting distress in terms of roughness measures, numerous relationships are discussed. The following observations, which apply to either the area of cracking and patching or the total area of distress, are among the most meaningful.

(a) For the 0 to 1-foot-long waves, the measures of isolated extreme roughness are better predictors (of distress) than are measures of overall roughness.

(b) Except for the overall roughness measures for 0 to 1-foot-long waves, all roughness measures in the range from 0 to 81 feet are related to distress to a statistically significant (i.e., measureable) extent. Measures of overall and extreme effects in both the longitudinal and transverse dimensions are included.

(c) The 81 to 180-foot-long longitudinal waves are much less clearly related to distress than the shorter waves.

(d) The 81 to 180-foot-long waves in the artificial profile computed by taking the vertical surface position in one wheelpath relative to that in the other wheelpath are related to distress. As discussed above, waves in this artificaial profile cause vehicle roll; thus, they are related to road-user comfort.

IMPLEMENTATION STATEMENT

The objective of this report is to present findings obtained in a pilot study done under Project 156. The study involves two phases:

(1) the comparison of roads of different types and different ages and

(2) analysis of relationships among roughness measured by the Surface Dynanamics Profilometer and various distress types.

Methods of analysis are demonstrated, and, within the scope of a pilot study, results are presented.

The motivation for researching these areas and the applicable results of the study are summarized below.

COMPARISON OF ROADS OF DIFFERENT TYPES AND AGES

The basic objective of this type of study is to gain insights about construction and maintenance practices so that (1) those practices can be applied in a more efficient way and (2) improvements can be formulated.

A full-scale follow-up to this pilot study, for example, might involve an investigation of the <u>progression</u> of roughness in different types of pavements. The ability to anticipate the type of deterioration which a given pavement was likely to undergo during the near future (say two years) would be an invaluable aid in determining whether maintenance was needed and, if so, what kind.

The following steps, which would be necessary for conducting such a full-scale study, have been carried out in the investigation reported herein:

(1) development of mathematical tools for analyzing road profile data. The digital filtering and statistical methods demonstrated in this report can be used to describe the condition of a road surface on the basis of (a) the lengths of the roughness waves, (b) the overall or average roughness of a section, (c) the presence of a few severe bumps, etc.,

(2) verification that it is possible to obtain a meaningful description of a road's quality by using these methods. The numerous physically realistic results presented in the report provide this verification. It is shown, for example, that it is possible to differentiate

between surface-treated and hot-mix asphalt-concrete roads on the basis of the severity of 0 to 1-foot-long waves. This is important because these short waves have very small amplitudes, and one might doubt whether they could be measured with sufficient accuracy.

ANALYSIS OF RELATIONSHIPS AMONG ROUGHNESS AND OTHER TYPES OF DISTRESS

Visual condition surveys to obtain areas of various kinds of cracking, patching, etc. are very time-consuming and expensive. Descriptive measures of road roughness using the methods discussed above, however, can be obtained relatively quickly. Thus, it is of interest to know whether the roughness measures contain a significant portion of the information which would be obtained from a visual survey. In particular, it is of interest to know whether the other types of distress can be <u>predicted</u> from the roughness for a given road section.

This type of investigation is important because of the numerous research and operational requirements for pavement condition evaluation, e.g., for prescribing maintenance.

In the pilot study, an investigation of the feasibility of predicting other distress measures was carried out. It was shown that a high percentage of the road-to-road variation in the areas of cracking, cracking plus patching, rutting, and total distress could be explained (i.e., predicted) in terms of roughness. The percentages are over 72 percent in all cases, and it is pointed out that inclusion of other variables, such as the pavement age, would probably improve the predictive accuracy.

Thus, a full-scale study to investigate the use of road profile measurements in place of visual condition surveys for some purposes appears to be fully justified.

In summary, the findings of this report include

(1) demonstration of analysis tools necessary to solve problems relating to pavement performance in two important areas,

(2) verification of the feasibility of full-scale studies in these areas, and

(3) within the scope of a pilot study, presentation of quantitative results.

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CHAPTER 1. INTRODUCTION

The objective of the pilot study reported here is to demonstrate several types of comparisons and analyses of pavement distress.

Chapter 2 includes a discussion of comparisons between two different populations of pavements on the basis of the various classes of roughness. Such analysis is of interest for various purposes, including determing what kinds of roughness are predominant in one type of pavement compared to another. Comparisons can be made between pavements of two different types: e.g., hot-mix asphalt-concrete pavements and surface-treated pavements; pavements of a given type with two base courses and pavements of the same type with more than two courses; asphalt pavements in cut areas versus other asphalt pavement; pavements immediately before and immediately after a given type of maintenance; and new and deteriorated pavements of a given type (to determine patterns of roughness development with age). Thus, much useful information would be gained about relative effectiveness of various construction and maintenance practices; the insights would, hopefully, contribute toward improvement of those practices. For the purpose of these comparisons, a decomposition of the roughness in a road can be made on the basis of wavelength, longitudinal versus transverse effects, and overall versus isolated extreme roughness in a section.

In Chapter 3 an investigation of various relationships among roughness and other types of distress is presented. Distress condition surveys to measure areas of various kinds of cracking, rutting, patching, etc., are very time-consuming. Since roughness measures via road profile data obtained from the General Motors Surface Dynamics Profilometer are, comparatively, very quickly obtained, and since roughness and other types of distress all tend to increase with time (the exception that maintenance alters this trend is discussed briefly), the feasibility of predicting other distress measures from roughness measures is investigated, and further study is shown to be justified. In addition to the feasibility of prediction, various interesting relationships among the roughness and other distress measures are explored in Chapter 3.

The conclusions are presented in Chapter 4.

The measuring system used to determine a road profile, which is simply the road surface elevation versus distance along the road, is discussed in Appendix 1 of this report and in Refs 1 and 2. Correlations among measures of roughness of different types are presented in Appendix 2. Plots which illustrate road profile analysis methods (digital filtering) used in this report are presented in Appendix 3.

CHAPTER 2. PAIRWISE COMPARISONS OF POPULATIONS OF PAVEMENTS

We turn to the comparison of two classes, or populations, of pavements. Although analyses are carried out for new versus deteriorated and for new hot-mix asphalt-concrete versus new surface-treated roads, the methods are clearly applicable for comparison of any two indentifiable classes of roads, as discussed in Chapter 1.

COMPARISON OF THE ROUGHNESS COMPONENTS OF NEW AND DETERIORATED PAVEMENTS

We first compare the roughness components of a random sample of new pavements (less than a year old)[1] and a sample of deteriorated pavements scheduled for maintenance at the time of the data collection.

The sample of new pavements includes one section selected[2] from each of a set of 21 projects investigated in Ref 5, which is a study of new flexible roads in Texas. The projects included in this study are described in Table 2.1.

The deteriorated pavements are those included in Ref 6, excluding sections which had maintenance after the condition study but before the profilometer runs were made and those for which SI values were not obtainable. The deteriorated pavements are summarized in Table 2.2.

The old pavements are all in counties near Austin, Texas. The new pavements cover more counties and are somewhat more geographically diverse. Additionally, a higher percentage of old pavements are state or federal highways. These differences in the sample are undesirable, but it is felt that the data are very adequate for the purposes of a pilot study.

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[1] All projects were rebuilt or reconstructed except one of the HMAC projects, which was overlaid (Job 32).

[2] Since only one section from each project was included, it was easily possible to choose sections with SI replication variation of ±.1 or less, and a second random selection was thereby necessitated for only five of 21 projects, i.e., in less than one fourth of the cases.

TABLE 2.1. SAMPLE OF NEW PAVEMENTS

Job Number	Highway Number	County	Pavement Type	SI*
2	RM 1623	Gillespie	ST	3.1
3	US 87	Mason	ST	3.7
4	RM 2147	Burnett	ST	4.1
5	RM 2147	Burnett	ST	2.8
6	US 80	Hayes and Caldwell	ST	3.5
7	FM 3159	Comal	ST	3.7
8	RM 3160	Kendall	ST	3.4
9	FM 473	Kendall	ST	3.8
10	FM 480	Kerr	ST	2.7
11	FM 3176	Medina and Frio	ST	3.7
12	RM 1604	Bexar	ST	3.8
22	SH 6	Grimes	HMAC	4.0
24	SH 71	Fayette	HMAC	4.1
26	IH 10	Guadalupe, Caldwell, and Gonzales	HMAC	4.1
27	SH 80	Guadalupe	HMAC	3.6
28	SH 123	Guadalupe	HMAC	3.7
29	SH 16	Bexar	HMAC	3.6
31	IH 35	Frio	HMAC	4.5
32	IH 35	Bexar	HMAC	3.5
33	IH 35	Atascosa	HMAC	4.4
34	US 181	Wilson	HMAC	3.8

*These are the SI values for the actual profilometer runs used. They are not project averages or averages of replications for the sections chosen within the projects.

TABLE 2.2. SAMPLE OF DETERIORATED PAVEMENTS

Section Number	Highway Number	County	SI
P-1	SH 71	Bastrop	3.4
P-2	L 360	Travis	2.2
P-3	Pleasant Valley Road	Travis	2.0
1	FM 621	Hayes	2.6
2	FM 621	Hayes	2.3
3	SH 80	Caldwell	4.1
5	SH 71	Bastrop	3.0
7	SH 71	Bastrop	3.4
8	SH 71	Bastrop	2.4
9	SH 71	Bastrop	3.3
10	SH 71	Bastrop	3.4
15	US 87	Mason	2.8
16	US 87	Mason	3.8
17	US 87	Mason	3.2
18	US 87	Mason	3.3
19	US 290	Gillespie	2.9
20	US 290	Gillespie	2.9
21	US 290	Gillespie	3.9
22	US 290	Gillespie	3.7
23	US 290	Gillespie	3.9

Digital filtering[1] was used to obtain measures of the various classes of roughness of the road sections studied.

While a background in the mathematics of digital filtering is not required for an understanding of the analyses of road properties presented in this report, it is felt that the following brief description of the objectives of using filtering will be helpful.

The output computed by filtering is a derived road profile which contains the components of the roughness from the original profile which are isolated by the filter (e.g., the roughness with wavelengths from three to nine feet). The filtering concept is illustrated in Appendix 3 by presenting a few exemplary plots of filtered profiles and of the measured profile from which they were computed. Numerous plots of filtered and unfiltered road profiles are also presented in the discussion of projects, including bridges and the approaching pavement, in Ref 3. The local roughness measures, the r.m.s. amplitudes[2] centered at each of a discrete set of points spaced by two inches longitudinally throughout the section, are computed. Thus, the 50th percentile amplitude (the amplitude greater than or equal to exactly 50 percent of the local amplitudes) is an overall roughness measure, while the 95th percentile amplitude, for example, is a measure of the extreme roughness within the section. The 50th, 75th, 90th, 95th, and 99th percentile amplitudes are used in this study.

Since the profile runs were not consistently made in either the inside or outside lane for the old pavements, no special importance can be associated with the right versus left roughness measures; hence, corresponding values were averaged to obtain a single set of longitudinal roughness measures.

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[1] Successive differences between the outputs of sixth-order low-pass filters specified by the tangent form of the squared-magnitude function were used as bandpass filtered outputs. Phase shifts were eliminated by filtering forward and then filtering the output backwards (Refs 6 and 7).

[2] The r.m.s. amplitudes are taken over one cycle of the longest wave in the passband under consideration. Thus, for the 3 to 9-foot-long band, each r.m.s. calculation involves the data in a 9-foot interval along the road.

Measures of transverse roughness were obtained by first taking the pointwise difference between the left and right wheelpath elevations and then processing the resulting "profile" the same as the right or left.

While statistical t and F-tests are the customary vehicles for making basic comparisons between populations, the plots of mean amplitudes with plus or minus one standard deviation[1] (of the mean) confidence bars versus percentile level presented in Figs 2.1 through 2.12 reveal at a glance several interesting relationships.[2] Regarding the comparisons between the old and new pavements, we note the following.

(1) The older pavements have larger roughness amplitudes, and, except for the 81 to 180-foot roughness, the separation is greater at the high percentile points than at the 50th percentile points.

(2) The confidence bars indicate that the sample of old pavements is more diverse than the sample new of new pavements, and both samples are more diverse at the high percentile points.[3]

(3) The transverse amplitudes are larger than the longitudinal amplitudes at short wavelengths, but smaller at long wavelengths.[4]

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[1] The standard deviation is a measure of the diversity of a sample. Defined as the mean of expected value of $(X - u)^2$, where X is the variable in question and u is the mean of X itself, the standard deviation increases as the diversity of the values of X increase.

[2] The inspection of the plots to see if the confidence limits are disjoint can be thought of as performing (nontraditional) hypothesis tests for equality of population means.

[3] Part of the larger diversity of the high percentile points is due to the larger sampling error typically incurred in estimating any quantity which is strongly influenced by a small subset of the sample. Although the considerable predictive value, discussed later in this report, of the high percentile points indicates that the sampling error cannot be extreme, a further study of sampling errors in the various roughness measures would be helpful.

[4] This result was expected. At short wavelengths, the transverse amplitude is analogous to the standard deviation of the difference between two uncorrelated random variables (the right and left profile elevations with long wavelengths removed by filtering), while the right or left longitudinal amplitudes are analogous to the standard deviation of one or the other of the random variables. The standard deviation of the difference is, of course, larger. At long wavelengths, the situation is reversed, since the right and left elevations are positively correlated.

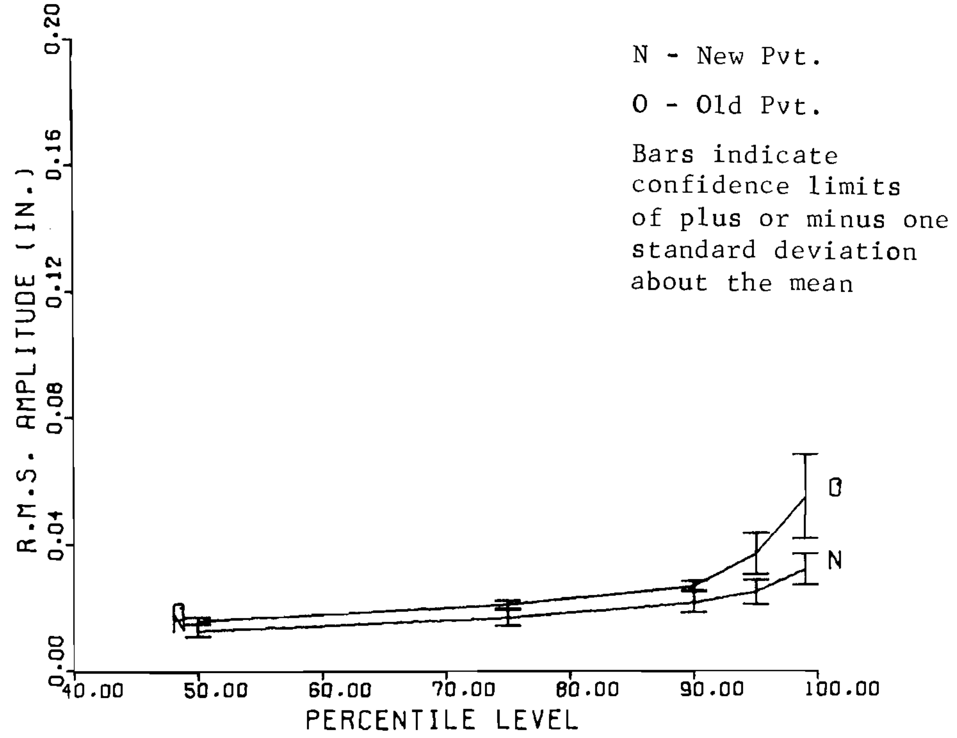

Fig. 2.1. R.m.s. amplitude versus percentile level longitudinal roughness - passband = 0 to 1 foot.

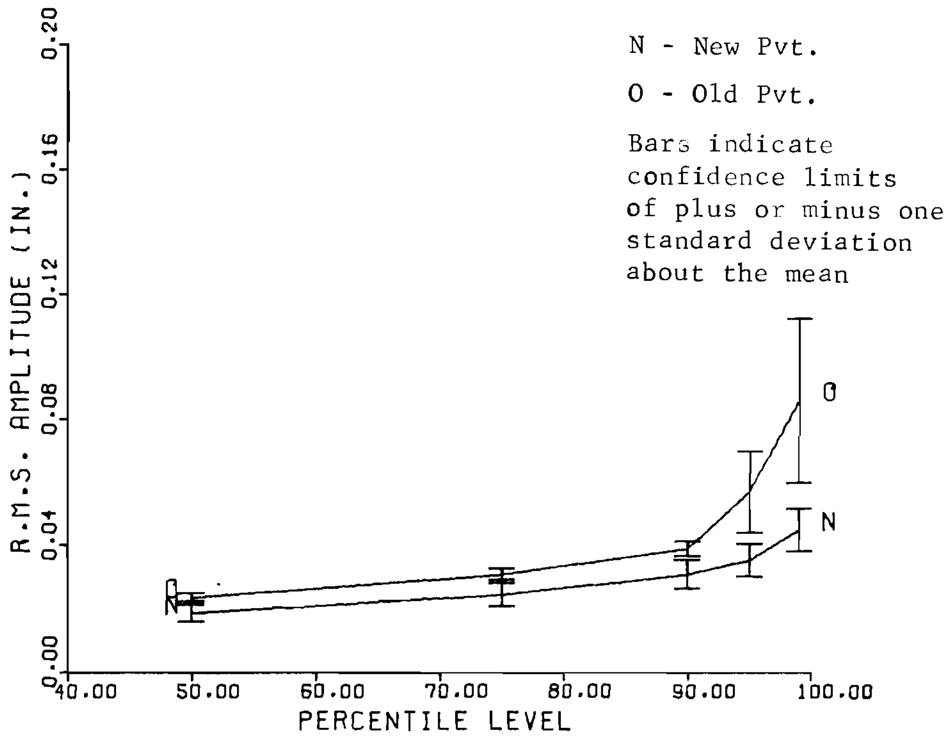

Fig 2.2. R.m.s. amplitude versus percentile level transverse roughness - passband = 0 to 1 foot.

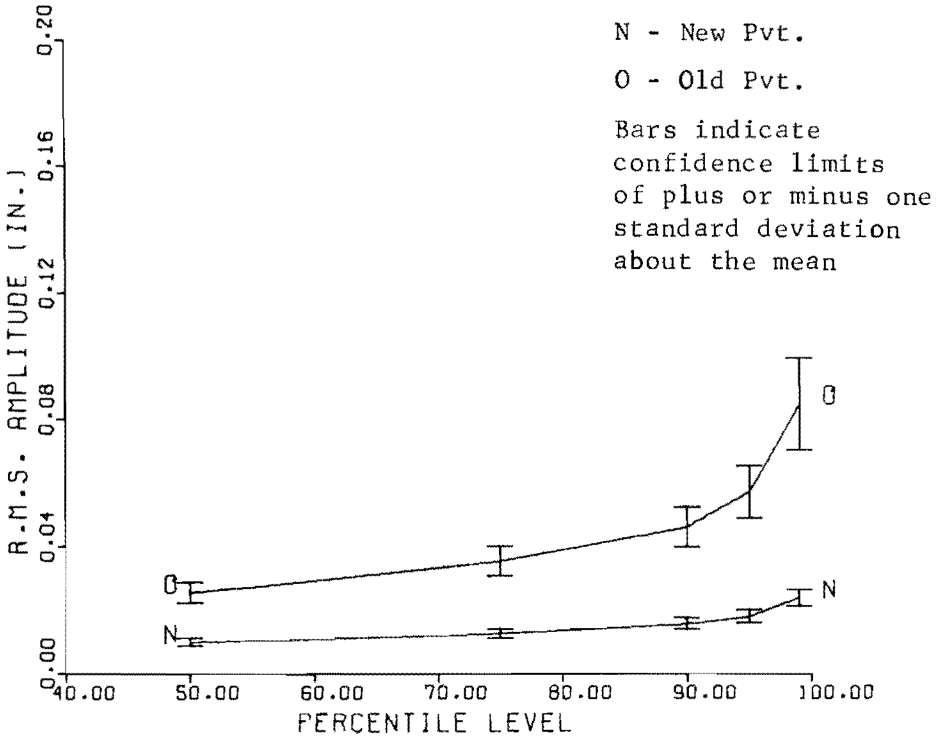

Fig 2.3. R.m.s. amplitude versus percentile level longitudinal roughness - passband = 1 to 3 feet.

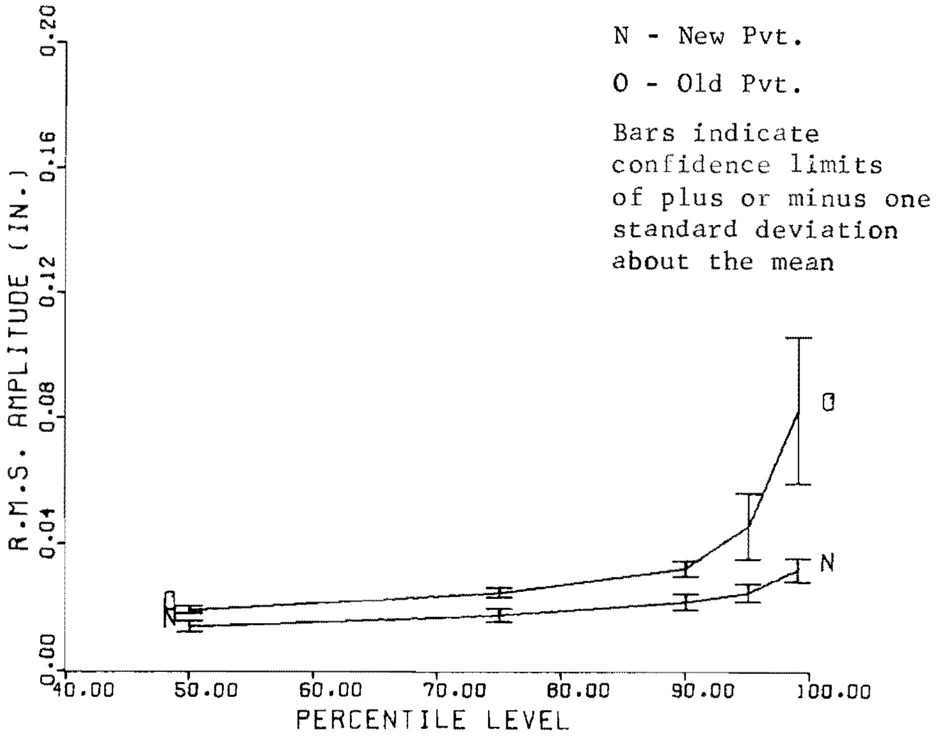

Fig. 2.4. R.m.s. amplitude versus percentile level transverse roughess - passband = 1 to 3 feet.

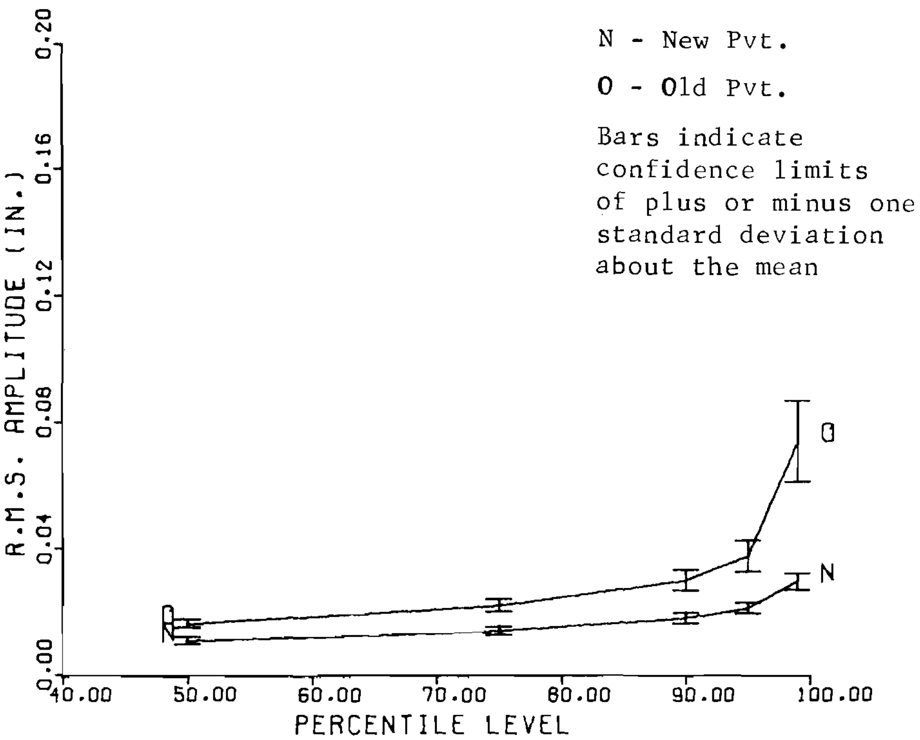

Fig. 2.5. R.m.s. amplitude versus percentile level longitudinal roughness - passband = 3 to 9 feet.

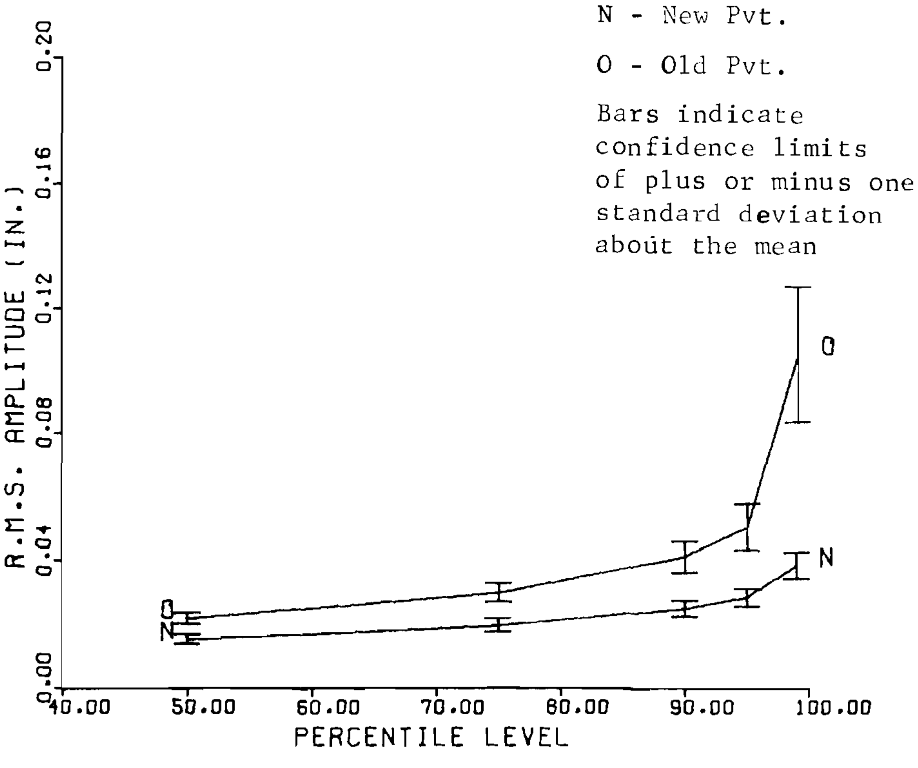

Fig. 2.6. R.m.s. amplitude versus percentile level transverse roughness - passband = 3 to 9 feet.

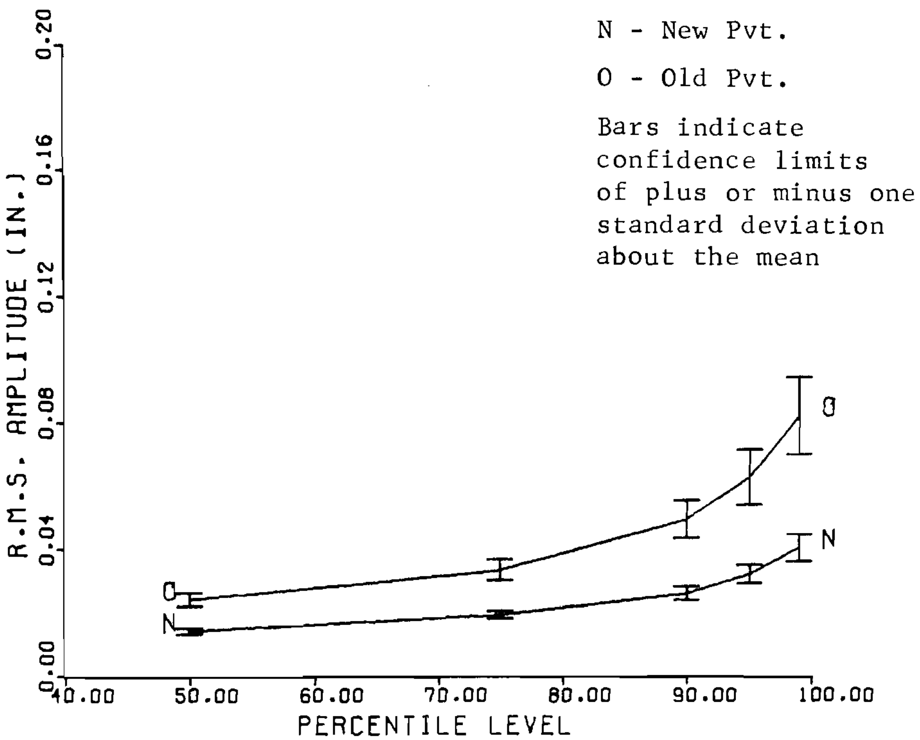

Fig. 2.7. R.m.s. amplitude versus percentile level longitudinal roughness - passband = 9 to 27 feet.

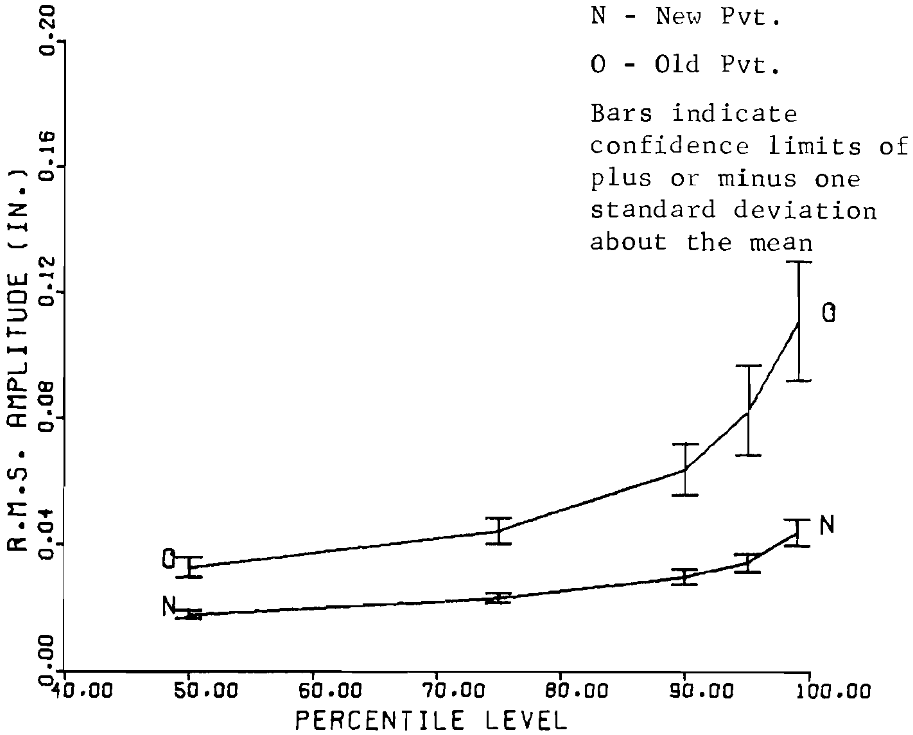

Fig 2.8. R.m.s. amplitude versus percentile level transverse roughness - passband = 9 to 27 feet.

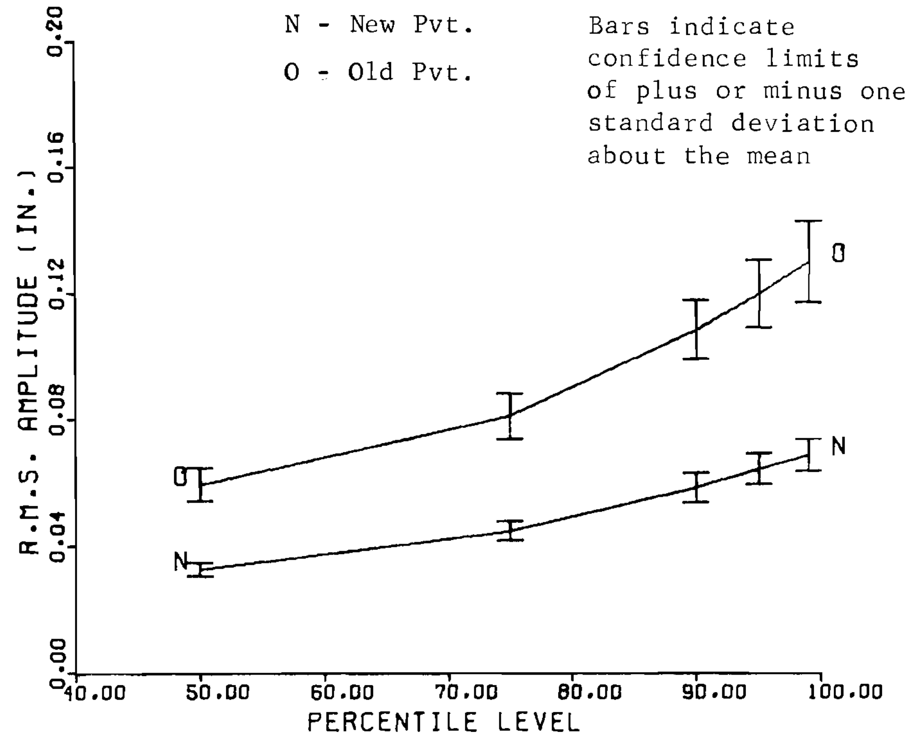

Fig 2.9. R.m.s. amplitude versus percentile level longitudinal roughness - passband = 27 to 81 feet.

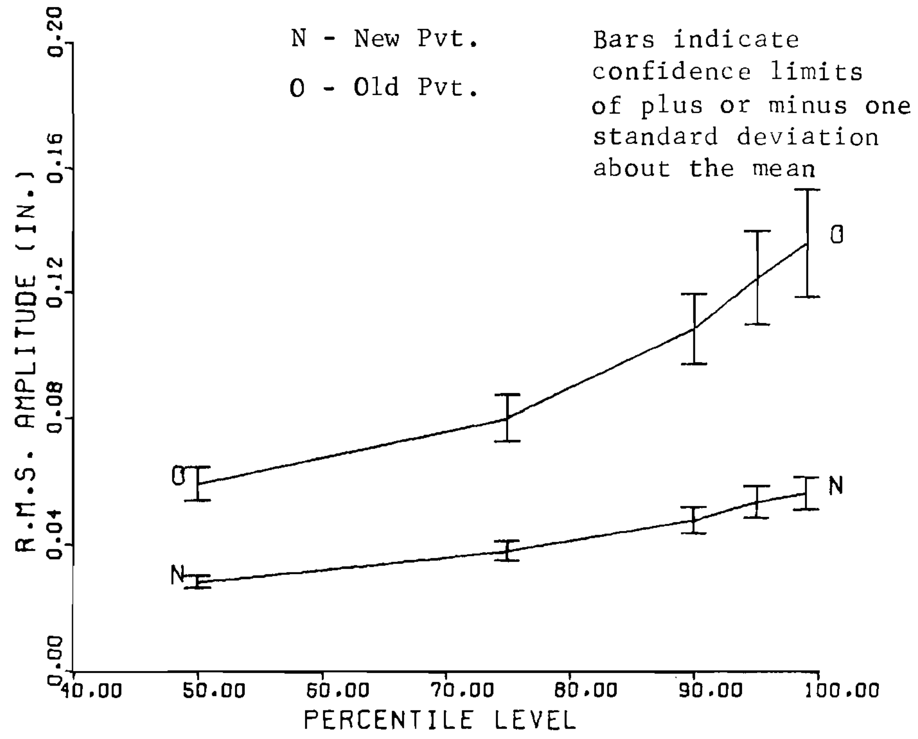

Fig. 2.10. R.m.s. amplitude versus percentile level transverse roughness - passband 27 to 81 feet.

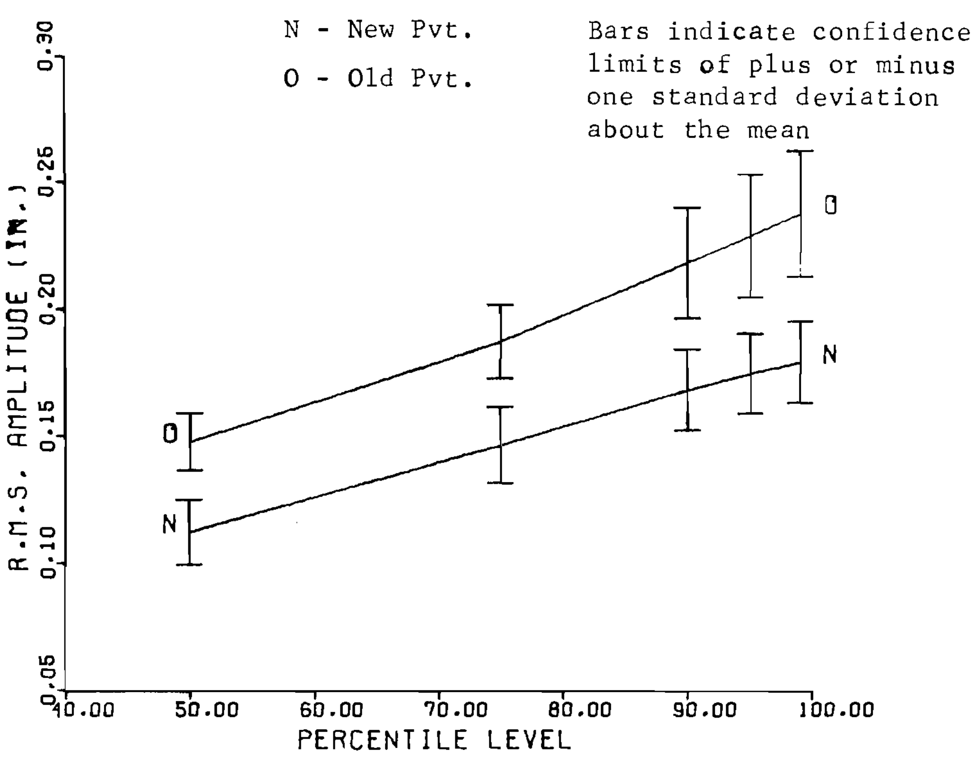

Fig. 2.11. R.m.s. amplitude versus percentile level longitudinal roughness - passband = 81 to 180 feet.

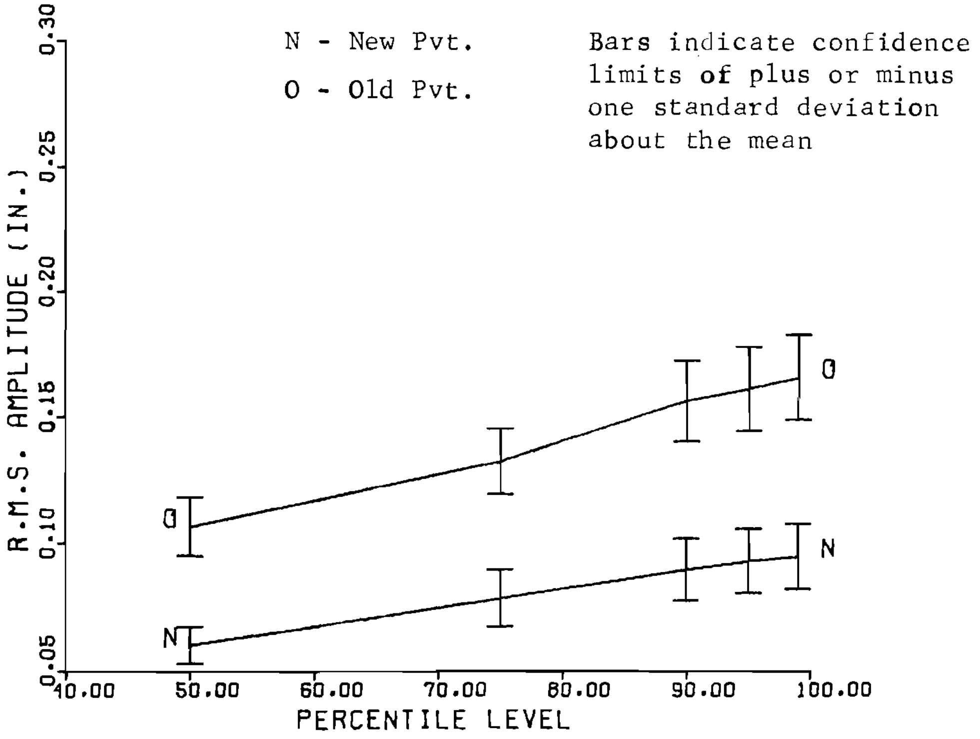

Fig. 2.12. R,m.s. amplitude versus percentile level transverse roughness - passband = 81 to 180 feet.

The comparisons made above by graphical presentation are made in the traditional ways in Tables 2.3 and 2.4 via t and F-tests.[1]

The (two-sample) t-statistic is a test for the equality of the new versus the old pavements. The two outcomes which we consider for each roughness measure are as follows:

(1) The means are so nearly equal that their difference could be explained in terms of random sampling variation. In this case, we cannot conclude that there is a true difference.

(2) The mean for the old pavements is sufficiently larger than that for the new pavemments to justify the conclusion with some confidence that we have identified an aspect of roughness for which the older pavements are worse than the new pavements, and the results are said to be statistically significant.

The F-test is a test for the equality of the variances of a given roughness measure for the new versus the old pavements. The two alternatives considered for each roughness measure are as follows.

(1) The section-to-section variation among the old pavements is not measurably greater than that among the new pavements.

(2) With some confidence, we can state that the old pavements are more diverse than the new pavements. In this case the results are said to be statistically significant.

It is possible for the new pavements to have a larger roughness measure or to appear to be more diverse in some respect because of sampling error.

COMPARISON BETWEEN HOT-MIX ASPHALT-CONCRETE AND SURFACE-TREATED ROADS

The HMAC and ST roads from the sample of 21 new pavements were compared using the same analysis techniques as in the new versus old pavement comparison.

The following relationships are observed from Figs 2.13 through 2.24.

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[1] The tests are one-tailed. The t-test for independent samples when $\sigma_1 \neq \sigma_2$, discussed in Ref 9, was used. It was felt that the convenient assumption of equal variances was unjustified, and the F-tests substantiate this suspicion.

TABLE 2.3. T-STATISTICS TO COMPARE NEW AND DETERIORATED SAMPLE ROUGHNESS AMPLITUDE MEANS

LONGITUDINAL ROUGHNESS

Wavelengths (feet)	Percentile				
	50	75	90	95	99
0-1	1.45	1.43	1.40	1.57	1.60
1-3	4.37	4.56	4.69	4.51	4.15
3-9	3.06	3.20	3.15	3.14	3.33
9-27	4.20	3.94	3.67	3.29	3.22
27-81	4.57	4.56	4.75	4.66	4.35
81-180	2.08	1.94	1.84	1.85	1.95

TRANSVERSE ROUGHNESS

0-1	1.51	1.54	1.59	1.56	1.52
1-3	2.44	2.67	2.92	1.93	2.13
3-9	2.72	2.79	2.93	2.79	3.02
9-27	4.48	4.68	4.01	3.29	3.40
27-81	5.44	5.25	4.96	4.47	4.35
81-180	3.34	3.07	3.23	3.22	3.30

$T \equiv \left(\text{Mean (Old)} - \text{Mean (New)} \right) / \text{Standard Error}$

All values are significant at the .10 level

TABLE 2.4. F-STATISTICS TO COMPARE NEW AND DETERIORATED ROUGHNESS AMPLITUDE VARIANCES

LONGITUDINAL ROUGHNESS

Wavelength (feet)	Percentile				
	50	75	90	95	99
0-1	.26	.24	.23	2.81	7.06*
1-3	7.49*	9.82*	10.96*	15.21*	26.46*
3-9	1.79*	2.17*	4.22*	6.65*	21.21*
9-27	4.66*	6.69*	7.18*	8.09*	7.74*
27-81	6.38*	4.96*	3.91*	4.53*	6.01*
81-180	.730	.89	1.75	2.21*	2.26*

TRANSVERSE ROUGHNESS

0-1	.26	.25	.24	5.61*	14.33*
1-3	.47	.51	.92	12.08*	36.96*
3-9	1.27	1.93*	3.55*	5.68*	27.48*
9-27	5.26*	6.37*	10.99*	22.96*	19.03*
27-81	7.39*	5.46*	6.29*	8.56*	10.88*
81-180	2.29*	1.30	1.66	1.69	1.71

$$F \equiv \frac{\text{BETWEEN SECTION MEAN SQUARE, OLD PAVEMENT}}{\text{BETWEEN SECTION MEAN SQUARE, NEW PAVEMENT}}$$

Each F has 19 and 20 degrees of freedom.

*Significant at the .10 level

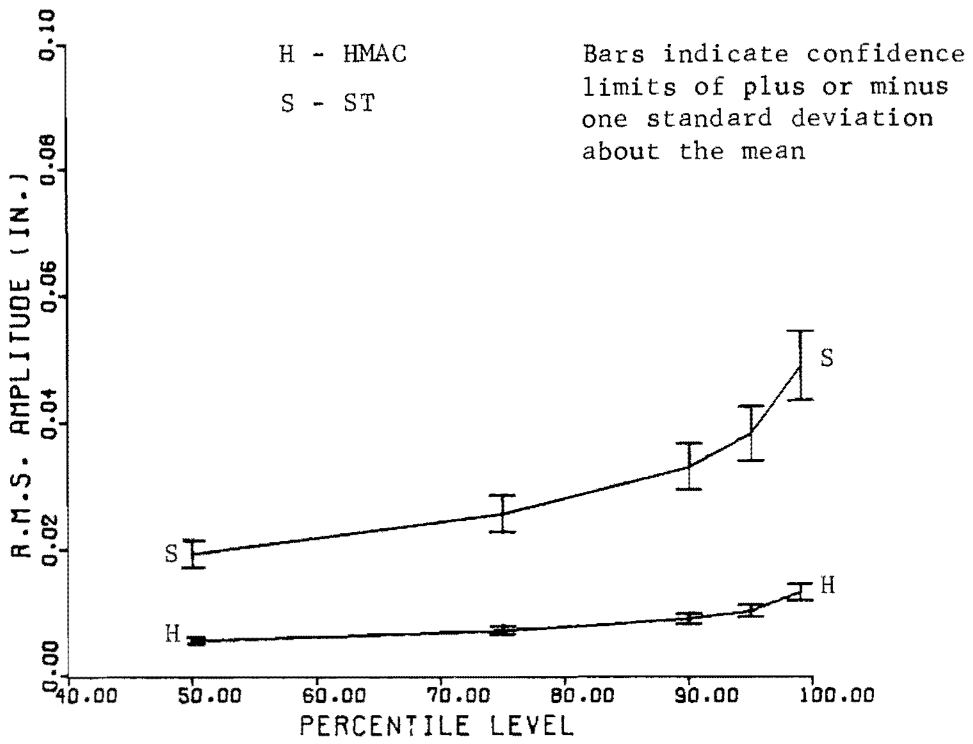

Fig. 2.13. R.m.s. amplitude versus percentile level longitudinal roughness - passband = 0 to 1 foot.

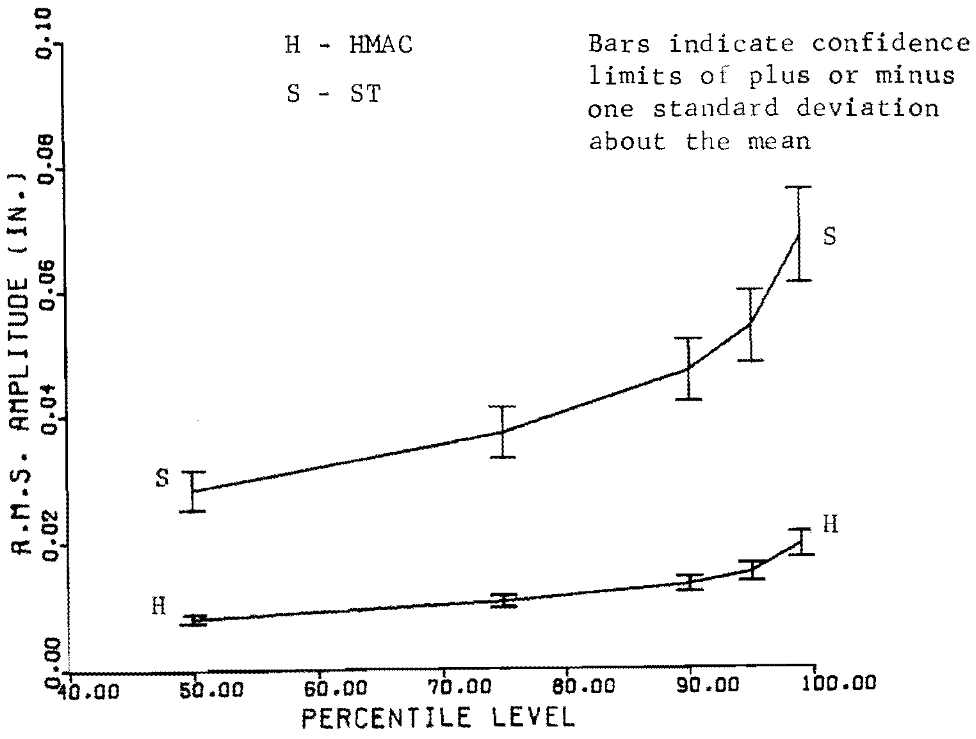

Fig 2.14. R.m.s. amplitude versus percentile level transverse roughness - passband = 0 to 1 foot.

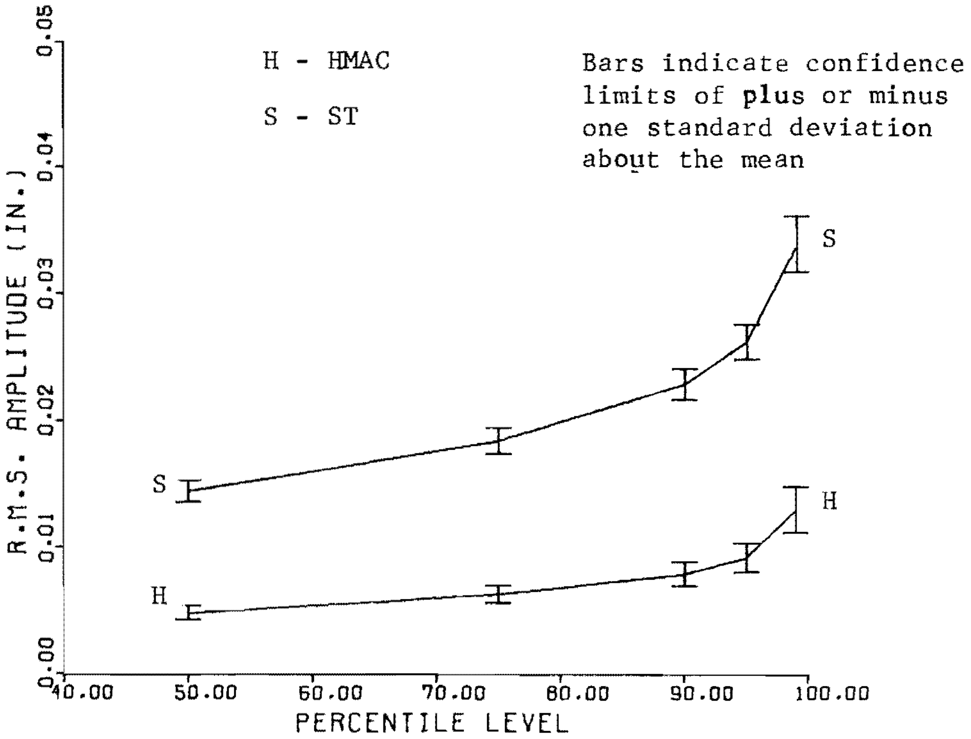

Fig. 2.15. R.m.s. amplitude versus percentile level longitudinal roughness - passband = 1 to 3 feet.

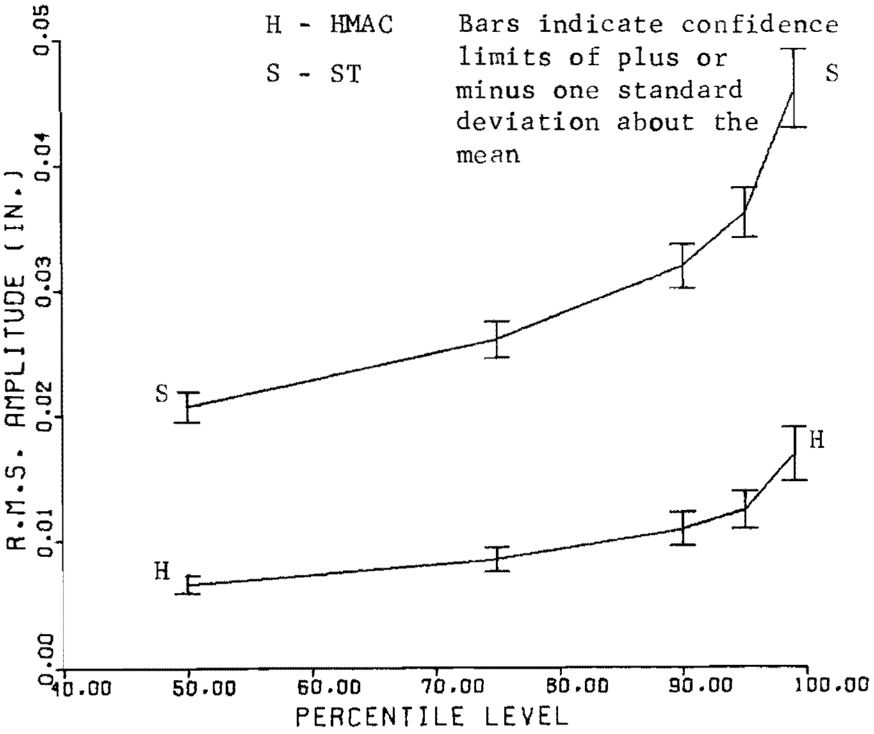

Fig 2.16. R.m.s. amplitude versus percentile level transverse roughness - passband = 1 to 3 feet.

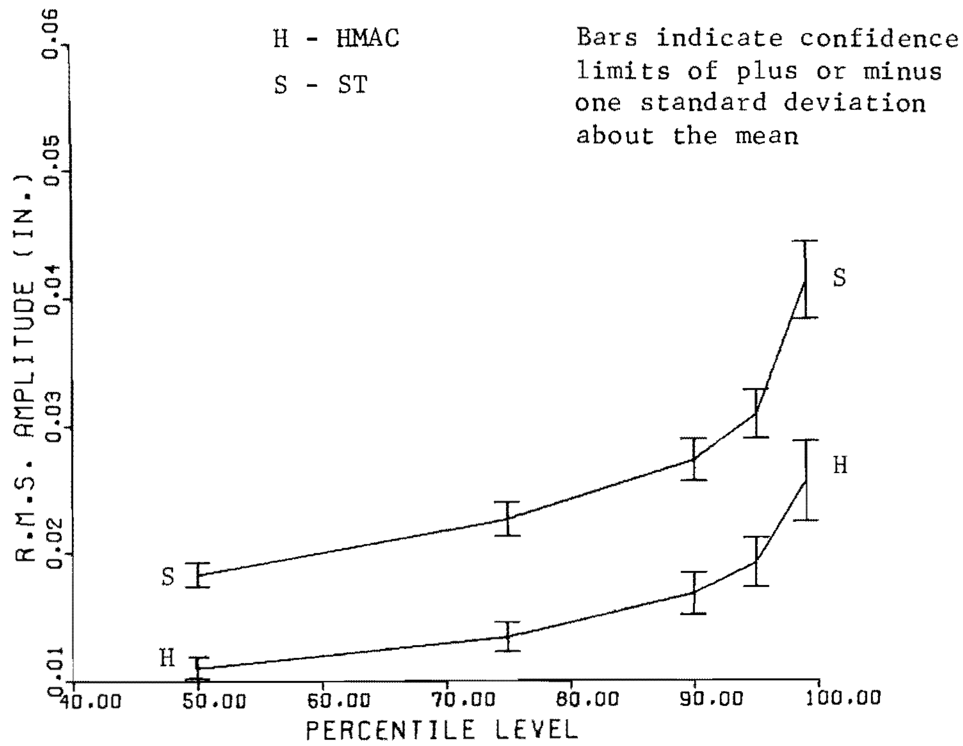

Fig 2.17. R.m.s. amplitude versus percentile level longitudinal roughness - passband = 3 to 9 feet.

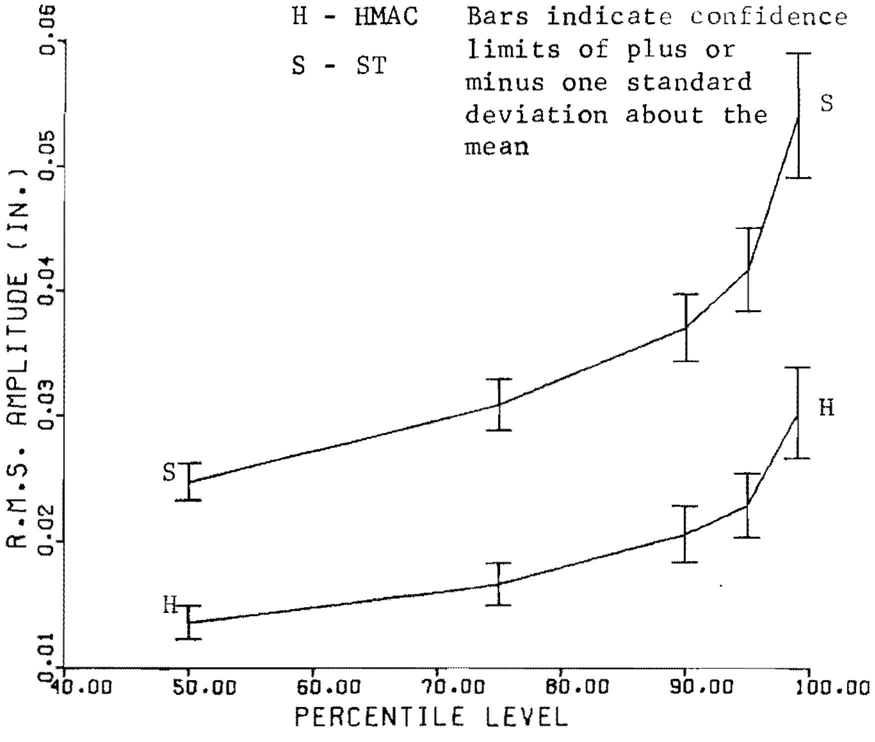

Fig 2.18. R.m.s. amplitude versus percentile level transverse roughness - passband = 3 to 9 feet.

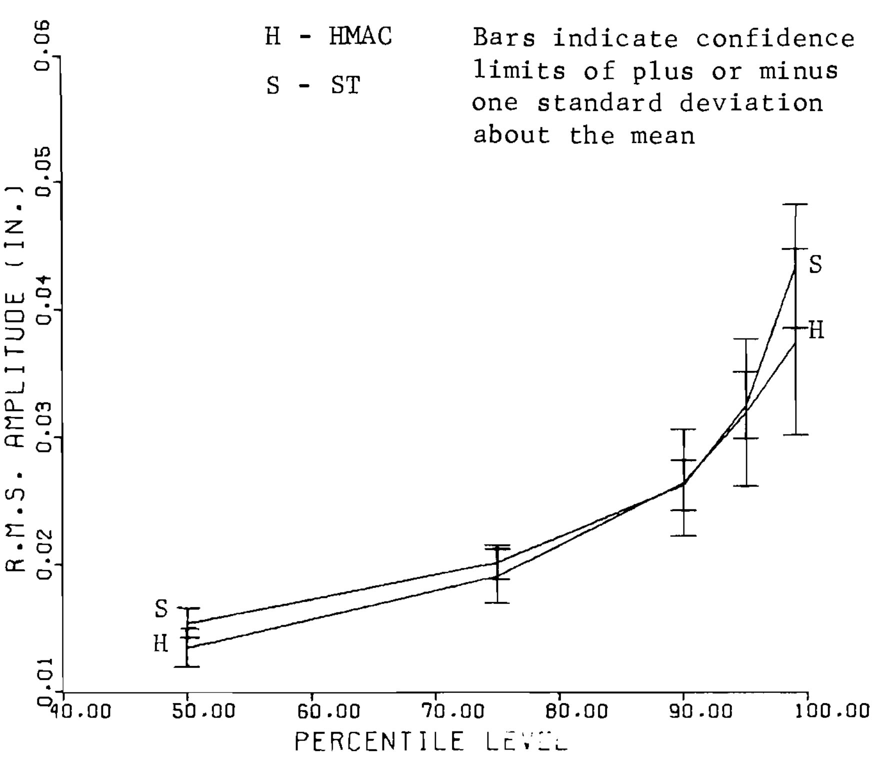

Fig 2.19. R.m.s. amplitude versus percentile level longitudinal roughness - passband = 9 to 27 feet.

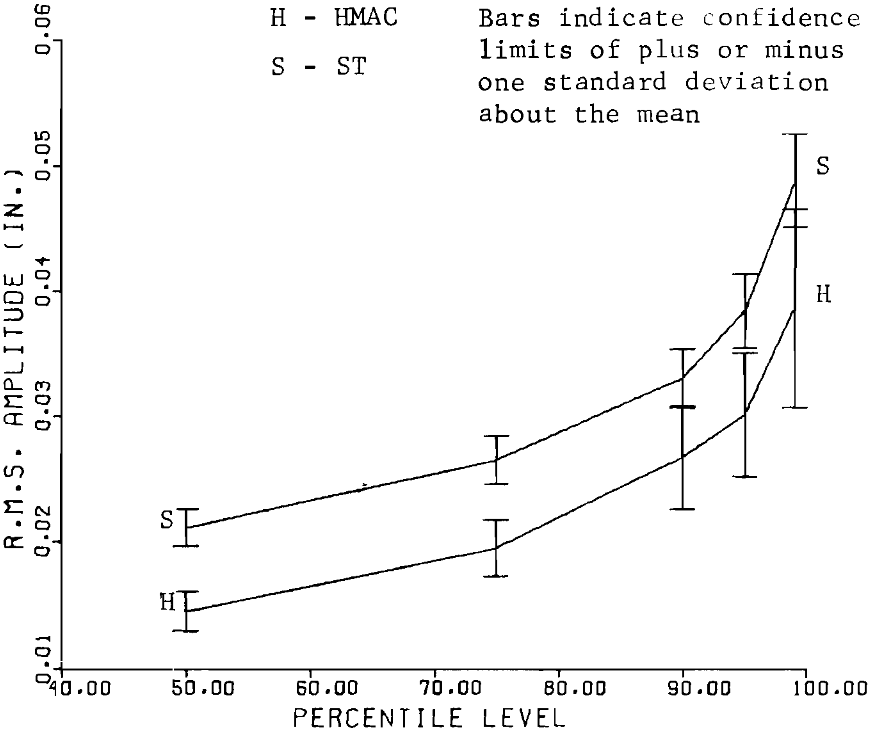

Fig 2.20. R.m.s. amplitude versus percentile level transverse roughness - passband = 9 to 27 feet.

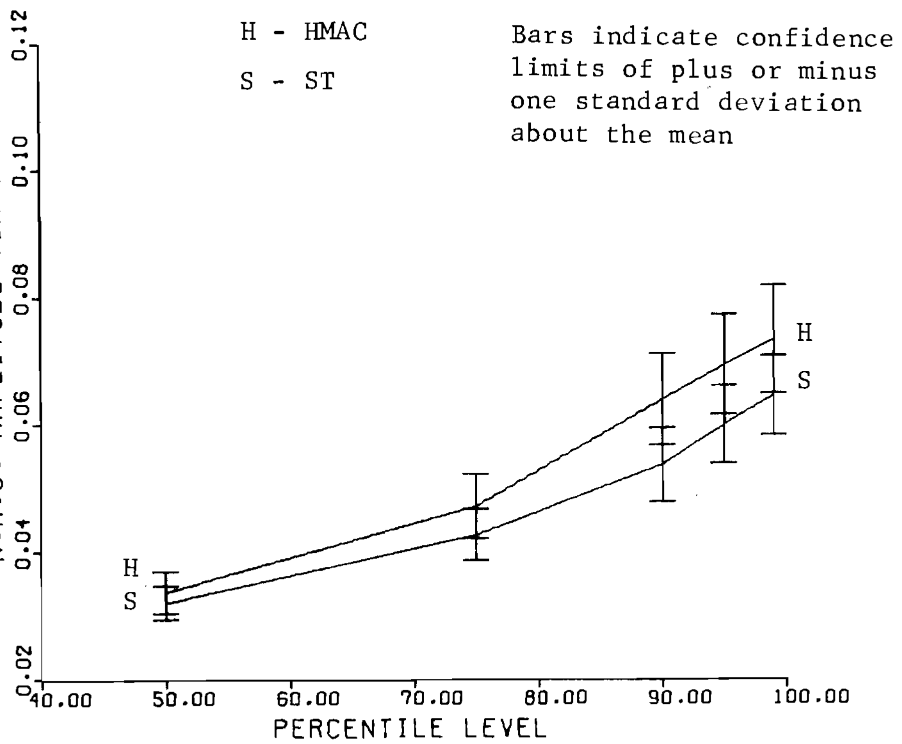

Fig 2.21. R.m.s. amplitude versus percentile level longitudinal roughness - passband = 27 to 81 feet.

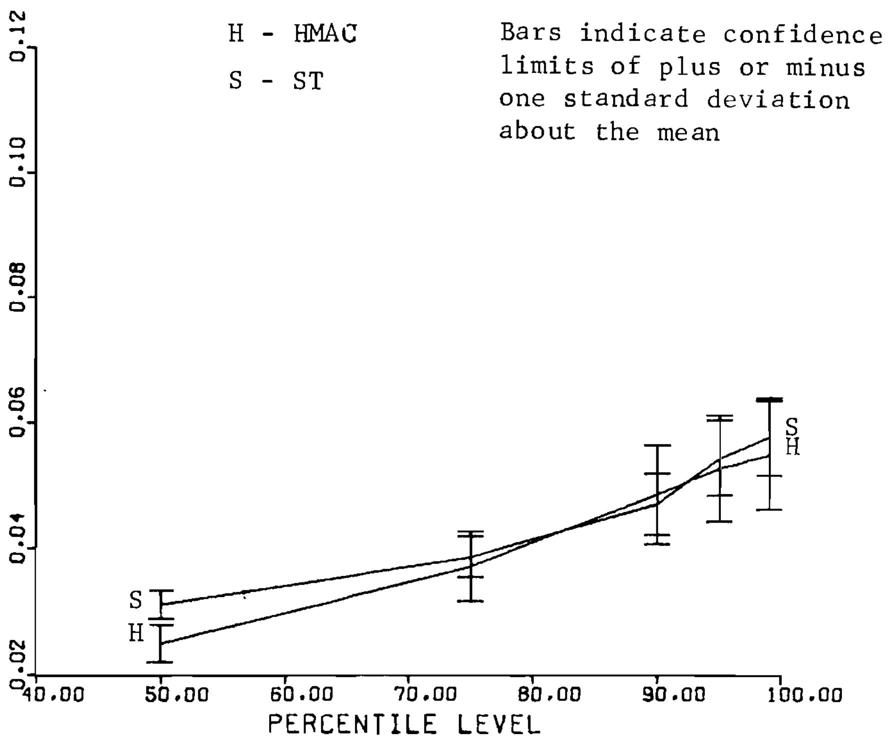

Fig 2.22. R.m.s. amplitude versus percentile level transverse roughness - passband = 27 to 81 feet.

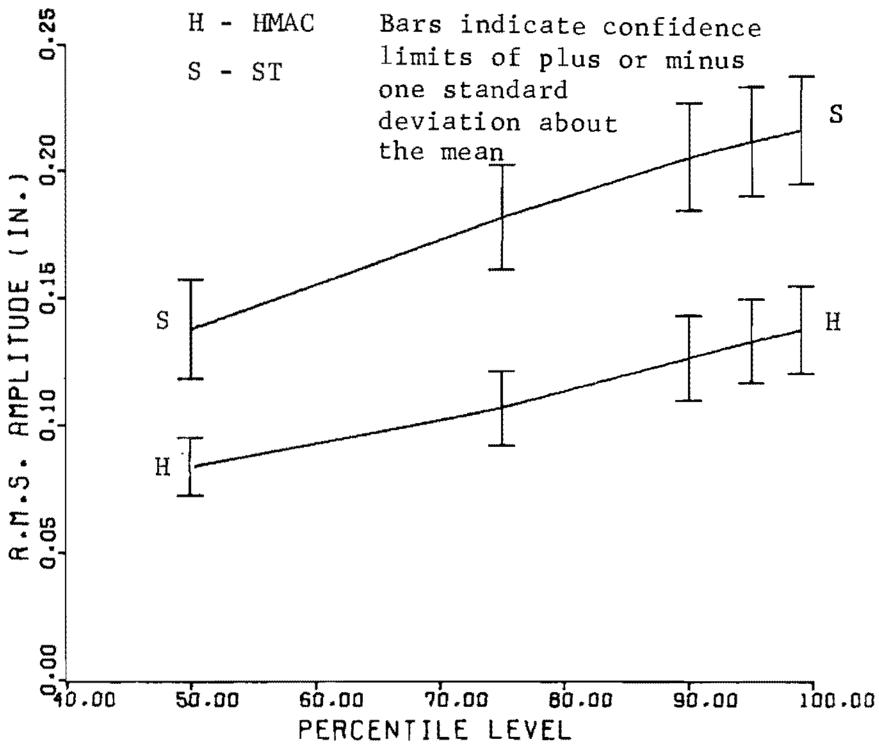

Fig 2.23. R.m.s. amplitude versus percentile level longitudinal roughness - passband = 81 to 180 feet.

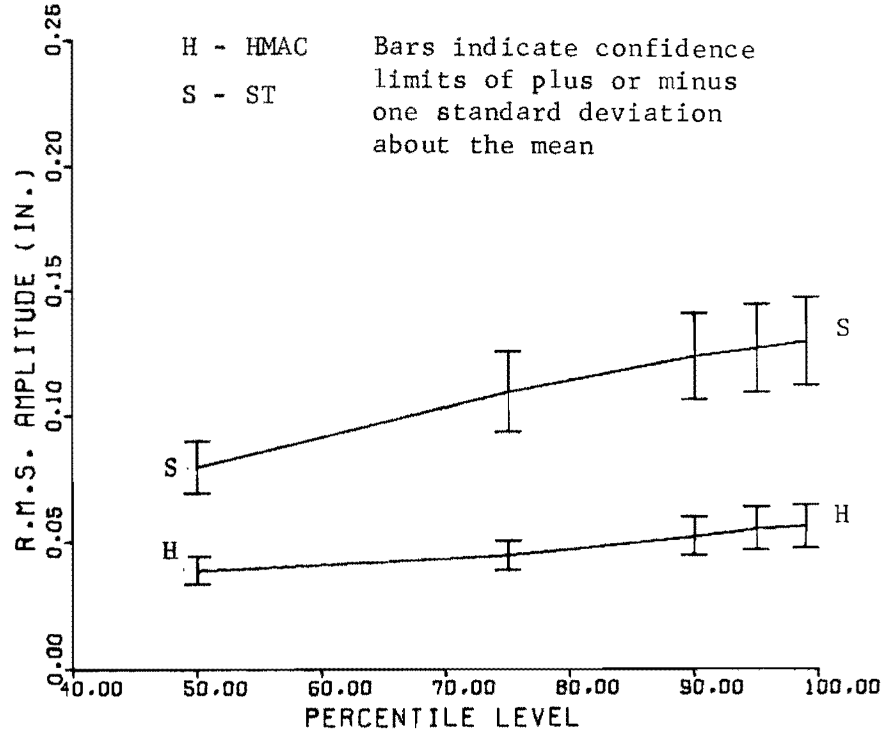

Fig 2.24. R.m.s. amplitude versus percentile level transverse roughness - passband = 81 to 180 feet.

(1) As expected, the ST roads have larger amplitudes for short wavelengths, and the section-to-section variation is greater than for the HMAC roads. Each sample is more diverse at the high percentile points than at the low points.

(2) For the 9 to 27 and 27 to 81-foot bands, we see an increasing similarity with increasing wavelenth between the two types of pavements. This is very reasonable. One would expect the differences between new HMAC and new ST pavements to be most pronounced in the short wavelengths.

(3) For the 81 to 180-foot band, the HMAC amplitudes are again significantly smaller than the ST amplitudes.

Although a generally lower quality among the ST sections was expected, the reversal of the trend of increasing similarity with increasing wavelength was not expected. There is no known construction difference that would consistently introduce larger amplitude long waves in new ST pavements as opposed to new HMAC pavements, but such a difference could easily exist between two small samples. A 40 to 90-foot bump (i.e., a half wave with wavelength to 80 to 180 feet) is definitely not in the range of a large hill which would be cut through. The reversal is believed to be due to random sampling error. This is possibly explained by the fact that measurements had to be made where new pavements had been built; an ideal sample of paired observations designed to eliminate geographical effects was not obtainable. The explanation is apparently not due to differential swelling clay effects in the two samples, however, because the HMAC sections are said in Ref 4 to be in swelling clay areas more often than the ST sections (some swelling clay effects could be observed in the first year).

The sampling anomaly does not affect the validity of the study (Ref 4) of SI values of new pavements, since the very long waves do not influence the SI values.

The t and F-statistics for the HMAC versus ST comparisons are presented in Tables 2.5 and 2.6.

A further comparison, new HMAC pavements with one surface course versus new HMAC pavements with two courses, was planned. An examination of the SI values, which are based on roughness amplitudes, however, indicated that the SI differences between the two samples was much less than the sampling error. Thus, it is unlikely that any information would have been gained that is not present in the pooled HMAC results, which are presented above. Samples larger than those obtainable by dividing the available sample of ten HMAC pavements into two parts would be required for a meaningful comparison.

TABLE 2.5. T-STATISTICS TO COMPARE HMAC AND ST
SAMPLE ROUGHNESS MEANS

LONGITUDINAL ROUGHNESS

Wavelength (feet)	Percentile				
	50	75	90	95	99
0-1	6.09*	6.14*	6.34*	6.29*	6.26*
1-3	9.20*	9.51*	9.46*	9.31*	7.23*
3-9	5.54*	5.15*	4.42*	4.23*	3.60*
9-27	1.01	.431	-.05	.09	.07
27-81	-.38	-.69	-1.10	-.94	-.84
81-180	2.37*	2.96*	2.91*	2.89*	2.84*

TRANSVERSE ROUGHNESS

0-1	6.15*	6.27*	6.54*	6.47*	6.28*
1-3	9.83*	9.89*	9.49*	9.39*	7.64*
3-9	5.51*	5.23*	4.68*	4.46*	3.84*
9-27	3.01*	2.35*	1.34	1.43*	1.15
27-81	1.65*	.24	-.16	.15	.26
81-180	3.42*	3.75*	3.75*	3.63*	3.73*

$T \equiv \left(\text{Mean (ST)} - \text{Mean (HMAC)} \right)$

* significant at the .10 level

TABLE 2.6. F-STATISTICS TO COMPARE HMAC AND ST SAMPLE ROUGHNESS AMPLITUDE VARIANCES

LONGITUDINAL ROUGHNESS

Wavelength (feet)	Percentile				
	50	75	90	95	99
0-1	1.28	1.46	1.07	1.06	1.01
1-3	2.94*	2.07	1.69	1.55	1.58
9-27	.61	.45	.24	.23	.49
27-81	.74	.74	.72	.67	.59
81-180	3.27*	2.13	1.73	1.85	1.68

TRANSVERSE ROUGHNESS

Wavelength (feet)	50	75	90	95	99
0-1	1.39	1.68	1.61	1.92	1.97
1-3	2.77*	2.52*	1.94	2.00	2.34
3-9	1.39	1.68	1.61	1.92	1.97
9-27	.95	.81	.36	.39	.24
27-81	.61	.37	.43	.54	.56
81-180	4.07*	8.07*	5.65*	4.74*	4.64*

$$F \equiv \frac{\text{BETWEEN SECTION MEAN SQUARE, ST}}{\text{BETWEEN SECTION MEAN SQUARE, HMAC}}$$

Each F has 10 and 9 degrees of freedom.

*significant at the .10 level

CHAPTER 3. RELATIONSHIPS AMONG DISTRESS MEASURES

Various distress measures are available (Ref 6) from a condition survey done for the sample of deteriorated pavements discussed above. The survey procedure of the .2-mile sections is described in that reference. The basic process included:

(1) marking the beginning of a section with spray paint,

(2) moving a measuring wheel linearly along the pavement and stopping each time a distress manifestation was encountered,

(3) recording the distance measurement in feet and drawing the distress manifestation on a graphical data sheet to scale at the appropriate position, and

(4) marking the end of the section with spray paint after .2-mile, 1056 feet, had been traversed.

HRB Special Report 113 (Ref 3) was the guide in identifying distress manifestations.

DISTRESS MANIFESTATIONS

Reference 5 contains tables of numerous distress measures, including several classes of cracking. All types of distress are given in square feet. Linear cracking, which is also given in feet, is measured in area units by assuming that a six-inch wide band is "distressed" by a crack.

In this pilot study, we examined the relationships among roughness measures and four distress measures: the areas of cracking, cracking plus patching, rutting, and total distress. The distress measures are given in Table 3 .1.

RELATIONSHIPS BETWEEN ROUGHNESS MEASURES AND OTHER DISTRESS MEASURES

Obtaining roughness measures from profilometer data is extremely fast compared to the very time consuming condition survey methods. Thus, it is of some interest to know whether it is feasible to predict, with reasonable accuracy, distress measures <u>from</u> roughness measures. Additionally, the

TABLE 3 .1. DISTRESS MEASURES (square feet)

Section	Cracking	Cracking + Patching	Rutting	Total Distress
P-1	48	48	0	54
P-2	22	22	0	526
P-3	3945	5398	72	5470
1	1270	7030	640	8200
2	479	5679	0	6648
3	81	1409	64	2604
5	1867	2315	0	2335
7	362	366	0	796
8	182	1601	0	1741
9	7	806	0	984
10	64	144	0	144
15	0	1339	320	2618
16	0	0	0	501
17	0	600	340	3710
18	0	90	0	790
19	599	5789	1000	7629
20	214	7619	80	7699
21	160	2540	400	2940
22	60	2030	0	2030
23	100	1170	0	2310

relationships among various distress measures, or the extent to which various distress types tend to be present simultaneously, is of general interest simply for understanding pavement distress.

The means and standard deviations of the variables are given in Table 3 .2.

Stepwise regression was used to develop models for predicting areas of cracking, cracking plus patching, rutting, and total distress (Refs 10 and 11). Stepwise regression is simply a method which successively enters terms into and deletes terms from a model in order to obtain a predicting equation with no unnecessary terms. Statistical hypothesis tests[1] are performed to determine which terms make a significant contribution to the predictive value of the model and which terms seem to follow only the noise in the data. The higher the significance level used in performing the tests, the more selective the regression method is in including terms.

Tables 3.3 to 3.7 summarize the results obtained using hypothesis tests at the 90 percent level (the probability of erroneously deciding that a given term should be included is .1).

The R^2 values are very important, since they are the proportions of road-to-road variations in the various distress measures that were explained or predicted in terms of the roughness measures. The percentages of the variations explained are 72.44 for area of cracking, 84.72 for cracking or patching, 90.87 for rutting, and 79.89 for the total area of distress. It is felt that these percentages are extremely good in view of the fact that the numbers of terms in the models were kept small for reasons discussed below.

Since the sample includes only 20 points, a model including a large number of terms would be suspect. The models for cracking, cracking or patching, and total area of distress have two terms, three terms, and three terms

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[1] Partial F-tests are used -- the F-to-remove statistics are included in the tables. The reader who is not interested in the statistical fine points can ignore these without losing the basic objectives of the study.

TABLE 3.2. MEANS AND STANDARD DEVIATIONS OF THE VARIABLES

Variable			Mean	Standard Deviation
R50	1	1	1.6032038E-02	4.5517060E-03
R90	1	2	2.6974630E-02	7.1850185E-03
R99	1	3	5.5212925E-02	6.0309546E-02
R50	2	4	2.5561742E-02	1.5074864E-02
R90	2	5	4.6499352E-02	2.8024241E-02
R99	2	6	8.5089355E-02	6.4565113E-02
R50	3	7	1.6254596E-02	6.3522837E-03
R90	3	8	3.0421547E-02	1.5497806E-02
R99	3	9	7.4213820E-02	5.8252508E-02
R50	4	10	2.4351227E-02	9.5253099E-03
R90	4	11	4.9840112E-02	2.6801888E-02
R99	4	12	8.2286962E-02	5.4507109E-02
R50	5	13	5.9621472E-02	2.4302822E-02
R90	5	14	1.0869526E-01	4.2195408E-02
R99	5	15	1.2999685E-01	5.8207307E-02
R50	6	16	1.4812227E-01	5.0495455E-02
R90	6	17	2.1860163E-01	9.7581552E-02
R99	6	18	2.3763157E-01	1.1174852E-01
D50	1	19	2.3586710E-02	6.5546151E-03
D90	1	20	3.9188080E-02	1.0353693E-02
D99	1	21	8.6303410E-02	1.1740567E-01
D50	2	22	1.9179775E-02	5.4566831E-03
D90	2	23	3.2527430E-02	1.1400877E-02
D99	2	24	8.2944405E-02	1.0522250E-01
D50	3	25	2.1957415E-02	8.1476235E-03
D90	3	26	4.1360000E-02	2.1965764E-02
D99	3	27	1.0569580E-01	9.7681087E-02
D50	4	28	3.2886975E-02	1.3653157E-02
D90	4	29	6.3826775E-02	3.6158112E-02
D99	4	30	1.1119608E-01	8.6208628E-02
D50	5	31	5.9192220E-02	2.3973469E-02

(Continued)

TABLE 3.2. Continued

Variable			Mean	Standard Deviation
D90	5	32	1.0855470E-01	5.1014742E-02
D99	5	33	1.3622322E-01	7.8667979E-02
D50	6	34	1.0671533E-01	5.2196937E-02
D90	6	35	1.5664395E-01	7.3595958E-02
D99	6	36	1.6608324E-01	7.7144515E-02
CR		37	4.7300000E+02	9.4696007E+02
C+P		38	2.2997500E+03	2.5278686E+03
RUT		39	1.4580000E+02	2.6931953E+02
TOTAL		40	2.9864500E+03	2.6873526E+03

The variable names of the roughness measures include R (for right-left average, or longitudinal, roughness measure) or D (difference, or transverse, roughness), percentile level, and passband number, in ascending order for increasing wavelengths. All roughness measures are in inches.

CR = area of cracking, sq. ft.
C+P = area of cracking or patching, sq. ft.
RUT = area of rutting, sq. ft.
TOTAL = total area of distress, sq. ft.

TABLE 3 .3. PREDICTION OF TOTAL AREA OF CRACKING (Ft.^{2}) FROM ROUGHNESS MEASURES

HYPOTHESIS TESTS FOR INCLUSION OF TERMS IN MODEL AT 90 PERCENT LEVEL

MULTIPLE R* .8511 R^2 .7244

STANDARD ERROR FOR RESIDUALS 526

ANALYSIS OF VARIANCE

	DF**	SUM OF SQUARES	Mean SQUARES	F RATIO
REGRESSION	2	1.23 E+7	6.17 E+6	22.338
RESIDUAL	17	4.70 E+6	2.76 E+5	

VARIABLES IN EQUATION

(CONSTANT -1.97 E+3)

VARIABLE	COEFFICIENT	STANDARD ERROR	F to REMOVE
R50 1	8.60 E+4	3.00 E+4	8.202
R90 3	3.51 E+4	8.82 E+3	15.808

* multiple correlation coefficient

** degrees of freedom

TABLE 3.4. PREDICTION OF TOTAL AREA OF CRACKING OR PATCHING (Ft.^{2}) FROM ROUGHNESS MEASURES

HYPOTHESIS TESTS FOR INCLUSION OF TERMS IN MODEL AT 90 PERCENT LEVEL.

MULTIPLE R .9204 R^2 .8472

STANDARD ERROR FOR RESIDUALS 1077

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	3	1.03 E+8	3.43 E+7	29.566
RESIDUAL	16	1.86 E+7	1.15 E+6	

VARIABLES IN EQUATION

(CONSTANT -6.07 E+2)

VARIABLE	COEFFICIENT	STANDARD ERROR	F to REMOVE
R 90 6	-9.94 E+3	2.89 E+3	11.842
D 90 3	5.40 E+4	1.33 E+4	16.394
D 99 5	2.09 E+4	4.16 E+3	25.271

TABLE 3 .5. PREDICTION OF TOTAL AREA OF RUTTING (FT.^{2}) FROM ROUGHNESS MEASURES

HYPOTHESIS TESTS FOR INCLUSION OF TERMS IN MODEL AT 90 PERCENT LEVEL

MULTIPLE R .9533 R^2 .9087

STANDARD ERROR FOR RESIDUALS 98

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	6	1.25E+6	2.09E+5	21.572
RESIDUAL	13	1.26E+5	9.68E+3	

VARIABLES IN EQUATION
(CONSTANT -5.24E+2)

VARIABLE	COEFFICIENT	STANDARD ERROR	F TO REMOVE
R 90 2	-9.36E+3	1.33E+3	49.700
R 50 5	1.44E+4	2.88E+3	25.038
R 50 6	4.31E+3	9.07E+2	22.567
R 90 6	-1.94E+3	4.57E+2	17.949
D 50 4	9.20E+3	3.29E+3	7.807
D 99 5	-2.00E+3	7.02E+2	8.097

TABLE 3.6. PREDICTION OF TOTAL AREA OF DISTRESS (FT.^{2}) FROM ROUGHNESS MEASURES

HYPOTHESIS TESTS FOR INCLUSION OF TERMS IN MODEL AT 90 PERCENT LEVEL

MULTIPLE R .8938 R^2 .7989

STANDARD ERROR FOR RESIDUALS 1313

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	3	1.10E+8	3.65E+7	21.184
RESIDUAL	16	2.76E+7	1.72E+6	

VARIABLES IN EQUATION
(CONSTANT -8.83E+2)

VARIABLE	COEFFICIENT	STANDARD ERROR	F TO REMOVE
R 99 6	-9.21E+3	3.03E+3	9.246
D 90 3	5.95E+4	1.55E+4	14.664
D 90 5	3.31E+4	7.42E+3	19.920

TABLE 3.7. PREDICTION OF TOTAL AREA OF RUTTING (FT.^{2}) FROM ROUGHNESS MEASURES

HYPOTHESIS TESTS FOR INCLUSION OF TERMS IN MODEL AT 90 PERCENT LEVEL

MULTIPLE R	.8572	R^2	.7989
STANDARD ERROR FOR RESIDUALS	151		

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	3	1.01E+6	3.38E+5	14.776
RESIDUAL	16	3.65E+5	2.28E+4	

VARIABLES IN EQUATION
(CONSTANT -3.19E+2)

VARIABLE	COEFFICIENT	STANDARD ERROR	F TO REMOVE
R 90 2	-8.11E+3	1.75E+3	21.370
R 90 5	5.91E+3	2.25E+3	6.899
D 50 4	1.49E+4	3.72E+3	16.042

plus a constant term, respectively. The model for rutting includes six terms plus a constant.

While the hypothesis tests indicate that there is excellent reason to include all of the six terms,[1] another model was developed using 95 percent confidence. A model with only three terms explaining 73.48 percent of the road-to-road variation in rutting area was obtained (see Table 3.7).

It is felt that these results, limited by the small sample size, indicate that a further investigation into the possibility of performing condition surveys by means of prediction from roughness measures is fully justified.

The residuals from the regression models, defined by

$$Y_i - \hat{Y}_i$$

where

Y_i = i^{th} value of the dependent variable,

$\hat{Y}_i$ = ith predicted value of the dependent variable

are plotted against the appropriate dependent variables in Figs 3.1 through 3.5 for the five regression models discussed above.

This type of plot is valuable in revealing remaining trends not predicted by the regression model.

Note that in each case the data are scattered considerably, indicating that the unexplained residuals have a predominant portion which is unrelated to the dependent variables. This is as it should be.

Notice also that in each case there is an apparently linear trend with positive slope.[2] Thus, the quantity $Y_i - \hat{Y}_i$ is, on the average, negative if Y_i is small and positive if Y_i is large; i.e., there is a tendency of the model to overpredict if the amount of distress is small and to underpredict if the amount is large.

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[1] See the F-to-remove statistics in Table 3.5.

[2] It is a slight inconvenience that the plots produced by the systems stepwise regression program have an inverted vertical scale.

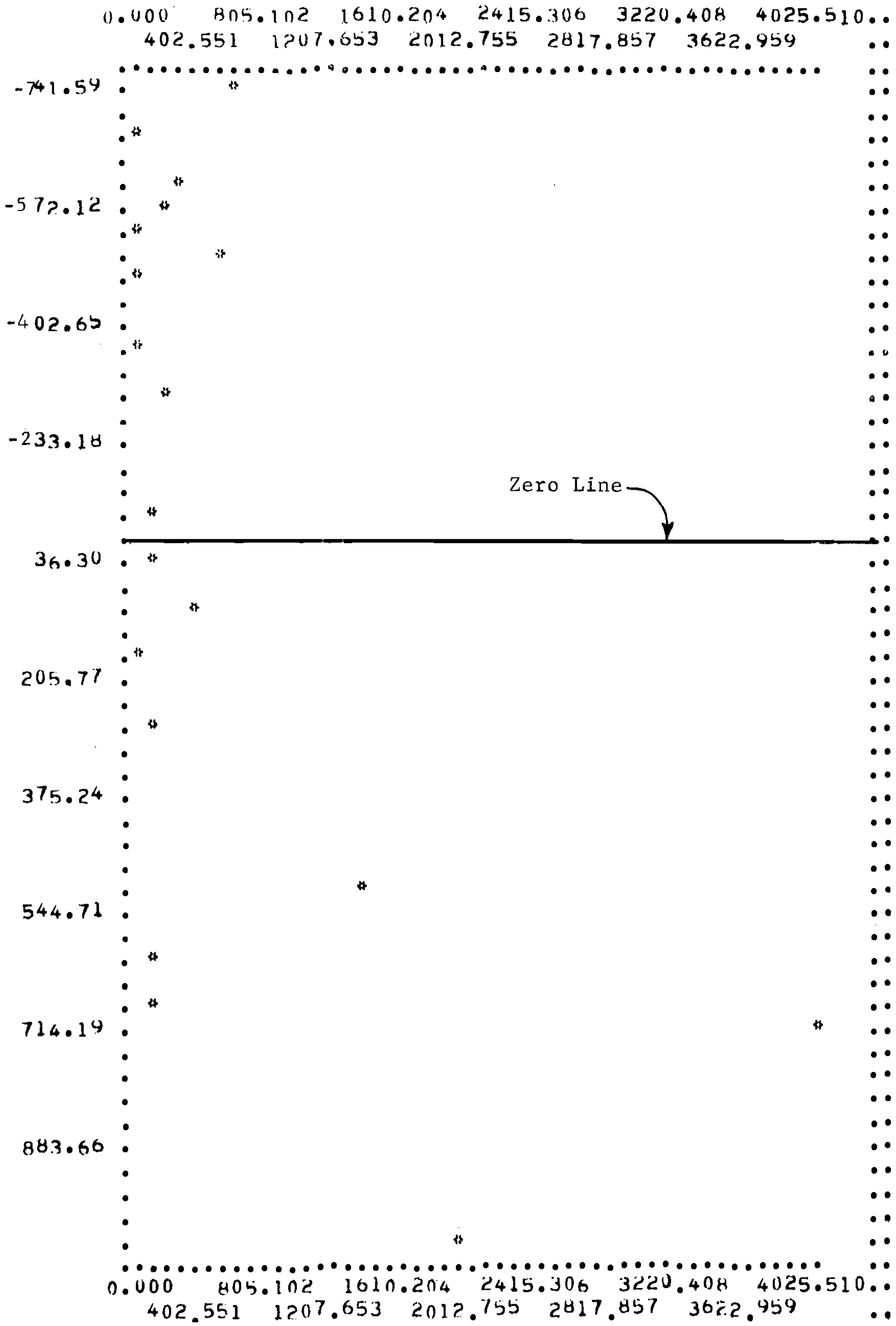

Fig 3.1. Plot of residuals (Y-Axis) versus area of cracking (X-Axis).

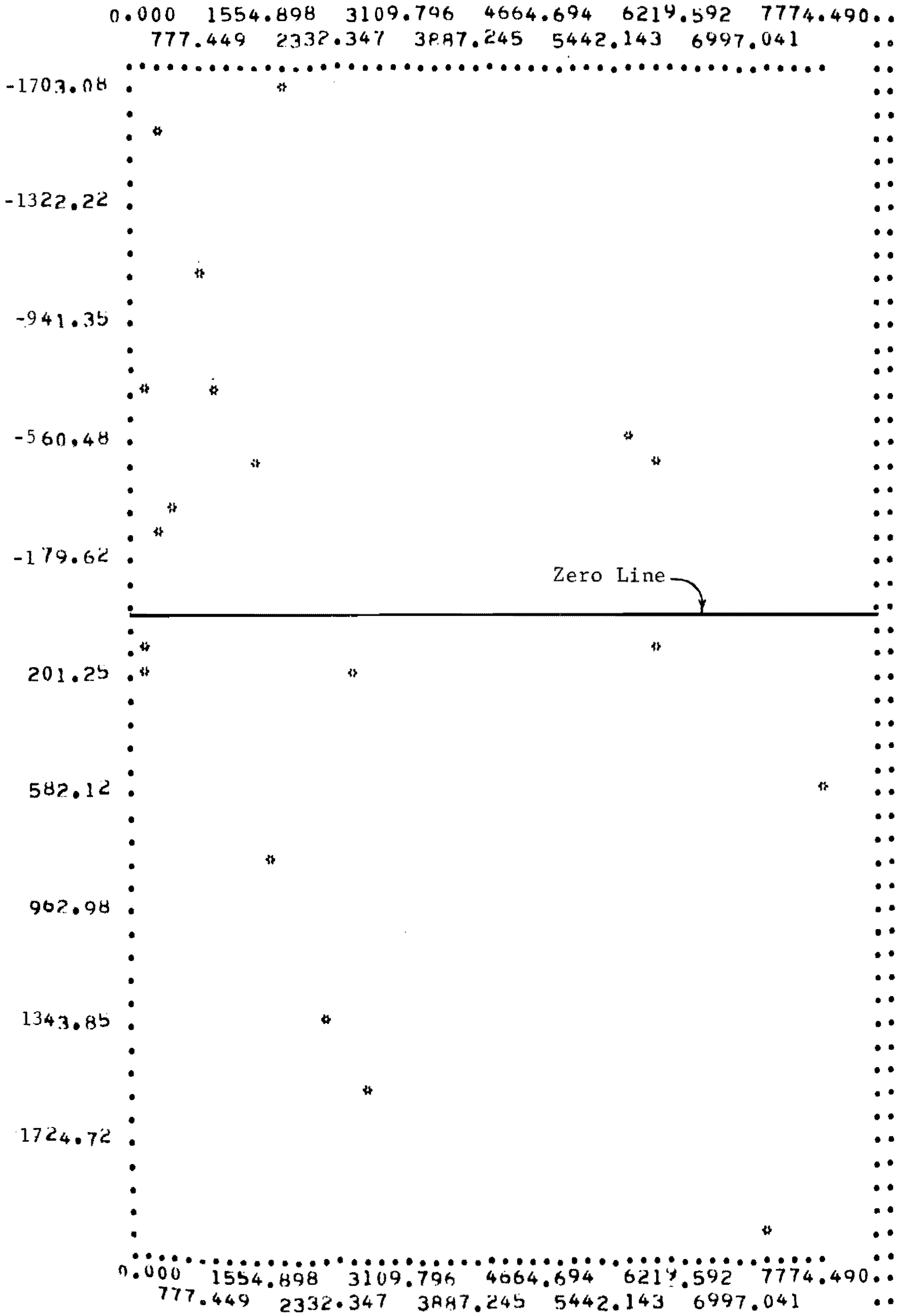

Fig 3.2. Plot of residuals (Y-Axis) versus area of cracking or patching (X-Axis).

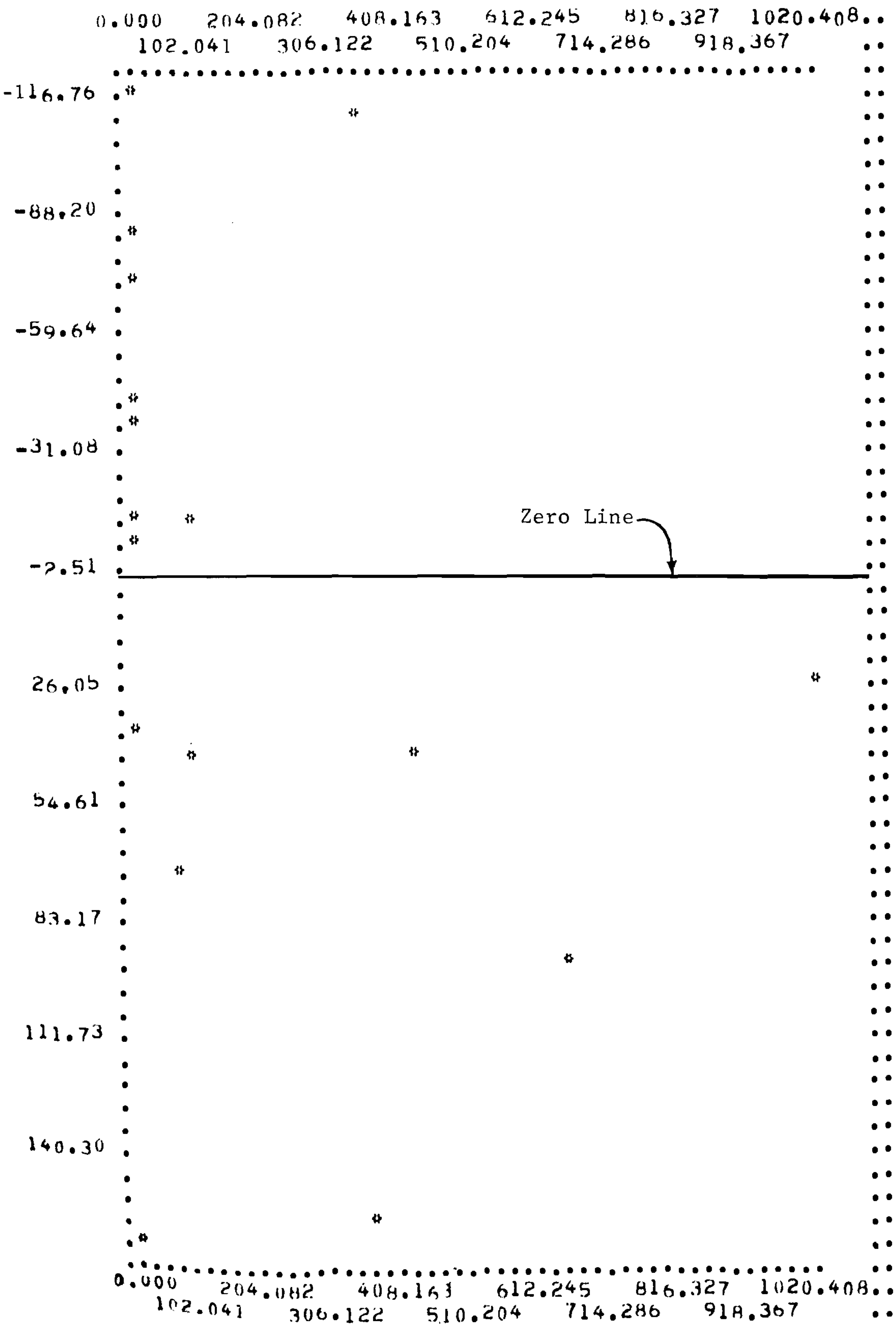

Fig 3.3. Plot of residuals (Y-Axis) versus area of rutting (X-Axis).

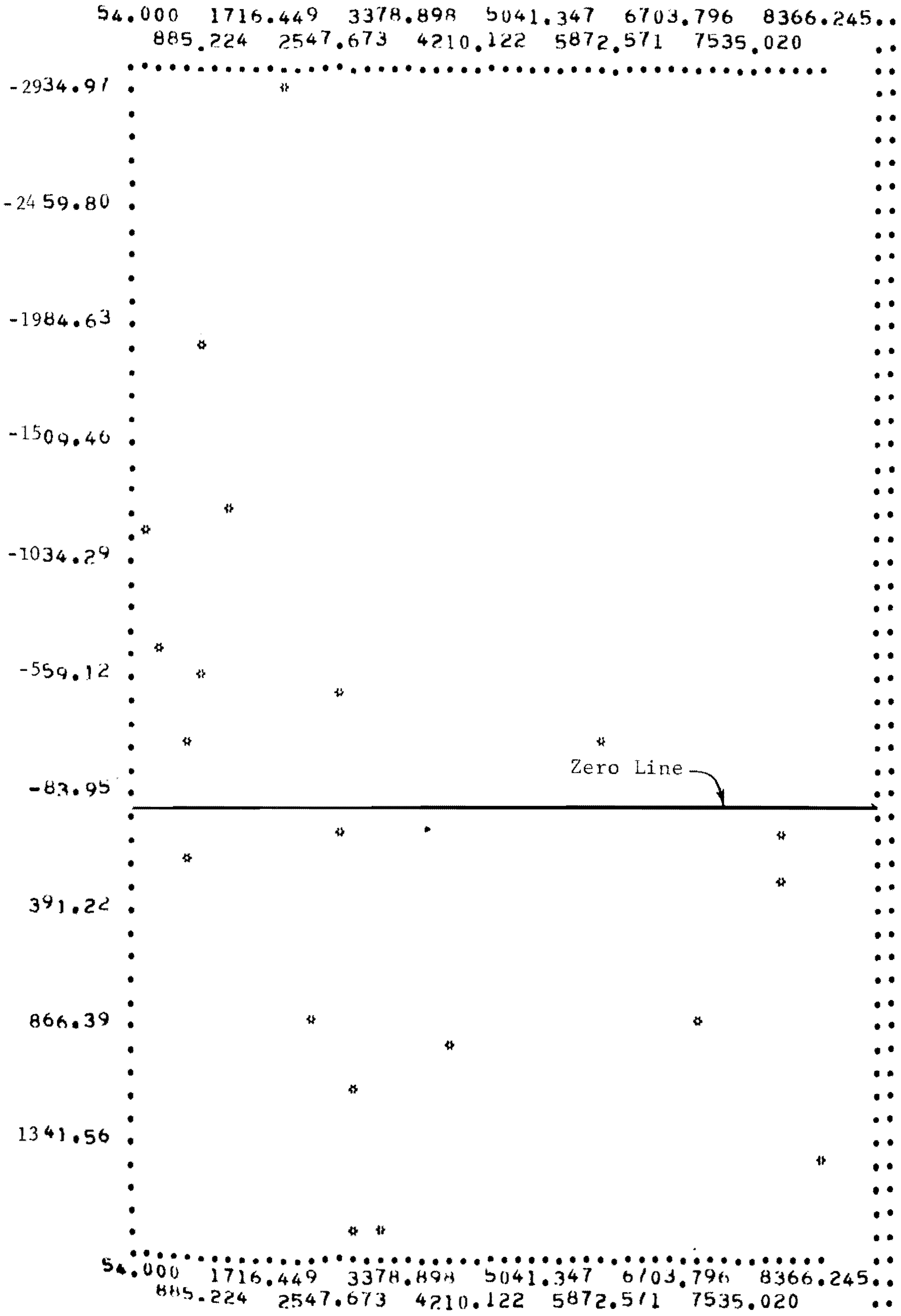

Fig 3.4. Plot of residuals (Y-Axis) versus total area of distress (X-Axis).

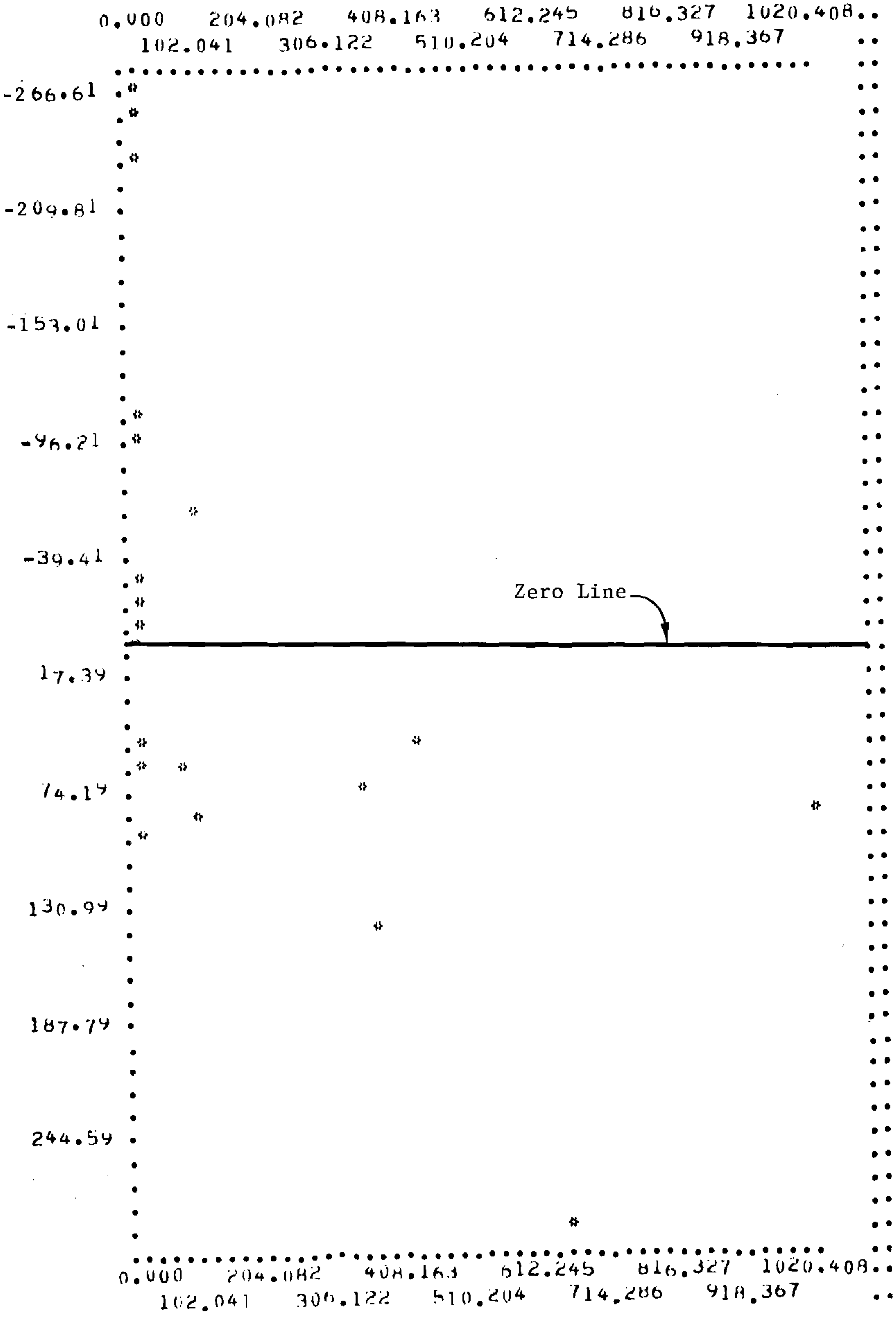

Fig 3.5. Plot of residuals (Y-Axis) versus area of rutting (X-Axis) 95 percent level used for hypothesis tests.

Experimentation with models with more terms yielded mixed results. The trends were absent from the cracking and the cracking plus patching plots obtained by building models using 80 percent confidence. The models included 13 and 5 terms (plus constants), respectively. The trends were not removed from the rutting or total distress models.

The use of advanced statistical techniques (principal component analysis) to explore the possibility of obtaining a transformed set of statistically independent predictor variables which were small in number but contained essentially all of the information in the original larger set would possibly solve the problem. A model would be sought involving few terms with high information content.

Investigation of other predictor variables, especially time since construction or since the last major maintenance, might yield a variable which explained distress differences among roads with similar roughness patterns.

Examination of the residuals plotted against selected independent variables gave no evidence of lack of fit.

The regression models cannot be used to infer a relationship between a given dependent variable and a given independent variable.

A note is in order on the negative coefficients of some of the variables in the equations. Where negative coefficients appear, one should not infer that a roughness measure is negatively or inversely related to the dependent variable. The explanation is that the other terms in the model taken alone tend to overpredict in such a way that the term with the negative coefficient tends to correct the error.

Individual relationships are obtained from the matrix of correlation coefficients. Our interest here is not in the theoretical properties of correlation but in the physical relationships which are revealed by this measure of predictability of one variable in terms of another.

The correlation coefficient is

1 if the distress measure is perfectly predictable from a linear function of the given roughness measure and the variables tend to increase simultaneously,

0 if there is no linear relationship, and

-1 if perfect linear prediction is possible and one variable increases as the other decreases.

Values between -1 and 1 are measures of the extent of predictability; the square of the coefficient is the proportion of the road-to-road distress variation explainable as a linear function of the given roughness measure.

Tables 3.8 to 3.11 give the individual correlations among the distress measures and the roughness measures. According to the method presented in Ref 9, page 185, a correlation coefficient from a sample of size 20 is significantly greater than zero if it exceeds .3 [1]. Because of sampling errors, there are some correlations which are negative but small in magnitude; none of these is significantly less than zero.

One must be very careful in examining the correlations for the area of cracking, since the value given is the area of unmaintained cracking; it is not clear what differential effects maintenance may have had on cracking and roughness. Thus, the very low correlations between the 99th percentile of both longitudinal and transverse roughness amplitudes for 0 to 1-foot wavelengths are probably misleading. Similar comments could possibly be made about rutting. The correlations for cracking or patching and total area of distress, however, are physically meaningful.

For the area of cracking or patching and the total area of distress, we make special note of the following relationships.

(1) For the 0 to 1-foot-long waves, the 99th percentile amplitudes are better predictors of distress than the lower percentile points.

(2) In the range from 0 to 81 feet, except for the lower percentile points for the 0 to 1-foot band, all roughness measures have significant correlations.

(3) The 81 to 180-foot longitudinal waves are much less clearly related to distress than the shorter waves; the high percentile amplitudes, which may be influenced by small hills, are apparently uncorrelated with distress.

(4) The amplitudes, including the high percentile points, of the long transverse waves are related to distress. Waves due to right-left profile elevation differences, upon which the transverse amplitudes are based, cannot be caused by hills and probably should be considered pavement roughness.

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[1] This applies for a one-tailed test.

TABLE 3.8. CORRELATIONS BETWEEN AREA OF CRACKING AND ROUGHNESS AMPLITUDES

Wavelengths (feet)	Percentile					
	Longitudinal			Transverse		
	50	90	99	50	90	99
0 to 1	.684	.613	.062	.656	.597	.037
1 to 3	.702	.706	.667	.736	.529	.277
3 to 9	.702	.769	.332	.994	.634	.254
9 to 27	.601	.552	.559	.540	.536	.518
27 to 81	.422	.290	.291	.407	.247	.321
81 to 180	.252	.105	.187	.338	.256	.264

TABLE 3.9. CORRELATIONS BETWEEN AREA OF CRACKING OR PATCHING AND ROUGHNESS AMPLITUDES

Wavelengths (feet)	Percentile					
	Longitudinal			Transverse		
	50	90	99	50	90	99
0 to 1	.299	.298	.517	.257	.317	.513
1 to 3	.450	.493	.635	.614	.802	.448
3 to 9	.512	.664	.532	.526	.769	.451
9 to 27	.543	.692	.672	.586	.736	.734
27 to 81	.609	.458	.422	.533	.666	.718
81 to 180	.300	-.051	-.030	.302	.293	.346

TABLE 3.10. CORRELATIONS BETWEEN AREA OF RUTTING AND ROUGHNESS AMPLITUDES

Wavelengths (feet)	Percentile					
	Longitudinal			Transverse		
	50	90	99	50	90	99
0 to 1	-.086	-.129	-.092	-.108	-.142	-.090
1 to 3	.016	-.014	-.111	.114	.101	-.091
3 to 9	.440	.375	.184	.559	.384	.207
9 to 27	.543	.304	.081	.611	.263	.143
27 to 81	.491	.298	.240	.397	.348	.194
81 to 180	.042	-.072	-.068	.520	.434	.397

TABLE 3.11. CORRELATIONS BETWEEN TOTAL AREA DISTRESSED

Wavelengths (feet)	Percentile Longitudinal 50	90	99	Transverse 50	90	99
0 to 1	.255	.269	.438	.223	.289	.428
1 to 3	.394	.429	.513	.569	.721	.353
3 to 9	.538	.640	.538	.562	.728	.482
9 to 27	.558	.675	.643	.616	.725	.722
27 to 81	.630	.443	.406	.570	.682	.703
81 to 180	.300	-.048	-.039	.387	.360	.399

CHAPTER 4. CONCLUSIONS

Analysis techniques employing digital filtering were used in computing various measures of roughness of the road sections studied. The use of these measures was demonstrated in comparing a sample of new pavements and a sample of old pavements and by comparing samples of new hot-mix asphalt-concrete and surface-treated pavements. Several interesting relationships involving the various components of roughness were obtained. It is felt that the potential of the methods presented in comparing pavements of different types and ages, as well as comparing pavement roughness immediately before and after maintenance, is great.

Further, the feasibility of predicting from the rouhness measurements certain classes of distress, such as the area of cracking or patching, was demonstrated by developing regression models which predicted large percentages (over 72 percent in all cases) of the road-to-road distress variations. The fact that the number of sections for which condition survey data were available is not large (20) and that the sections are all located in central Texas (all in Texas Highway Department District 14) should be considered before using the models. Moreover, the sections were all scheduled for maintenance at the time of the measurements, and, therefore, are not a random sample of Texas roads. It is felt, however, that the results fully justify further study in this area.

The following specific observations were made regarding the new versus deteriorated pavement comparison.

(1) The old pavements have greater roughness amplitudes (more severe roughness) than the new pavements. The difference in the severity is greater for isolated extreme roughness than for measures of overall roughness.

(2) The sample of old pavements studied is more diverse from road section to road section in its roughness than is the new sample. Both samples are more diverse with respect to isolated extreme roughness than with respect to overall roughness.

(3) For short wavelengths (0 to 1 foot), the amplitudes of the vertical movement of one wheel relative to the other (i.e., the vehicle

roll) are greater than the roughness amplitudes for longitudinal waves in either wheelpath. The opposite is true for longer waves.

For surface-treated (ST) versus hot-mix asphalt-concrete (HMAC) roads, the following points were made.

(1) As expected, the less expensive ST roads have more severe roughness and are more diverse than the HMAC roads. Each sample is more diverse with respect to isolated extreme roughness than with respect to overall roughness.

(2) The differences between the HMAC and ST roads are most pronounced for roughness with wavelengths less than nine feet. As the wavelength increases beyond nine feet, the two samples become increasingly similar.

(3) The transverse waves have greater amplitudes than the longitudinal waves for short wavelengths, but the reverse is true for long wavelengths.

In connection with the pilot study for predicting distress in terms of roughness measures, numerous relationships are discussed. The following observations, which apply to either the area of cracking and patching or the total area of distress, are among the most meaningful.

(1) For the 0 to 1-foot-long waves, the measurements of isolated extreme roughness are better predictions (of distress) than are measures of overall roughness.

(2) Except for the overall roughness measures for 0 to 1-foot-long waves, all roughness measures in the range 0 to 81 feet are related to distress to a statistically significant (i.e., measureable) extent. Measures of overall and extreme effects in both the longitudinal and transverse dimensions are included.

(3) The 81 to 180-foot-long longitudinal waves are much less clearly related to distress than the shorter waves.

(4) The 81 to 180-foot-long waves in the artificial profile computed by taking the vertical surface position in one wheelpath relative to that in the other wheelpath <u>are</u> related to distress. As discussed above, these transverse waves cause vehicle roll; thus they are related to road user comfort.

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APPENDIX 1

DESCRIPTION OF PROFILE MEASURING SYSTEM

APPENDIX 1. DESCRIPTION OF PROFILE MEASURING SYSTEM

The General Motors Surface Dynamics Profilometer (SDP) was used to collect road profile data for this study. The SDP is owned by the Texas Highway Department and is being operated by the Center for Highway Research.

The SDP is a special purpose van with equipment needed to measure the road surface elevation in the right and left wheelpaths versus distance along the road. Two non-inflated measuring wheels are mounted on trailing arms underneath the vehicle, one arm in each wheelpath. The wheels are held in contact with the road by a 300 lb. spring force. The motion of each wheel relative to the vehicle body is monitored by means of a potentiometer. An accelerometer is positioned in the truck above each measuring wheel; double integration of the accelerations yield the vertical position of the vehicle body in an earth-fixed coordinate system, which can be combined with wheel (i.e., road surface) position relative to the truck to obtain road-surface elevation in an earth-fixed coordinate system. Continuous monitoring of this quantity yields the road profile.

The above is a very simplified description. References 1 and 2 contain more detailed discussion of the measuring process.

APPENDIX 2

RELATIONSHIPS AMONG ROUGHNESS MEASURES

APPENDIX 2. RELATIONSHIPS AMONG ROUGHNESS MEASURES

Relationships among roughness measures are important since these measures are convenient predictors of panel serviceability ratings, and as noted previously, possibly of other distress measures. If it were known that the various percentile amplitudes were very highly intercorrelated for each given passband, or if the corresponding measures for two successive passbands were highly correlated, then perhaps the redundant measures should be omitted.

Thus, the correlations among the roughness measures for the deteriorated road sample are included here for future reference in research studies involving roughness characterization.

The full correlation matrix is given in Table A2.1. Specific elements from the full matrix are presented in Tables A2.2, A2.3, A2.4, and A2.5 in a format which illustrates several comparisons.

Although there are some high correlations, it is clear that there is a diversity of information among the various roughness measures. The very high correlations among corresponding longitudinal and transverse roughness measures for wavelengths under 27 feet are the most striking results.[1]

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[1] It was expected, however, that the correlation between corresponding roughness measures would decrease with wavelength. If two random variables are uncorrelated, their standard deviations determine the standard deviation of their difference. As the variables become increasingly ocrrelated, the covariance explains an increasing portion of the standard deviation of the difference.

TABLE A2.1. CORRELATION MATRIX FOR THE ROUGHNESS MEASURE

CORRELATION MATRIX

	R 50 1	R 90 1	R 99 1	R 50 2	R 90 2	R 99 2
VARIABLE NUMBER	1	2	3	4	5	6
	1.000	.954	.066	.680	.676	.540
		1.000	.249	.560	.574	.634
			1.000	-.022	.074	.688
				1.000	.993	.547
					1.000	.619
						1.000

(Continued)

TABLE A2.1. Continued

R 50 3	R 90 3	R 99 3	R 50 3	R 90 4	R 99 4	R 50 5	R 90 5
7	8	9	10	11	12	13	14
.475	.471	.241	.411	.449	.445	.387	.226
.385	.434	.426	.325	.414	.453	.302	.143
-.100	.268	.797	-.046	.231	.472	.054	.033
.728	.694	.167	.729	.752	.692	.685	.561
.707	.710	.237	.709	.773	.744	.682	.562
.374	.625	.732	.407	.599	.704	.427	.334
1.000	.908	.244	.861	.760	.611	.611	.476
	1.000	.538	.824	.811	.778	.573	.461
		1.000	.323	.439	.580	.215	.072
			1.000	.866	.661	.795	.637
				1.000	.905	.738	.674
					1.000	.573	.537
						1.000	.865
							1.000

(Continued)

TABLE A2.1. Continued

R 99 5	R 50 6	R 90 6	R 99 6	D 50 1	D 90 1	D 99 1	D 50 2	D 90 2
15	16	17	18	19	20	21	22	23
.247	.438	.272	.323	.995	.928	.017	.782	.480
.169	.319	.188	.236	.965	.995	.194	.715	.552
.041	.011	-.101	-.097	.059	.329	.998	.120	.748
.559	.532	.376	.415	.651	.525	-.049	.933	.597
.565	.549	.384	.421	.647	.549	.047	.938	.666
.338	.164	.071	.124	.524	.670	.663	.648	.896
.472	.311	.165	.211	.455	.356	-.122	.771	.482
.460	.293	.118	.173	.442	.435	.250	.759	.726
.081	-.105	-.158	-.116	.230	.483	.774	.324	.767
.616	.225	.243	.295	.379	.295	-.063	.753	.533
.681	.377	.259	.291	.425	.407	.212	.819	.742
.567	.440	.275	.306	.425	.476	.453	.755	.828
.842	.432	.533	.559	.358	.287	.040	.701	.563
.991	.465	.615	.626	.208	.138	.033	.521	.441
1.000	.491	.670	.683	.232	.166	.039	.521	.440
	1.000	.668	.635	.445	.327	-.000	.495	.288
		1.000	.993	.290	.196	-.109	.306	.120
			1.000	.337	.241	-.106	.348	.152
				1.000	.942	.009	.759	.453
					1.000	.276	.692	.590
						1.000	.085	.728
							1.000	.725
								1.000

(Continued)

TABLE A2.1. Continued

D 99 2	D 50 3	D 90 3	D 99 3	D 50 4	D 90 4	D 99 4
24	25	26	27	28	29	30
.158	.393	.366	.200	.382	.469	.402
.363	.325	.385	.407	.337	.460	.423
.830	-.084	.541	.764	.029	.307	.506
-.053	.645	.581	.069	.635	.752	.618
.031	.625	.625	.139	.617	.782	.674
.800	.329	.726	.670	.406	.629	.675
-.055	.943	.734	.156	.842	.727	.595
.254	.865	.936	.436	.811	.791	.764
.765	.261	.712	.982	.406	.469	.581
.007	.905	.738	.245	.959	.774	.583
.194	.791	.797	.341	.818	.967	.864
.330	.590	.816	.473	.599	.917	.964
.074	.653	.570	.161	.707	.673	.482
.033	.534	.466	.018	.504	.604	.445
.032	.519	.459	.027	.466	.611	.465
-.218	.302	.274	-.119	.148	.484	.482
-.187	.179	.086	-.164	.070	.233	.141
-.152	.212	.128	-.130	.113	.249	.154
.161	.378	.335	.200	.355	.454	.387
.428	.302	.412	.467	.314	.465	.453
.817	-.104	.528	.738	.011	.284	.487
.122	.718	.676	.229	.715	.837	.706
.654	.475	.865	.680	.552	.785	.816
1.000	-.031	.461	.766	.082	.224	.344
	1.000	.754	.202	.909	.760	.588
		1.000	.625	.752	.803	.820
			1.000	.341	.386	.491
				1.000	.756	.568
					1.000	.924
						1.000

(Continued)

TABLE A2.1. Continued

D 50 5 31	D 90 5 32	D 99 5 33	D 50 6 34	D 90 6 35	D 99 6 36
.504	.320	.397	.310	.200	.223
.442	.264	.348	.191	.117	.149
-.004	.205	.284	-.226	-.015	.057
.708	.562	.632	.483	.336	.359
.705	.584	.669	.457	.330	.363
.439	.427	.520	.024	.062	.126
.532	.387	.408	.572	.501	.489
.452	.384	.440	.444	.466	.475
.166	.179	.218	-.036	.111	.148
.693	.505	.468	.551	.400	.383
.663	.615	.703	.329	.252	.280
.490	.519	.674	.220	.222	.271
.938	.856	.772	.620	.477	.484
.770	.782	.737	.412	.420	.432
.744	.757	.735	.376	.399	.413
.515	.580	.675	.556	.519	.564
.528	.464	.450	.451	.379	.380
.539	.448	.436	.448	.371	.369
.492	.297	.376	.300	.184	.207
.424	.273	.360	.180	.132	.169
-.031	.195	.271	-.238	-.018	.053
.732	.606	.685	.503	.356	.387
.515	.586	.669	.191	.251	.315
.073	.148	.185	-.287	-.149	-.095
.582	.446	.433	.631	.551	.536
.443	.462	.512	.371	.451	.481
.152	.147	.168	-.044	.102	.135
.633	.473	.418	.556	.425	.410
.650	.640	.761	.346	.281	.325
.433	.516	.686	.215	.242	.300
1.000	.873	.801	.627	.427	.443
	1.000	.948	.546	.517	.558
		1.000	.418	.399	.460
			1.000	.864	.845
				1.000	.994
					1.000

TABLE A2.2. CORRELATION MATRICES FOR 50, 90, 99th PERCENTILE AMPLITUDES

Wavelengths (feet)	Percentile					
	Longitudinal			Transverse		
	50	90	99	50	90	99
0 to 1	1.000	.954	.066	1.000	.942	.009
		1.000	.249		1.000	.276
			1.000			1.000
3 to 9	1.000	.908	.244	1.000	.754	.202
		1.000	.538		1.000	.625
			1.000			1.000
27 to 81	1.000	.865	.842	1.000	.864	.845
		1.000	.991		1.000	.994
			1.000			1.000

TALBE A2.3. CORRELATIONS BETWEEN CORRESPONDING LONGITUDINAL AND TRANSVERSE ROUGHNESS MEASURES

Wavelengths (feet)	Percentile		
	50	90	99
0 to 1	.995	.995	.998
1 to 3	.933	.666	.800
3 to 9	.943	.936	.982
9 to 27	.959	.967	.964
27 to 81	.938	.782	.735
81 to 180	.556	.379	.369

TABLE A2.4. CORRELATIONS BETWEEN CORRESPONDING ROUGHNESS MEASURES FOR 0 to 1-FOOT WAVELENGTHS AND 1 to 3-FOOT WAVELENGTHS

Roughness Measure	Correlation
50th Percentile, longitudinal	.680
90th Percentile, longitudinal	.574
99th Percentile, longitudinal	.688
50th Percentile, transverse	.759
90th Percentile, transverse	.590
99th Percentile, transverse	.817

TABLE A2.5 CORRELATIONS BETWEEN CORRESPONDING ROUGHNESS MEASURES FOR 3 to 9-FOOT WAVELENGTHS AND 9 to 27-FOOT WAVELENGTHS

Roughness Measure	Correlation
50th Percentile, longitudinal	.861
90th Percentile, longitudinal	.811
99th Percentile, longitudinal	.580
50th Percentile, transverse	.909
90th Percentile, transverse	.803
99th Percentile, transverse	.491

APPENDIX 3

ILLUSTRATION OF THE DIGITAL FILTERING CONCEPT

APPENDIX 3. ILLUSTRATION OF THE DIGITAL FILTERING CONCEPT

Digital filtering can be used to isolate for further analysis a particular part or aspect of the roughness represented in a measured road profile. An artificial profile, which has the roughness characteristics of interest, is calculated mathematically from the measured profile.

A test section on the Old San Antonio Road near Bryan, Texas, was chosen because of its interesting roughness patterns. The two-lane surface-treated road is quite rough; there are both long waves, which are caused at least in part by a swelling subgrade, and short waves.

The isolation of roughness with 0 to 10-foot wavelengths is illustrated in Fig A3.1. Isolation of 60 to 100-foot-long waves is demonstrated in Fig A3.2. Notice especially the pronounced long waves present in both the measured and the filtered profiles in frame 2 of Fig A3.2.

Because of the presence of roughness with a wide range of wavelengths, it is sometimes very difficult to filter "by eye" to see what should and should not be present in the filtered profile. This is especially true when one bump actually involves a range of wavelengths; see, for example, the V-shaped fall and rise at about position 330 feet in Fig A3.1. Nevertheless, close examination of the plots definitely shows that the filter is capable of isolating the desired information.

A sixth-order filter specified by the tangent form of the squared-magnitude approximating function was used in this study (Ref 6).

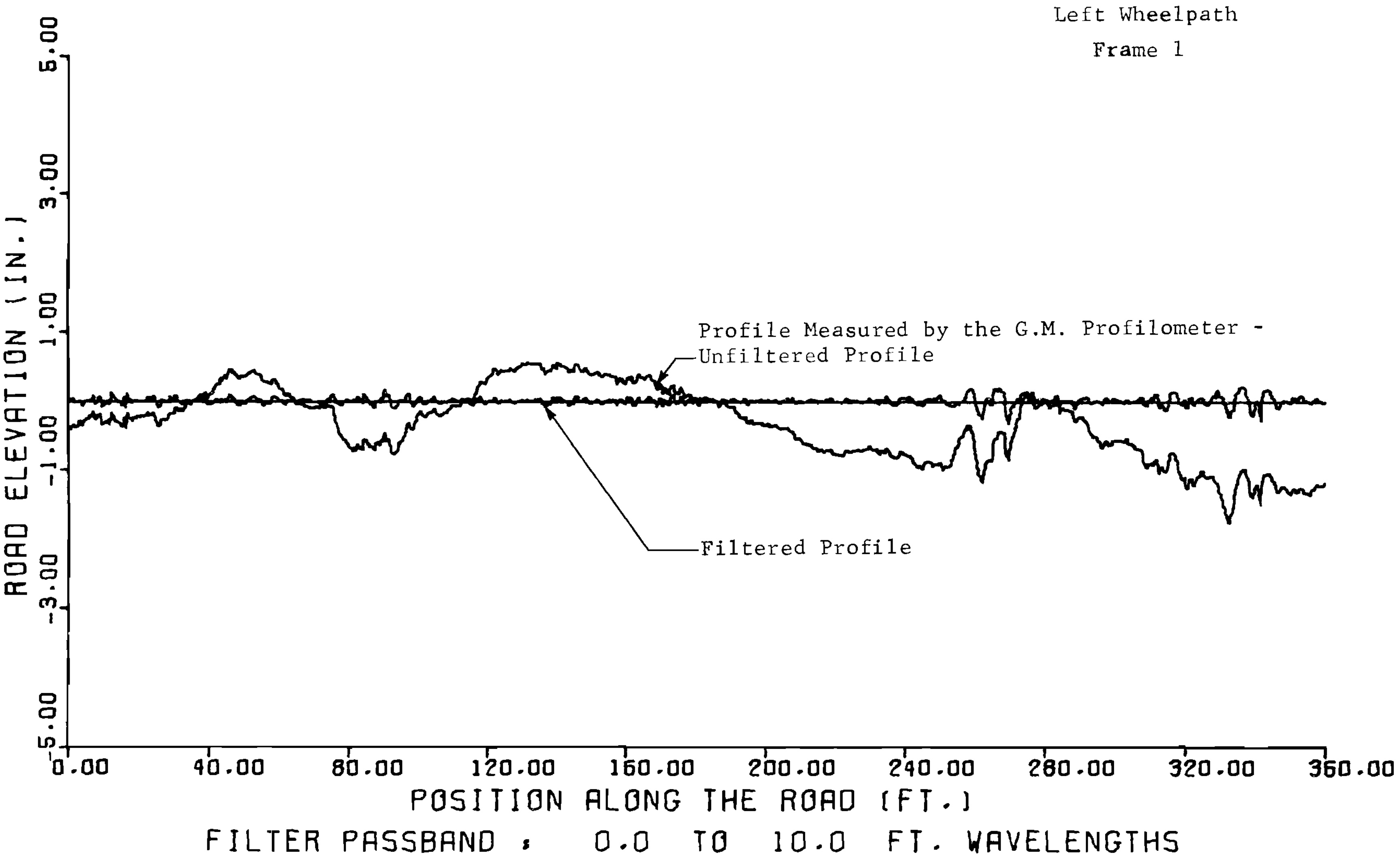

Fig A3.1. Old San Antonio Road: roughness with 0 to 10-foot wavelengths isolated by filtering.

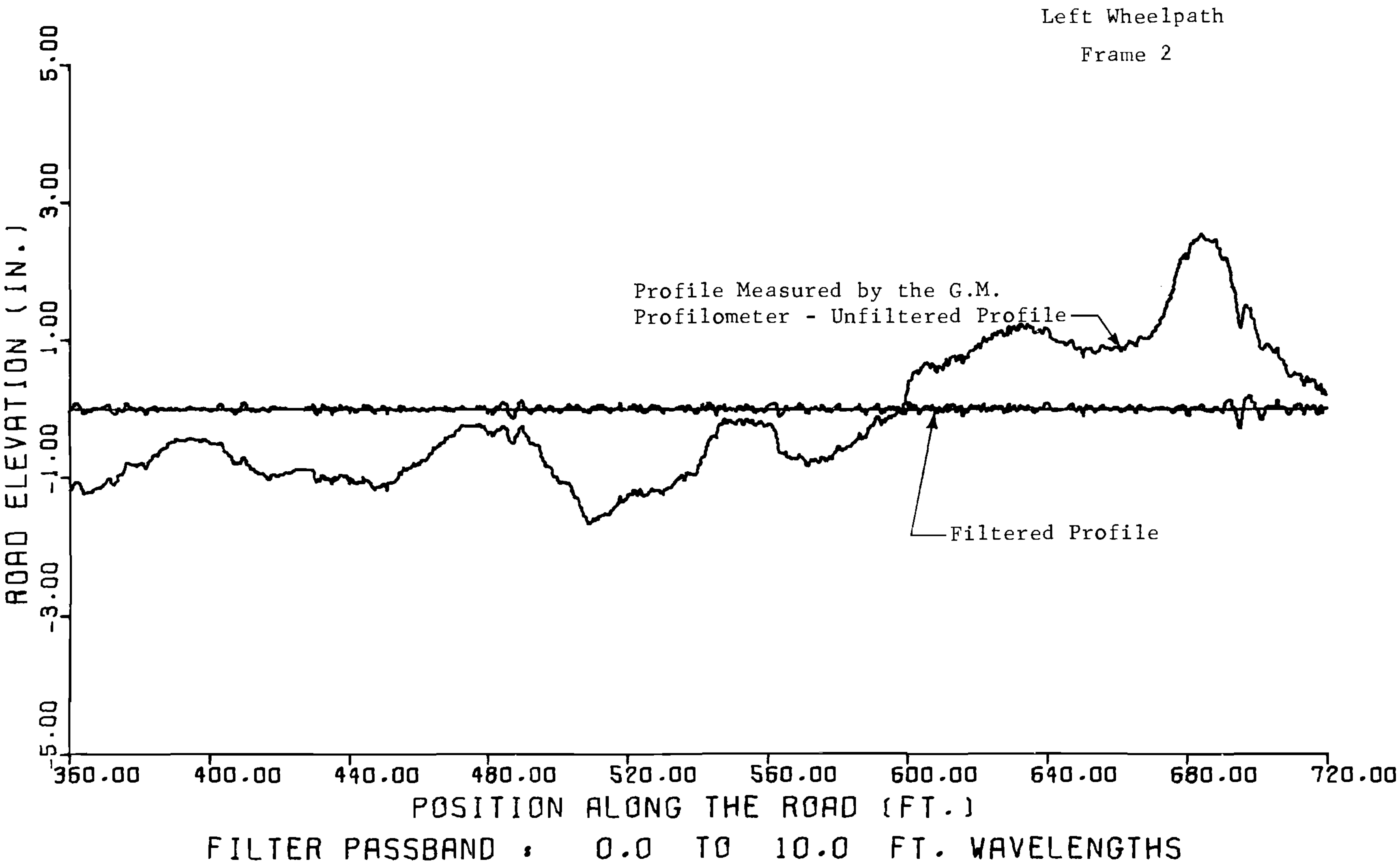

Fig A3.1. (Continued)

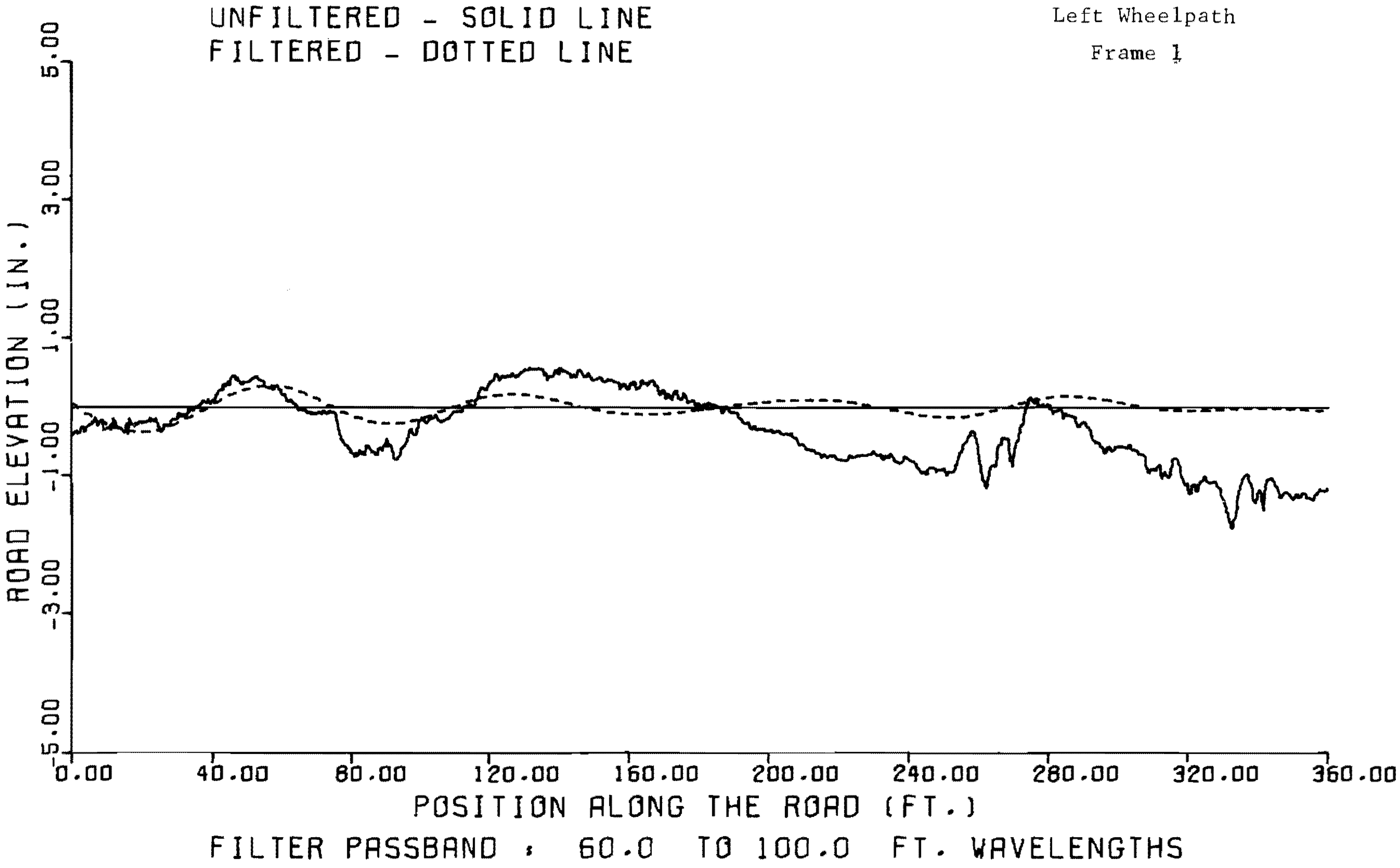

Fig A3.2. Old San Antonio Road: roughness with 60 to 100-foot wavelengths isolated by filtering.

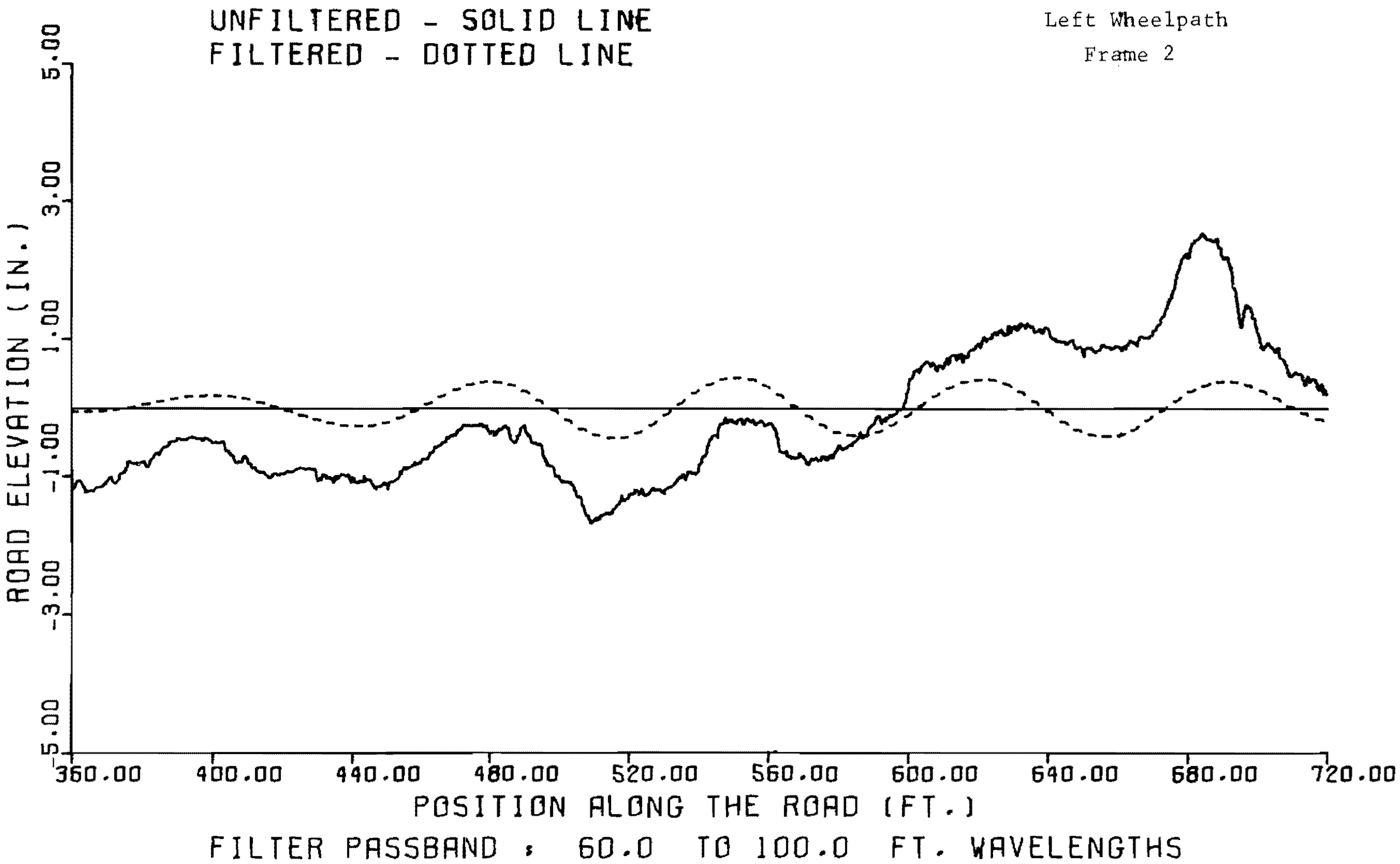

Fig A3.2. (Continued)

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