EVALUATION AND APPLICATION STUDY OF THE GENERAL MOTORS CORPORATION RAPID TRAVEL PROFILOMETER

OCTOBER 1970

MICHIGAN
DEPARTMENT OF STATE HIGHWAYS

EVALUATION AND APPLICATION STUDY
OF THE GENERAL MOTORS CORPORATION
RAPID TRAVEL PROFILOMETER

J. R. Darlington

Final Report on a Highway Planning & Research Investigation
Conducted in Cooperation with the U. S. Deparment of Transportation
Bureau of Public Roads

Research Laboratory Section
Testing and Research Division
Research Project 62 F-73
Research Report No. R-731

Michigan State Highway Commission
Charles H. Hewitt, Chairman; Wallace D. Nunn, Vice-Chairman;
Louis A. Fisher; Claude J. Tobin; Henrik E. Stafseth, Director
Lansing, October 1970

INFORMATION RETRIEVAL DATA

REFERENCE: Darlington, J. R. Evaluation and Application Study of the General Motors Corporation Rapid Travel Profilometer. Michigan Department of State Highways Research Report No. R-731. Research Project 62 F-73.

ABSTRACT: In addition to evaluation of the General Motors Rapid Travel Profilometer (RTP), this paper provides important information about the device and its output. Details of the measurement system itself are limited; having been covered in an earlier report by the General Motors Corporation. It is shown that the RTP measures profile with respect to an arbitrary and moving reference. Consequences of this property are explored and found to be no problem when properly accounted for. Accuracy, defined with regard to this reference, is found to be very high when RTP and precise level profiles are compared. RTP accuracy is also shown to be theoretically superior to that for rolling straightedges, BPR roughometers, and CHLOE profile devices. A survey of profile analysis equipment preceeds a discussion of powerful analysis options made possible by magnetic tape data recording. All methods of profile analysis are examined, including simulation of other profile devices to obtain their indices from RTP profiles. Particular emphasis is given to modern time series methods of random signal analysis, the most powerful of which appear to be Power Spectral Density measures. The Department has used this instrument, among other things, to: study 24-hr slab movement, record actual slab curling; study cross-section profiles of joint blowups; compare bridge deck finishing methods; profile experimental pavements; profile airport runways, etc.

KEY WORDS: profilometers, analysis, data systems, data sampling, road surfaces.

CONTENTS

Page

CONTENTS (Cont.)

I
INTRODUCTION

In February 1963, the Research Laboratory of the Michigan Department of State Highways submitted a proposal to the Bureau of Public Roads under the Highway Planning and Research Program, to "...determine the accuracy, reliability and applicability to routine highway testing of the General Motors Rapid Travel Road Profilometer, and having done so attain the best possible instrumentation system for this purpose..." The specific objectives cited were to "...thoroughly scrutinize all elements of the system with the intent of discovering any inherent inaccuracies or limitations...procure and assemble all mechanical and electronic components of the measuring and data processing system...establish calibration, field test and data processing procedures...execute an extensive and intensive field testing program for determining all those factors pertinent to the system, i.e., repeatability, accuracy, test speed limitations, measurable wavelength limitations, etc. ...resolve any and all problems arising as a result of the field test program...to write complete specifications on the finally evolved and evaluated system and make a cost analysis."

The proposal was subsequently approved by the Bureau and the Laboratory procured the necessary components and assembled a system identical to the GM unit. The GM device was still under development when the proposal was submitted, but it had evolved sufficiently to demonstrate its potential as the first practical, accurate, high-speed road profilometer. A very brief description of the system is included here since details are provided by Spangler and Kelly (1).

Relatively direct methods were used to determine accuracy and reliability so these aspects do not occupy a great deal of this report. Applicability of the system to highway work is another matter and requires understanding of the RTP itself, as well as re-examination of traditional profile analysis. Much of the report deals with these matters. In response to many inquiries about the system, specific aspects of profile analysis, field operations, and special equipment are covered. It is hoped the report can thereby function as a teaching aid and operational handbook.

There are very few traditional methods of profile analysis beyond visual inspection or direct measurements from a graph such as pot hole depth.

Inches per mile and slope variance are the major current measures. There are, in fact, only a few modern methods of analyzing the random signal known as profile. Development of these methods began around 1958 to enable rational analysis of random signals. To quote from page 13, reference (2); "Four main types of statistical functions are used to describe the basic properties of random data: (a) mean square values, (b) probability density functions, (c) autocorrelation functions and (d) power spectral density functions." These four categories allow classification of traditional roughness measures. Inches per mile is found to fit no standard classification and is in fact, an undefined measure. This measure is not supported by signal measurement theory even though it may correlate with subjective ride quality or various objective measures. Slope variance is classifiable under mean square values, and is a rudimentary measure of average intensity for the profile's first derivative. Neither measure provides any information about average intensity in a given wavelength band. This is vital information since it relates roughness to specific profile features. There is, for instance, no way to determine the cause of a high inches per mile or CHLOE count. It could be due to misalignment of paving forms, poor finishing, cracked slabs and so forth. Furthermore, traditional measures provide no measure of intensity for wavelengths known to cause bad riding qualities. In addition, of course, current instruments used to produce the traditional roughness measures "see" a distorted version of the actual profile.

Power spectral density (PSD) alone, of the four available measures, supplies average intensity of the profile in given wavelength bands. For this reason PSD is said to completely characterize the random process. It will show intensities of profile in selectable wavelength bands that are directly related to actual profile features. The RTP lends itself perfectly to this type of analysis since an undistorted profile is recorded on magnetic tape and because vital filtering functions are performed. One chapter of this report is devoted to these analysis methods since they are now feasible and appear very promising.

Throughout the report extensive use is made of a viewpoint adopted in fields dealing with fluctuating signals. Whether these be stock market trends or random radio noise from space they are treated in what is called the frequency domain. This is a viewpoint from which moving profilometers and vehicles are described by their response to frequencies induced by the profile. Descriptive units would be cycles or radians per second. Profiles in this domain are seen as random signals with specific statistical properties. Units would be cycles or radians per foot. Profiles can be analyzed in the frequency domain as explained previously and in references (2, 3).

It will aid the reader to bear in mind the relationship between profile wavelength, vehicle speed, and induced frequencies. For example, a 20-ft wave traversed at 60 mph will produce a 4.4 cps signal while the same wave traversed at 30 mph induces a 2.2 cps signal.

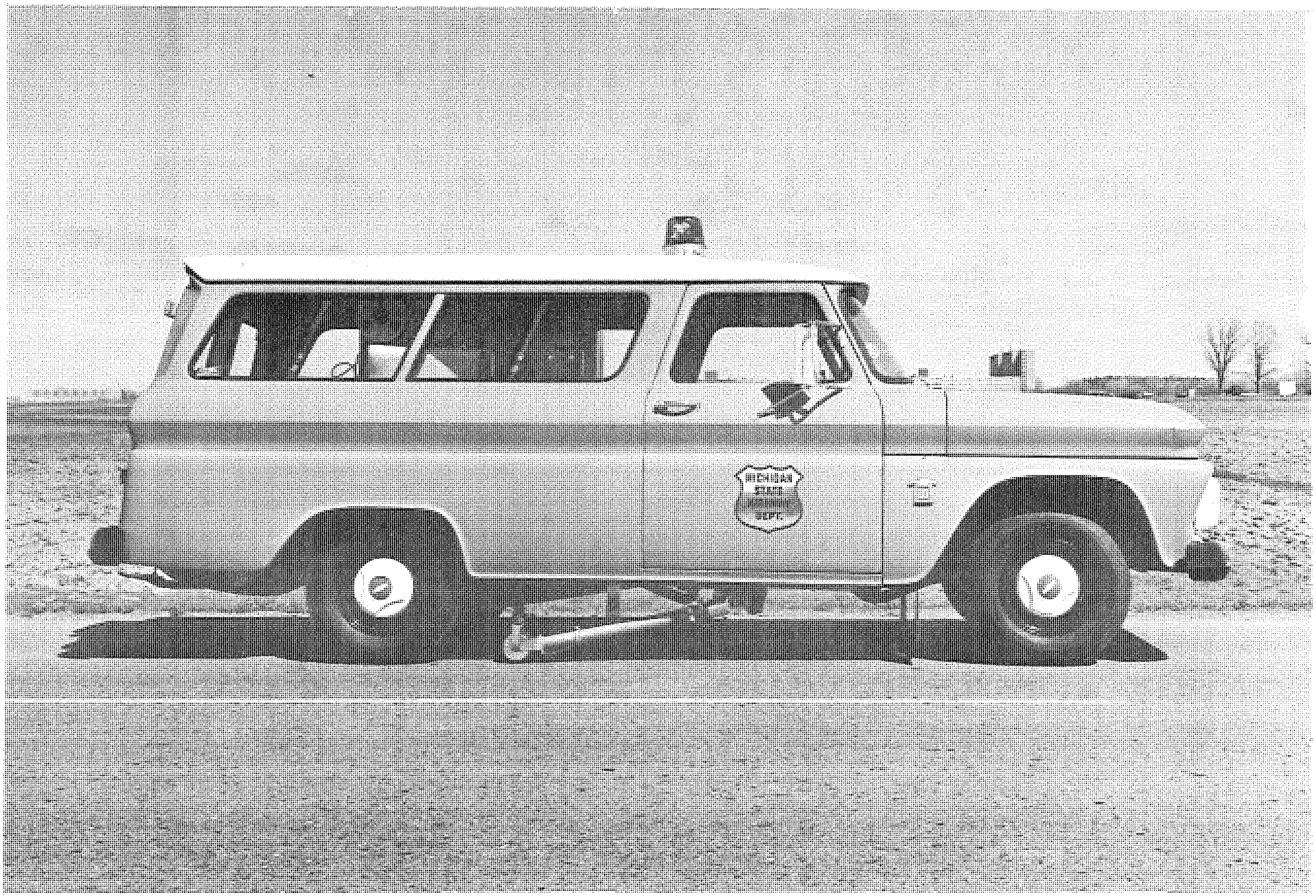


Figure 1. Michigan's GMR-type Rapid Travel Profilometer.

II
RAPID TRAVEL PROFILOMETER

For the benefit of readers unfamiliar with the RTP a brief and greatly simplified system description follows.

Figure 1 shows Michigan's version of the General Motors RTP. It consists of a small truck with a spring-loaded pavement follower-wheel mounted underneath. A linear potentiometer is connected between the follower-wheel axle and truck body to measure distance between body and roadway. An accelerometer secured to the truck body directly over the follower-wheel senses vertical motion of the body. Each transducer senses two components of motion. The follower-wheel picks up body bounce and changes in surface elevation that occur too rapidly to move the entire system as a unit. The accelerometer picks up body bounce and elevation changes that occur slowly enough to move the entire system as a unit. Acceleration data are then integrated twice to produce a displacement signal. When follower-wheel and accelerometer displacement signals are summed the result is a road surface profile. Body bounce is cancelled since it appears with equal magnitude but opposite polarity in each signal. It is evident that long waves such as grade elevation changes, are picked up by the accelerometer and short waves such as surface irregularities by the follower-wheel; vehicle characteristics are cancelled out by this process.

A photocell beneath the truck picks up changes in reflected light from a small floodlamp aimed at the pavement. Signals from the cell can be recorded and used later to identify pavement features such as joints, cracks, or markers. Another device, working from the speedometer cable, provides a distance marker signal and a vehicle speed signal.

System control is centered in a monitor box package which provides transducer calibration, signal routing, power control, and other necessary functions. In addition, an optional analog computer package can convert transducer signals to profile which can be recorded on magnetic tape in the vehicle. Transducer signals can also be recorded directly and processed later in a laboratory based analog computer. The second alternative permits greater flexibility in processing and utilizing the profile for further analysis.

III
PROFILE REFERENCE CONSIDERATIONS

Purpose of Discussion

The phrase "faithful reproduction of the profile" refers to a true elevation profile as determined by a precise level and rod. The survey reference from which that profile is measured is an infinite plane at right angles to gravity and located at the instrument. The RTP, however, uses a reference plane which is not only placed arbitrarily with respect to gravity but which slowly changes position as the roadway is traversed. This problem has raised a number of questions and has produced inquiries from potential RTP users. Although the problem is implicitly covered by mathematical analysis of the system in reference (1), no intuitive grasp of the situation is gained. The problem was of no consequence to the original developers since they did not use RTP profiles in a geometrical sense as is often done in highway work. Thorough understanding of this matter is essential since accuracy and use of the RTP for highway work must be defined with respect to its reference.

It is important to note that the RTP profile reference is established when raw signals from the transducers are processed. Up to the processing point, the transducer signals do contain information from which a precise level profile could be obtained. Reasons for not producing this type of profile will be explained later.

Current Reference Planes

Establishment of a reference plane from which to measure a road profile has been the major problem confronting designers of profile devices (4). Of the many attempts to solve this problem only a lightbeam device, developed some years ago, actually established a survey reference plane over short distances (4). Unfortunately the device was cumbersome and required placement of a collimated lightbeam aimed at the profilometer from one end of the test section.

Only two methods of reference establishment are in widespread use (4). These are the rolling straightedge in various forms and the inertial mass as used in the BPR Roughometer. Results of a brief analysis of these devices appear in Figure 4. The plots show that straightedge devices fail to faithfully record any band of profile wavelengths. The analysis is based on simple profilometers with single bogey wheels; it is doubtful if significant improvement results from complex bogey wheel arrangements. The basic problem still remains, that the reference is dependent on the profile and will change continuously. Analysis of the CHLOE shows that straightedges do a better job when measuring the profile's first derivative instead of elevation. This is largely a result, however, of the nature of the first derivative. Error would be reintroduced if the CHLOE trace were continuously integrated to recover the elevation profile.

Figure 4 also shows results of an analog computer analysis of a typical BPR Roughometer. It is apparent that only wavelengths from approximately 6 to 12 ft are recorded with reasonable fidelity. Wavelengths outside this region are distorted or lost, due again to a rapidly changing reference. Further explanation of the analysis presented in Figure 4 appears in the section Theoretical Accuracy under the ACCURACY STUDIES Chapter of this report.

The Theoretical RTP Reference Plane

A perfect accelerometer, if available, would produce some output for any motion, no matter how small. This output could be double-integrated to produce a displacement signal which would appear as a voltage above or below a zero frequency, hence steady level of zero volts dc. In effect, this "d-c level" represents a true survey reference plane established in space where the accelerometer was located when first switched on. Establishment of such a reference by the RTP is limited only by quality and sensitivity of its accelerometer. Thus, within reasonable limits, it can be stated that signals recorded from the accelerometer and follower-wheel contain information which can yield a "true" survey profile. This profile would include all hills and valleys measured with respect to the zero frequency, zero volts accelerometer reference.

Need for Filtration and Its Effect on the Theoretical Reference

Presence of long, hence low frequency, hill and valley waves in the final profile is not desirable for three important reasons. The first reason is not due to properties of the equipment but is concerned with wavelength content of the final profile. Wavelengths of more than 200 ft have very little effect on ride quality even when amplitudes are relatively high. Therefore, any study involving ride quality does not need, and may even be harmed by, such data. The second problem involves the analog computer used to process transducer signals and the medium on which processed profile is recorded. This is the matter of scaling. Most longwave components of any profile are also of great amplitude. If the computer and output medium are scaled to accommodate these waves there will be very little surface detail visible. On the other hand, scaling for surface details will cause overloading of the computer and output medium when high amplitude longwaves are encountered. This problem arises because road profiles generally have a very high dynamic range. In terms of signal theory this would be termed a great spread in decibels (db) between surface details and general elevation changes. The third problem arises because the accelerometer signal is unavoidably contaminated with very low frequency noise. This noise arises from drifts in the electronic equipment and tilts of the accelerometer from a true vertical during a run. These components in the accelerometer signal are strongly amplified by the process of double integration. Specifically, the amplitude of any double integrated signal is multiplied by $\frac{1}{4\pi^2 f^2}$ and as f (frequency) goes to zero this factor gets infinitely large. If these low frequency components are not removed the analog computer soon overloads. This problem is most restrictive of the three since it determines the longest wave that can be faithfully recorded.

These problems require removal of longwave (low frequency) components from the transducer signals at processing time. This is accomplished by a third-order high-pass filter which is made part of the double integration performed on the analog computer. The process is actually one of double integrating the accelerometer signal, summing this with the follower-wheel signal and subjecting both to simultaneous filtration. The filter passes all information above a selected frequency and attenuates lower frequencies at a rate of 60 db per frequency decade. Thus, as frequency goes down (increasing wavelength), the filter attenuates more strongly. This is also true for the zero frequency "d-c level" that would have formed a survey type reference for the unfiltered profile. It is the filter which destroys the true survey reference plane inherent in the raw accelerometer signal. The remainder of this chapter resolves the question; with respect to what reference is the filtered profile measured ?

A Mechanical Equivalent of the Filter

As stated previously, mathematical analysis of filter action does not provide an intuitive grasp of the manner in which it inserts its own reference. Direct insight is gained if the filter, wired up on the analog computer, is viewed as a mathematically equivalent mechanical system traversing the actual roadway. The RTP and its transducers play no part because they do no more than bring a "true" profile to the filter. The filter is, in a real sense, the actual profilometer.

A simplified version of the filter model would be similar to current seismic roughometers such as the BPR unit but with two important differences. First, mass of the analogous frame would be very high, typically 6,400 lb. Second, the analogous spring supporting this mass would have a rate of only 20 lb per ft. The mass would fall 320 ft merely coming to equilibrium with the spring! This particular combination would have a natural period of approximately 20 seconds. General Motors investigators chose a damping factor of 50 percent critical damping and this can be considered inherent in the spring. Mass, spring rate, and damping are adjustable on the computer allowing complete freedom in choice of filter characteristics. Clearly, a profilometer such as this could be synthesized only on the analog computer.

The model described is a second-order system which attenuates less sharply than the standard third-order filter; however, it behaves similarly and facilitates explanation. It is helpful to visualize the model as a very heavy mass supported by a very weak spring. The lower end of the spring is attached to a single small wheel that rolls along the roadway. Distance between the wheel and mass is recorded as filtered profile. Properties of the filter reference are now easily explained in terms of the filter model and are covered in the next five sections.

Definition of Linear Reference

As the model rolls along, shortwave features will be measured faithfully since plus and minus excursions of the wheel would occur too rapidly for the mass to respond. Also, long waves will be filtered out since they tend to move the entire model as a unit, resulting in little relative displacement between wheel and mass. It is apparent that the profile is measured with respect to position of the mass which forms an arbitrary reference plane. Moreover, the road profile will excite the system to oscillation near its natural frequency thus continuously changing the reference plane. This is the objection to current seismic highway profilometers. The filter model removes this objection because of its very low natural frequency. This permits a standard definition for the longest wavelength in a filtered profile that has a linear reference. It is that wavelength for which movement of the analogous filter mass can be considered linear. This wavelength will be roughly one-tenth as long as the longest wave passed by the filter without attenuation. Since the filter mass moves so slowly this can be a relatively long distance; typically 100 ft. This distance is in marked contrast to that for even the best standard profilometers; typically 1 to 6 ft.

Choice of RTP speed and analog filter frequency determine the longest wave passed and hence the longest wave recorded with respect to a linear reference. (i.e., one-tenth the longest wave passed). As a consequence, any piece of measured profile equal to or less than one-tenth the longest wave passed has a linearly rising or falling ramp voltage as its reference. It is helpful to think of the reference as a long straightedge at some arbitrary angle and location from which a segment of roadway is measured. The next segment, even if overlapping almost all of the previous piece, has a slightly different reference angle and location. Figure 2 illustrates these properties by showing filter model behavior under typical conditions.

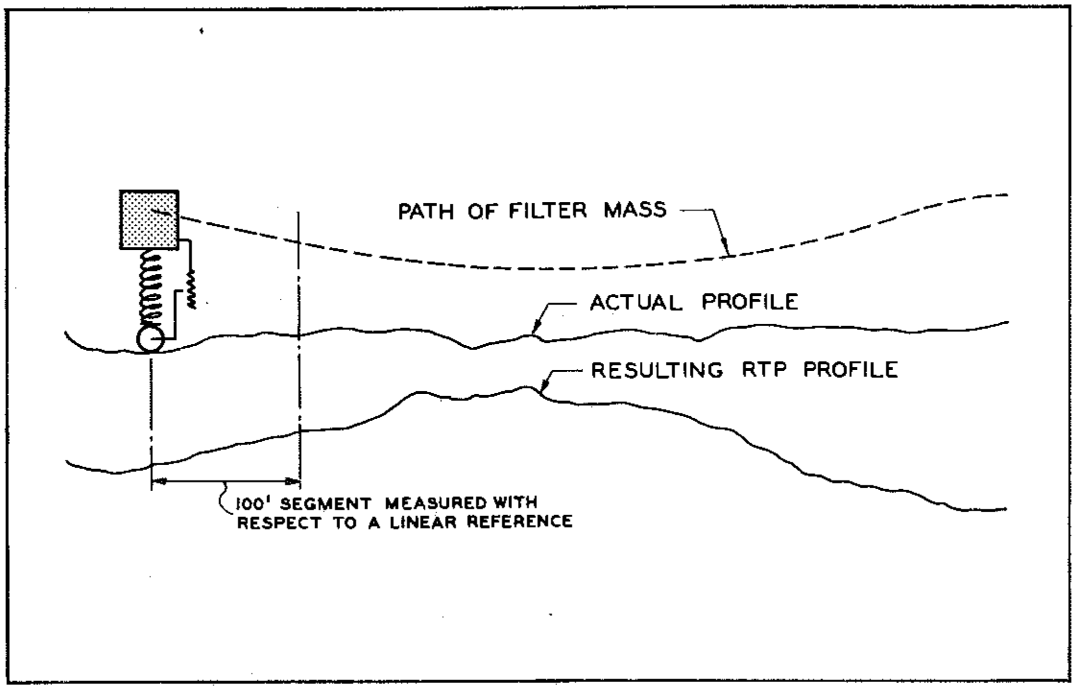


Figure 2. Effects of the changing filter reference and a typical segment for which reference change is considered linear.

Phase Shift and Attenuation

Waves longer than approximately one-tenth the maximum passed by the filter begin to appear ahead of their actual position in the roadway and reduced in amplitude. This phase lead builds to about 90 degrees for the longest wave passed by the filter. Such phase lead and attenuation is readily explained by considering filter model behavior when encountering a long sinusoidially shaped hill. The small wheel would initially rise toward the mass, accurately measuring the initial slope. As the wheel continued to rise it would hold the spring compressed against the mass. Soon the mass would respond to increasing spring pressure and begin to rise. This would open the distance between wheel and mass causing measured amplitude of the hill to fall below the actual. The mass, having been set in motion, would continue to move upward as vertical rise of the wheel slowed near the wave crest. Thus, closure between wheel and mass would reach a maximum before the wheel reached the actual peak. Maximum closure is recorded as maximum height of the hill. It is clear that this occurs before the actual hilltop is reached. Figure 3 illustrates this behavior for an idealized profile.

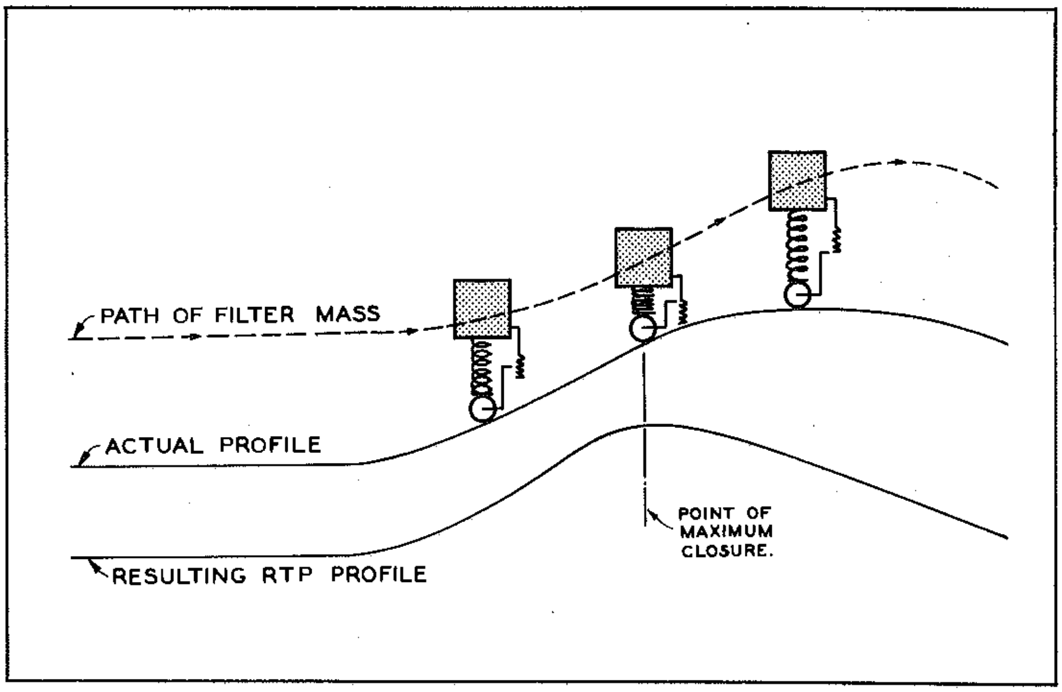


Figure 3. Filter induced phase lead illustrated by the model.

Profiles Run in Opposite Directions

Clearly, position and motion of the analogous reference mass at a given time is a function of all profile previously encountered on the run. Thus, position and motion of the filter mass would differ when arriving at a given region from opposite directions. This generates the seeming paradox that two different but equally valid profiles can be obtained by running a test section in opposite directions. Each profile is simply measured with respect to different instantaneous reference position and motion.

Pre-Test Stabilization

Another problem readily explained in terms of the filter model is the need for a stabilizing approach run whenever a profile is taken. Vehicle accelerations causing wide swings in the acceleration signal would appear, during profile processing, as violent oscillations of the analogous filter mass. To prevent this, a short run ahead of the test section allows these perturbations to fade. Duration of stabilization run required varies inversely with filter frequency and is thus reducible by proper filter choice. A typical pre-run with a 0.3 radian per second filter frequency might be 500 ft. At 1.0 radian per second, 100 ft would suffice. In any event, when recording raw data for later analysis, the longest pre-run consistent with possible filtration choices should be used. It should be noted that profiles recorded after a short pre-run would still be accurate, they would merely be measured with respect to a rather unsettled filter reference. This would cause overloading of the computer or recorder not scaled for such large signals.

Reference Changes

For most applications the arbitrary filter reference is adequate and even desirable. This is true when analysis does not need or must not contain waves longer than some predetermined maximum. All shorter wavelengths will be retained and measured with respect to the piecewise linear reference. It is possible, however, to reorient the entire RTP profile piece by piece to any other reference desired. Each piece should be roughly one-tenth the maximum wavelength passed by the filter so that it will have a linear reference. Reorientation is accomplished by remeasuring each segment of profile with respect to a "correcting reference" which is actually another linear reference. Each correcting reference is tailored to bring end points of the RTP profile segment to predetermined elevations. In practice this "tipping" operation consists of summing a unique linear ramp with each profile segment on the analog or digital computer. Elevation and tilt of each ramp are determined by a simple calculation involving the RTP profile and the desired end point elevations of each profile segment. This process also restores longwave components to their proper position and amplitude including those that have been phase shifted and partially attenuated.

Two important applications of this technique arise in practice. One is reorientation of RTP profiles to a "true" survey reference. In this case precise level shots might be required every 100 ft for example. The second application occurs when comparing runs made at different times on the same test section. Such runs will have different arbitrary references. In this case the first profile taken might be considered the standard and all subsequent runs adjusted to match its arbitrary reference.

There are at least three cases in which error may arise in the tipping process.

First, there may be failure to insure that the segment of RTP profile being tipped terminates at the exact points where the level shots were taken. This can be avoided by taking level shots at points where reflective markers have been placed on the pavement. The RTP photocell pickup will then provide a marker pulse at each point surveyed.

The second case arises when tipping one profile to match the arbitrary reference of a previous profile. There may be an actual difference in end point elevations due to changes in the pavement. This problem can be particularly troublesome if profiles from different paths on the same road are to be compared. Attempts to tip the profile from one path to match the arbitrary reference of the other are not valid if the end points of segments from the two paths actually have different elevations.

The third case is more serious and is due to the phase shift previously discussed. A longwave feature may be shifted into a segment to be tipped thus distorting the final fit. Fortunately the longest waves, which are shifted most, will merely insert another essentially linear trend into the segment. Both this trend and the arbitrary reference will be removed by the tipping process. Nevertheless, under certain conditions the tipped segment may not conform exactly to the original profile because of this problem. A solution to the problem may lie in choosing a type of profile processing filter that produces minimal phase shift. This possibility is considered in Chapter VI.

IV
ACCURACY STUDIES

Discussion

Since the RTP returns a filtered version of the actual profile, statements about its measuring ability must be restricted to those wavelengths passed by the system without change in amplitude. A range of frequencies passed without amplitude change is known as a region of flat frequency response. The section below compares the flat frequency response curve of the RTP with those for current profile and roughness devices. Since these other devices have very restricted flat regions or none at all, there is no point in attempting to compare RTP accuracy with theirs. Subsequent sections will explore the two traditional properties of all measuring devices, namely precision (or resolution) and accuracy for those wavelengths in the RTP passband.

Frequency or Wavelength Response

In theory, a profilometer of the RTP type should exhibit accuracy superior to that of current profile and roughness devices. This is due to its flat, extended frequency response range which is limited at the high end by size (6 in.) of the measuring wheel and at the low end by quality of the electronic equipment. Accuracy of the system is unaffected by vehicle properties since they are cancelled out during profile computation. Wavelengths from 3 in. to 1,200 ft have been successfully measured and reproduced with the RTP during this study.

Figure 4 illustrates the superior response of the RTP by means of Bode plots. These are plots in which the ratio of output to input is plotted on the vertical scale against frequency or, in this case, wavelength on the horizontal scale. They provide an immediate sense of which frequencies are attenuated or amplified by the system under investigation. If the output and input were equal at all times, the ratio would be 1.0 and there would be no error at any frequency. This is the case for the RTP over the range of wavelengths given.

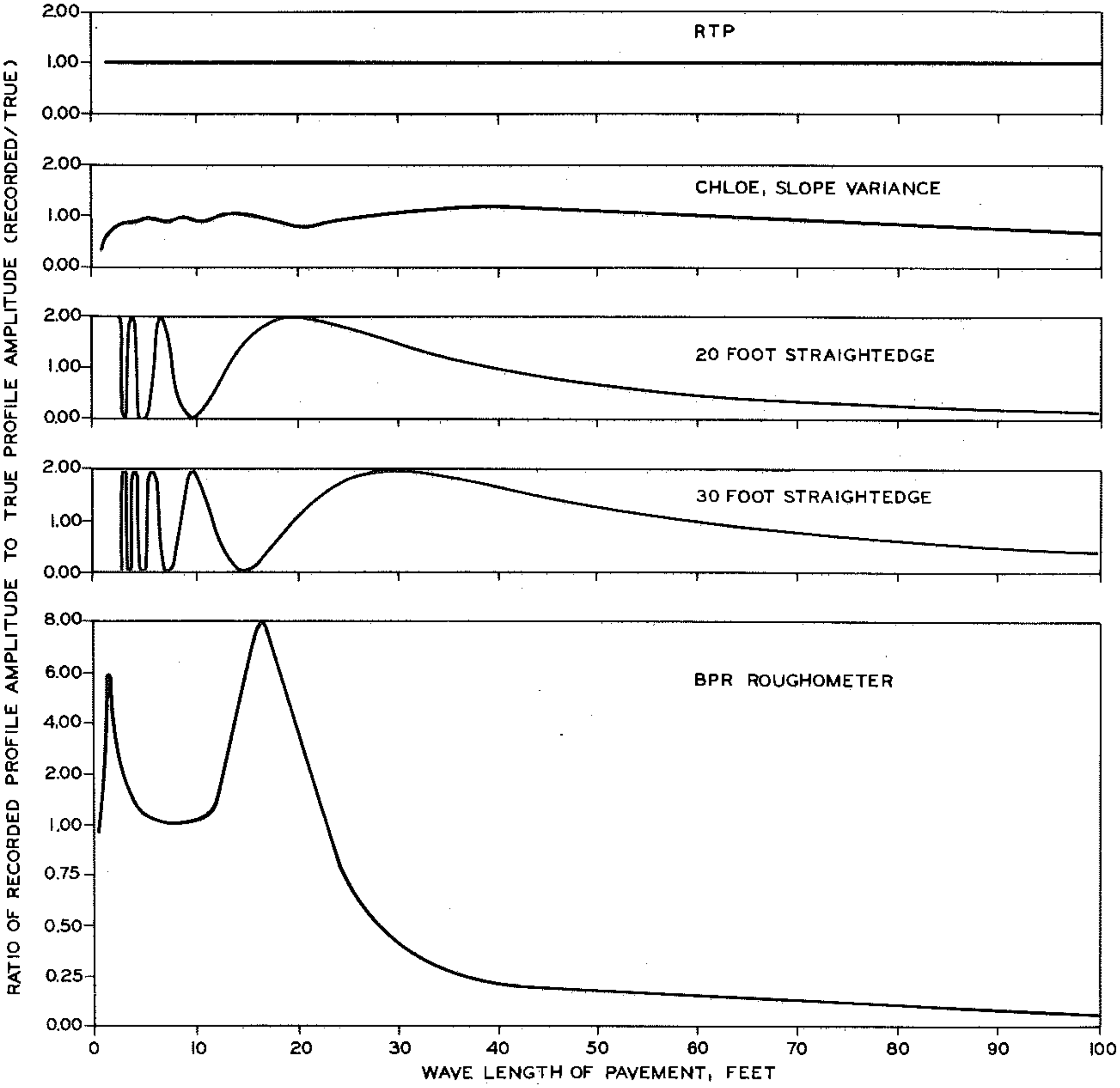


Figure 4. Theoretical differences between RTP, CHLOE, rolling straightedges and seismic roughometers.

Bode plots for the other devices clearly illustrate their inability to "see" a true profile. While it appears that the CHLOE does a better job than the 20- or 30-ft straightedges, it must be noted that CHLOE measures the profile's first derivative. If the CHLOE signal were integrated to provide an elevation profile, additional error would be introduced. The rolling straightedges have hopeless passbands which are probably not helped much by complex bogey wheel arrangements. Although single bogey wheels were assumed for this analysis, it must be noted that multiple bogey wheels may pick up multiple wheel path information which could wipe out the intended improvement. A model of the BPR Roughometer, simulated on the analog computer, provided the Roughometer Bode plot. The model was based on parameters measured from Michigan's BPR unit. Its flat response region extends from about 6- to 12-ft waves, and outside of that response region the profile is either strongly amplified or attenuated. Analysis for the CHLOE and rolling straightedges on sine wave profiles are given in Appendices A and B. A description of the BPR Roughometer model appears in Appendix F as part of the inches per mile analysis.

It may be felt that sine wave profiles are an unrealistic input to profile devices and that their behavior would be different on actual roads. While it is true that a random profile will not be distorted as markedly as the Bode plots indicate, nevertheless, there is partial attenuation and amplification of profile waves as shown in the plots. Experimental verification of this effect was noted by Spangler and Kelly (1). Their report indicates pronounced amplification of 30-ft waves by the 30-ft University of Michigan straightedge profilometer.

Precision (or Resolution)

Precision, sometimes called resolution, is merely the number of significant digits which can be confidently used to establish the level of an RTP profile at any point. The number of significant digits in electronic measuring systems is determined by the smallest readable, non-noise voltage and the maximum output voltage of the transducers. This would allow four significant digits for the RTP since its transducers operate noise free from 0.000 to about ± 7.999 volts. There is a complication in the RTP case, however, since its transducer usually feeds one or more processing units before the final profile emerges. Since each processing unit has its own precision, the final profile will have the same precision as the weakest link in the processing chain. Thus, if one processing unit in the chain has two digit resolution, the final profile will also have two digit resolution. Generally, the final profile will have three digit resolution since this is the same as most analog computers, digitizers, recorders, etc., in the moderate price range. Given a specific number of significant digits, the precision in terms of inches or feet is strictly a matter of scaling. For instance, the resolution would be 0.01 in. if the system had three digit precision and was scaled to handle profile from 0.00 to ± 9.99 in. Similarly, the resolution would be 0.1 in. for profiles running from 00.0 to ± 99.9 in.

Accuracy

Accuracy of a measuring system is broadly defined as the degree of agreement between a measured quantity and a specific standard quantity. That is, when 0.50 volts is defined as 1 in. in the RTP profile, does this actually result from raising the follower-wheel one "Bureau of Standards" inch.

There are two major aspects to consider in evaluating RTP accuracy; static calibration accuracy and accuracy under dynamic conditions. For each of these general cases there are two minor considerations. First, are the transducers linear, i.e., does twice the input yield exactly twice the output. Second, are the transducers stable, which determines the quality of repeatability. These secondary considerations were not extensively tested. The manufacturers specifications concerning linearity and stability were accepted since they varied only in the fourth decimal place and no accuracy beyond the third place was sought for RTP use. Ability of the transducers to hold linearity and stability under dynamic conditions was tested implicitly during dynamic evaluation.

First of the major aspects, static accuracy, is simply a matter of accuracy of the standards used to calibrate the transducers. Follower-wheel calibration is accomplished by a 1-in. block, accurate to 0.0001 in., which provides the required accuracy to the third decimal place. Accelerometer calibration is based on acceleration of gravity as determined for the Michigan area. This is known to the fourth decimal thus providing the necessary third place accuracy. The remaining major factor, dynamic accuracy, is probably the most important but is most difficult to test.

Dynamic accuracy can be determined by running RTP profiles and comparing them with precise level profiles of the same test sections. It was decided that overall accuracy would be adequately determined by intensive study of agreement between RTP and precise level profiles for wavelengths from 1/2 to 100 ft. For reasons discussed in Appendix C, three criteria of agreement between RTP and precise level profiles were used. Dynamic accuracy from 100- to 50-ft waves was established by direct linear correlation between points from both profiles. A statistical process known as coherence function analysis was used from 50- to 1-ft waves. Direct fit comparison was used from 1- to 1/2-ft waves. Results of each comparison are presented in the remaining three sections of this chapter.

RTP profiles were produced from nine, 1,000-ft test sections of various surface materials and roughness. These were processed through the analog computer and simultaneously recorded for the correlation analysis. The analog computer filter was set such that wavelengths up to 100 ft suffered no phase shift or attenuation. Anchor points between RTP and precise level profiles were provided by RTP photocell pickup of reflective markers placed at 100-ft intervals. Precise level readings were made at 5-ft intervals along each test section including a reading at each reflective marker. The 5-ft sampling intervals were shortened to 1 ft in regions of rapid profile change to provide greater detail. Precise level readings were then plotted by digital computer providing a true survey type profile. Since RTP profiles are measured with respect to the arbitrary filter reference, each 100-ft section had to be tipped using precise level readings made at the reflective markers. (See Reference Change). This brought each 100-ft segment of RTP profile to a true survey reference and allowed comparison with precise level profiles. A typical 100-ft segment was picked from each 1,000-ft test section for correlation analysis. Each RTP profile segment picked was then plotted along with its corresponding precise level segment for comparison (Fig. 5). For visual inspection only, each RTP profile segment has been elevated 0.2 in. to prevent overlapping.

Visual inspection of the selected 100-ft sections reveals close agreement between RTP and precise level profiles. The slightly smoother appearance of precise level profiles is due to the 5-ft sampling intervals which miss shortwave features. Agreement between RTP and precise level profiles for 100- to 50-ft waves was determined by sampling each trace of a pair at 2-ft intervals. A linear correlation was performed on these data, first for each 100-ft segment and then for nine 50-ft segments, one from each 100-ft section. Table 1 summarizes the results, which show high correlation and low standard error for both 100- and 50-ft sections. On the basis of these high correlations between RTP and precise level profiles and on visual inspection, it was assumed that close agreement holds for all wavelengths from 100 to 50 ft.

Comparison by Coherence Analysis: 50- to 1-ft Waves

Direct correlation between RTP and precise level profiles could not be used for wavelengths from 50 ft to 1 ft because amplitude intensity fell off more slowly from 50- to 1-ft wavelengths than from 100- to 50-ft waves.

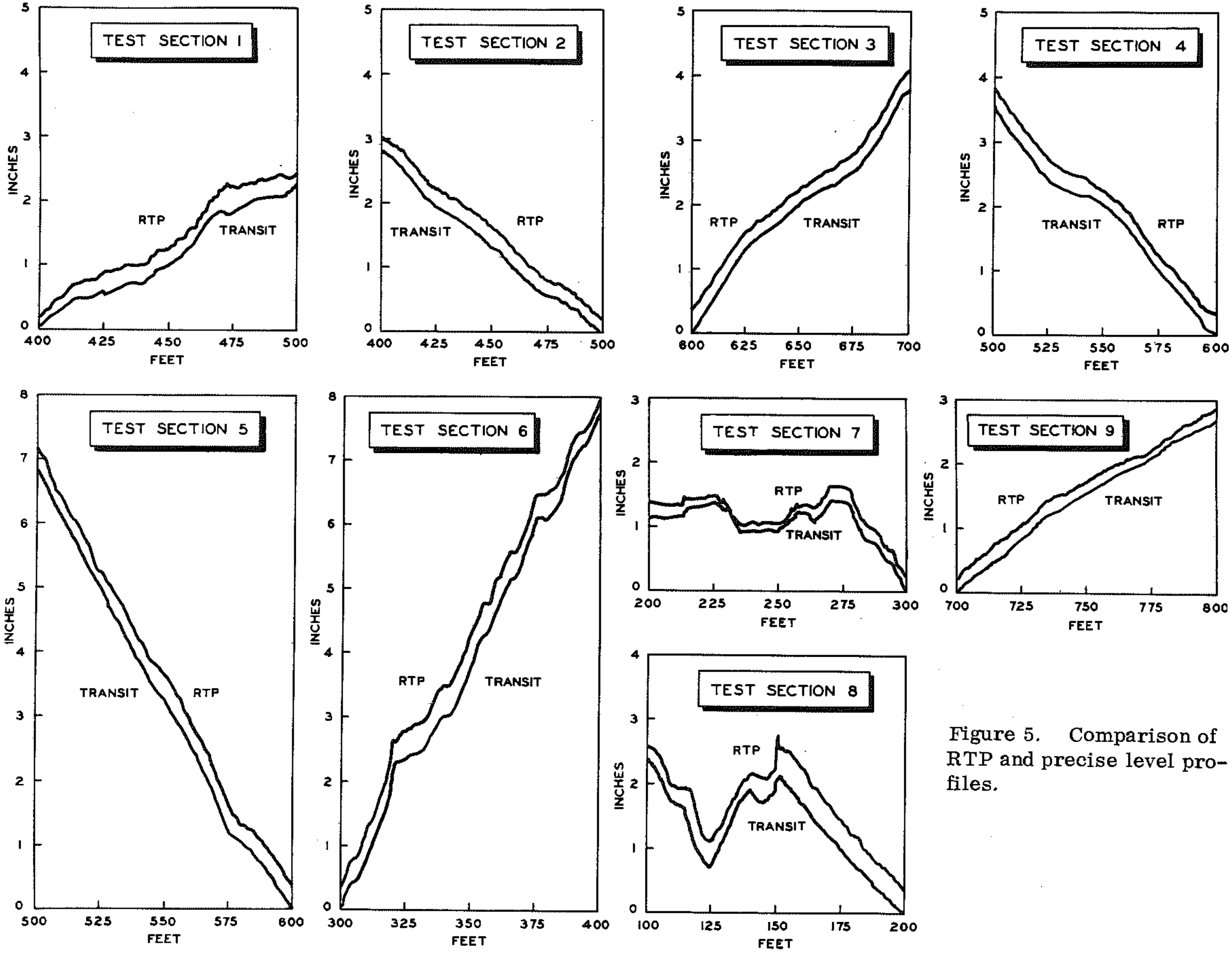


Figure 5. Comparison of RTP and precise level profiles.

TABLE 1
LINEAR CORRELATIONS BETWEEN RTP AND PRECISE LEVEL PROFILES (100 FT AND 50 FT SECTIONS)

Test Section	Slope		One Standard Error, in.		Correlation Coefficient	
	100 ft	50 ft	100 ft	50 ft	100 ft	50 ft
1	0.97	0.88	0.050	0.030	0.997	0.992
2	0.98	1.05	0.034	0.021	0.999	0.999
3	1.00	1.07	0.046	0.021	0.999	0.999
4	0.97	1.02	0.031	0.025	0.999	0.999
5	1.01	1.03	0.044	0.044	0.999	0.999
6	1.02	1.09	0.074	0.044	0.999	0.999
7	0.99	0.99	0.056	0.044	0.982	0.994
8	1.01	0.94	0.096	0.041	0.986	0.998
9	1.05	1.04	0.027	0.028	0.999	0.998

See Appendix C for additional commentary on this problem. Instead, agreement was determined by a technique developed in the early nineteen-sixties as part of a general attack on problems in signal theory. It is a statistical process defined by the expression: $\gamma_{xy}^2(f) = \frac{|Gxy(f)|^2}{Gx(f)\ Gy(f)}$ in which Gx(f) and Gy(f) are power spectra for each signal and Gxy(f) is the cross spectra at frequency (f). This coherence function statistic reveals the extent of agreement between two signals in a narrow frequency band centered at frequency (f). The result, after evaluating the function for various (f), is a graph or table showing amplitude correlation (zero to one) for all wavelengths in question.

The analysis requires uniform and closely spaced precise level readings from a test section containing equal intensity of roughness at all wavelengths. A careful search located approximately 600 ft of unbroken bituminous pavement with appreciable roughness down to one-foot waves. Precise level readings were made at 6-in. intervals and punched on cards for digital computer entry. The RTP profile of this section was electronically digitized to provide a sample every 6 in. for digital computer entry. A reverse tipping operation was then performed on the precise level profile to convert its survey reference to the arbitrary reference established by the RTP. This also performed the filtering necessary to remove longwave data from the precise level profile.

Two problems arose that were only partially solved and may explain the slightly low coherence values and the few anomalous lower ones. The first problem occurred because most road surfaces lose roughness intensity at approximately 20 db per frequency decade as the wavelength shortens. Rate of loss is twice as high from about 12- to 1-ft waves. This rapidly falling power spectrum for road surfaces tends to bias the coherence analysis so that it underestimates the actual coherence. This problem was mitigated by breaking the analysis into two sections, each of which had a smaller total drop in roughness intensity. The first analysis covered wavelengths from 50 to 12 ft and the second from 12 to 1 ft. The second problem is due to variations in speed of the RTP vehicle. This produced a small varying phase error between RTP and tipped precise level profiles that was highly detrimental to the coherence analysis. The problem was solved satisfactorily, but not completely, by a digital program that stretched small segments of RTP profile back and forth until they matched the precise level profile. Fit was assumed optimal when the least squares error between profiles was a minimum.

Figure 6 shows three versions of the test section. The upper trace is that recorded by the RTP and adjusted to match phase with the tipped precise level profile. Next is the precise level profile, tipped to match the reference established by the RTP. The bottom trace is the untipped precise level profile. These operations were performed and plotted by digital computer.

Table 2 summarizes results of this analysis for the bituminous test section. The 20 values span frequencies from 0.02 to 1.00 cycles per foot in fairly uniform steps. Despite the difficulties mentioned, most correlations are high. All are significantly high and it can be safely concluded that the RTP will faithfully reproduce profile features over the region of wavelengths from 50 to 1 ft.

Comparison by Direct Fit: 1- to 1/2-ft Waves

Direct correlation of longwave trends has shown the RTP to be accurate from 100- to 50-ft waves. Coherence analysis provided proof of accuracy from 50- to 1-ft waves. RTP accuracy for waves shorter than 1 ft was tested by more direct methods. Three short waveforms, a semicircle, triangle, and rectangel were fabricated from steel plates and secured to a pavement surface. Their dimensions are shown in Figure 7. These shapes, in the order presented, require increasingly better RTP high frequency response for faithful shape reproduction.[1]

---

[1] Frequency response in this sense means ability to respond correctly to increasingly intense high frequency terms found in the Fourier decomposition of these waveforms.

TABLE 2

COHERENCE VALUES BETWEEN RTP AND A PRECISE LEVEL PROFILE

Wavelength, ft.	Frequency, cycles per foot	Coherence Value (Correlation)
50.0	0.02	0.984
25.0	0.04	0.979
16.7	0.06	0.959
12.5	0.08	0.947
10.0	0.10	0.951
8.4	0.12	0.956
7.2	0.14	0.909
6.3	0.16	0.963
5.5	0.18	0.843
5.0	0.20	0.872
4.2	0.24	0.944
3.1	0.32	0.918
2.5	0.40	0.954
2.1	0.48	0.991
1.8	0.56	0.979
1.4	0.72	0.858
1.3	0.87	0.816
1.1	0.91	0.891
1.0	1.00	0.916

From the results obtained, it appears that mass of the follower-arm and wheel is the major limitation to RTP high frequency response. In addition; it is evident that the circumference of the wheel tends to smooth sharp discontinuities in the profile. Also, there is probably an enveloping effect as the wheel rolls over small sharp features which sink into the tire. The metal waveforms were profiled at 12.5 ft per second, since higher speeds caused considerable follower-wheel bounce. Figure 7 also shows the expected and actual profiles superimposed. Expected profiles are axle paths of the 6-in. follower-wheel over the waveforms. Except for follower-wheel bounce over the rectangle, agreement of the traces is so close that quantitative comparison was deemed unnecessary.

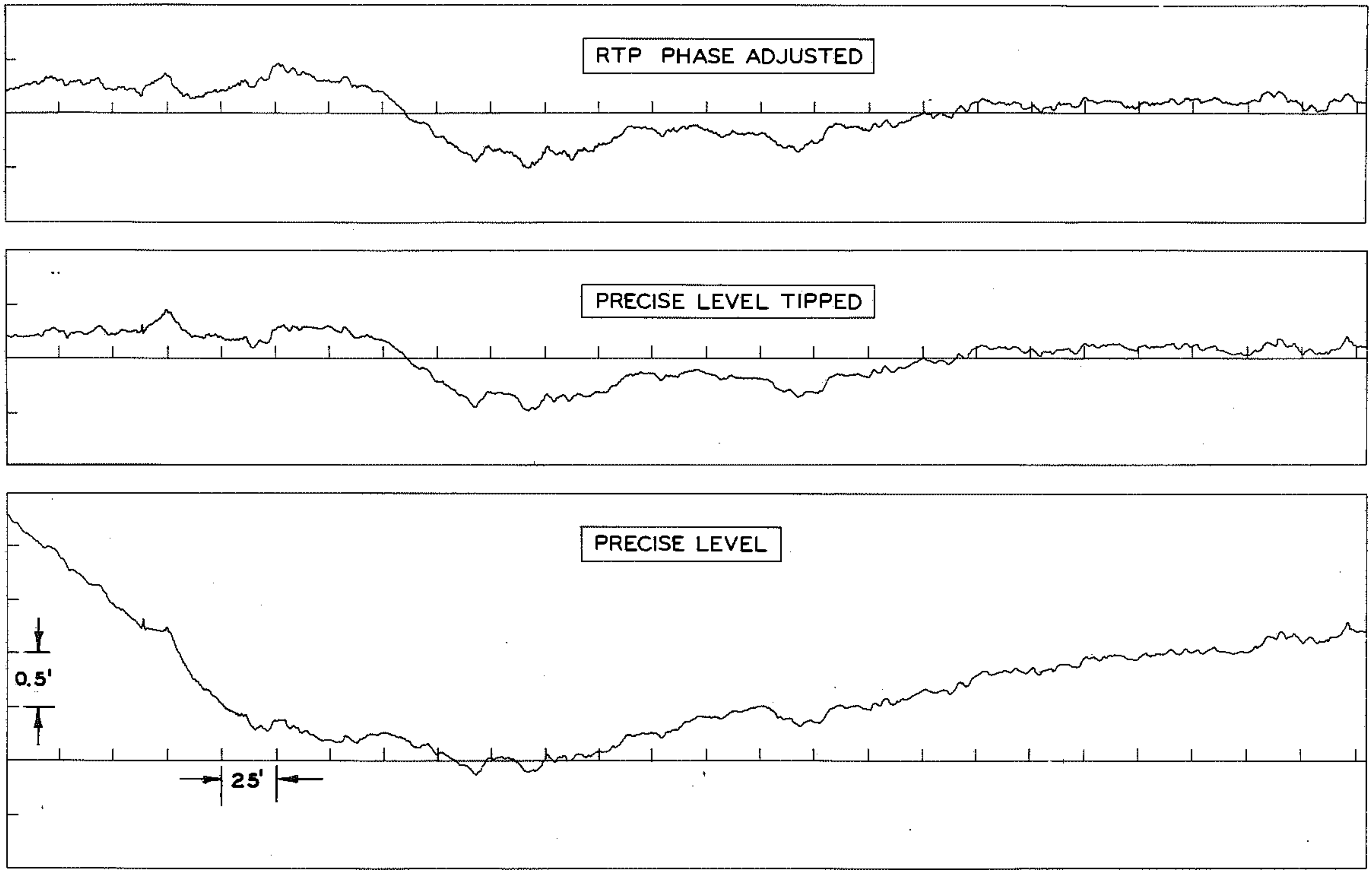


Figure 6. RTP (phase adjusted) and precise level (tipped) profiles used in coherence analysis. Original precise level profile is shown for comparison.

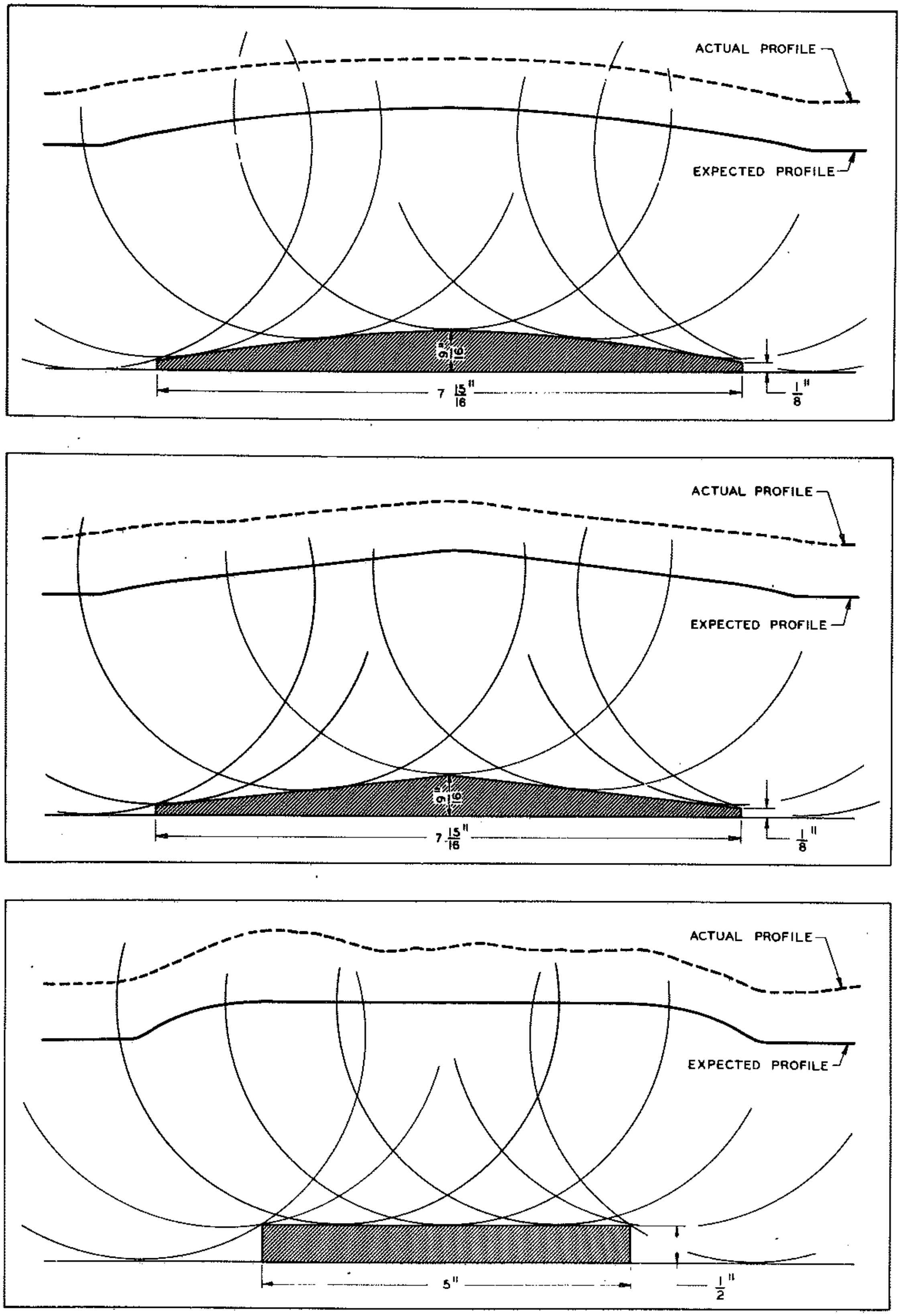


Figure 7. Expected and actual profiles of known waveforms.

V

PROFILE ANALYSIS EQUIPMENT

Discussion

A great deal of work with RTP data has provided a clear picture of profile analysis methods and necessary equipment. It is evident that the depth of analysis desired and budgetary considerations determine the analysis equipment configuration. The simplest configuration results if visual inspection of the RTP trace is all that is desired. For this case an optional analog computer package in the RTP will compute profile that can be recorded directly on strip chart paper during the run. Any analysis beyond this point requires a data processing chain of two or more instruments. The usual operation is to tape record raw transducer signals in the field and then partially or completely process these in a lab based analog computer. Note that a lab based analog computer may remove need for a truck based unit and offers much greater processing flexibility.

Analysis beyond the lab based analog computer will usually involve digitization of the profile or raw transducer signals. These data can then be processed by much more powerful digital computer techniques. A highly desirable but expensive alternative to the analog tape-analog computer-digitizer chain is to record raw transducer signals directly in digital format. The advantages of the process are many but the system might be difficult to implement in the RTP truck. An alternative to digitization might be found in one of the many signal processors of various types now on the market. These processors provide such measures as amplitude distributions or power spectral density graphs. Another possibility, but one that is rarely available, is to feed the tape recorded transducer signals into a hybrid system. This is an analog computer coupled to a digital computer which allows powerful profile analysis to be accomplished in one pass.

In addition to decisions regarding the processing configuration needed, a prospective user must decide which equipment items to purchase. This report should aid in the latter consideration since many factors about processing equipment have emerged during this study.

Analog Magnetic Tape Recorders

If profile analysis is desired and digitization in the field not available, then RTP transducer data will have to be recorded on magnetic tape. This generates some practical difficulties and introduces additional noise into the data chain. At present the Michigan RTP uses a seven-channel FM recorder with half-inch tape. A major disadvantage arises since the unit must be removed from the truck for profile processing. A second, lab based, half-inch recorder would solve this problem but seven channels are usually inadequate for general processing. The best arrangement would seem to be a one-inch recorder permanently based in the truck and a lab based one-inch unit for processing. Fourteen-channel capacity would then be available and only the tapes would be transported from truck to lab. To insure tape compatability, recorders should conform to IRIG standards for FM recording. They should also have tape index counters to aid in a fast search for specific data. A single one-inch recorder could be used in both truck and lab if a sufficiently portable unit could be located. Since new and smaller decks are appearing on the market, a careful search is in order.

By its nature, the tape recorder may introduce noise of a periodic nature. This is extremely detrimental if spectral studies of the profile are desired. A small amount of this noise may arise internally but most is generated by resonant shaking of the deck in its shock mounts. For this reason, and to protect the unit from physical damage, an extremely soft shock mount is recommended. Ideally, a well of thick foam material should cradle the unit providing a very low natural shake frequency, thus reducing tape wow. This should be done even if common mode noise rejection is utilized since unique shake noise may be induced in each channel through its own electronics. Another type of noise, primarily arising from the electronics, is low frequency random drift. It is unique to each channel, therefore not removable by common mode rejection and most troublesome when found in the accelerometer channel. When attempts are made to record long profile waves by lowering the analog filter frequency, this noise injects false waves into the profile. This problem can be minimized by choosing a recorder with the least low frequency noise. In one important respect, low frequency noise injected by the tape deck may cause no additional difficulty. This occurs if the roadway tips the RTP truck enough to cause an accelerometer tip error signal equal to or greater than low frequency recorder noise. In this case, lower filter frequencies could not be used even if there were no recorder noise.

Analog-to-Digital Conversion and Recording

There is a great advantage in recording profile information in digital format as close to the RTP transducers as possible. In fact, it would be best to record the transducer signals in digital format during the profiling run and do all subsequent work in a digital computer. A few of the many advantages are: 1) no injection of noise or degradation of data beyond the digital recording point, 2) greater dynamic data range is permissible, 3) very powerful filtering and analysis of the profile is permitted, 4) complete one pass processing to the final analysis is provided, saving large amounts of work, and 5) complete freedom of output, including scaled plots, graphs, and analysis printouts, is permitted.

There are four elements to a digital recording system. Closest to the signal sources is a multiplexer that switches among the inputs allowing multi-channel input. Next is the analog-to-digital converter (written A/D) which usually provides three digits and sign to represent the instantaneous value of an input signal. These digits are then sent to the tape handler where they are written on magnetic tape. Overseeing the operation is the controller which triggers the other devices and moves data from the A/D to tape.

There are three methods of utilizing these basic building blocks. The first is called synchronous recording, which samples the signal at a rapid rate and writes its value on tape immediately. The sampling rate is usually fixed and too high for RTP work. In addition, the rapid rate of digital tape use would permit only short profile runs. The second method is incremental recording, which samples and writes once for each external activation command. This method samples too slowly for RTP work. Most incremental units have a maximum sampling rate of 400, four character samples per second. RTP work requires at least 640 samples per second in all cases. In addition, both methods lose data during placement of an inter-record gap on the tape. The final method is called buffered recording and is recommended for both RTP and general data acquisition. In this method the system samples once for each command from an external trigger, acting at almost any rate, from as long as desired to ten thousand or more times per second. The data are not written immediately but stored in one of two memory units in the controller. When one memory unit (buffer) is full, data begin to fill the other and contents of the first are written on tape at high speed. No data are lost and the sampling rate can be set at virtually any speed. The only drawback to this system appears to be availability and, possibly, cost since the controller is actually a very small standard or custom built computer. This is also the ideal system for digitization at any stage of profile analysis. Transducer signals could be tape recorded, partially processed on a lab based analog computer then digitized, or digitized directly from tape. In either case the digitizer would be lab based which might permit lower system costs since portability and field capability would be unnecessary.

Digits derived from analog signals will most often go on digital tape for subsequent computer processing. This will be the case for all field digitization but may not apply to all lab installations. Many digital computer systems now provide facilities for direct digitization from analog signals. All hybrid systems include direct digitization features.

Analog Computers

Analysis requirements play a decisive role in choice of analog computers. As mentioned earlier, the RTP is available with an optional analog computer package built in. It is only used for profile computation from transducer signals and has provisions to select several filter cutoff frequencies. The computed profile can then be recorded on strip chart paper for immediate inspection and on magnetic tape for further analysis if desired. There are two cases for which the RTP computer would be sufficient: The first case arises if no further analysis beyond visual inspection of the computer profile is desired. The second and more realistic case occurs if the computer profile is digitized in the truck or recorded for lab digitization. In this case there may be a real advantage since low frequency noise from the recorder is kept out of the accelerometer signal before profile computation. Insertion of low frequency noise into the computer profile is not as serious as pre-inserted noise which is highly amplified during profile computation.

In any case, if further analysis is required, then either computed profile or raw transducer signals will be returned to the lab on tape. If this tape is digital, further processing will be done in the digital computer. If the tape is analog, the user must choose between three alternatives: 1) digitize directly from the tape and enter a digital computer, 2) partially process the data through the analog computer then digitize, and 3) do all profile analysis with an analog computer. Case one has been discussed but cases two and three lead to different analog computer needs.

If RTP data are to be partially processed by analog computer then digitized, a small computer will suffice. Partial processing implies computation and bandpass filtration of the profile before digitization. It may include simple simulations such as the BPR Roughometer (see Appendix F).

This offers an ideal trade-off between analog and digital processing since filtration and simple simulation is time consuming and difficult to implement in the digital computer. In addition, pre-filtration may drastically reduce the number of data points per second needed for digitizing, thus further reducing digital computer time. A sufficient computer for this application would be of the twenty amplifier class. A large number of integrators, at least twelve, is desirable. The non-linear row should include multiplier, X^2, and comparator units. Finally, it should be noted that ten-volt analog computers are best for modern, solid-state data handling equipment.

If profile analysis is to be done entirely by analog computer, a rather extensive unit is needed. It should have at least 48 amplifiers, four-place resolution, and a transport delay package. The non-linear row would have to be fully expanded with multiplier, X^2, log x, comparator, and diode function generator units. A minimum of 20 integrators would be essential. This configuration could perform most currently envisioned profile analyses. It would handle simulation of current profile and roughness devices and all current signal measures such as autocorrelation, power spectral density, and so forth. Total cost of this setup would be less than a digitizer, digital computer, and digital tape system but analysis flexibility would be somewhat less with the analog unit.

Peripheral Analysis Equipment

Several items of peripheral equipment have been found indespensible for profile analysis. These are the oscilloscope, x-y plotter, function generator, and random noise generator.

The oscilloscope need not be elaborate for profile work but should include the following features: 1) two channels; chopped or two gun, 2) frequency response down to dc, 3) triggered sweep, 4) long persistence phosphor, and 5) stable beam position circuitry since a fixed baseline is very desirable in profile work.

If final analysis is done digitally, the computer's digital plotter can be used for output. For most applications an analog x-y plotter of the servo null type is very useful since it combines a wide writing surface with high linearity. A two pen model with a roll chart drive is preferable. These units suffer from very low frequency response but this is no problem if amplitudes are small at high frequencies as is the case for most profiles. If high frequency, high amplitude data need plotting, a frequency reduction can be obtained by playing out of the tape deck at slower speeds.

A high quality function generator is useful for many purposes in profile work. It should have the following features: 1) a full array of waveshapes, square, triangle, ramp, and sine, 2) external trigger operation, 3) external control of frequency by an input voltage, and 4) switchable number of cycles per signal burst. The generator will be very useful for evaluating filters, determining frequencies, evaluating roughness and profilometer simulations and pulse shaping. A random noise generator will be helpful if spectral analysis of the profile is contemplated, since spectral programs can be most conveniently tested by random noise input. The generator should be a low frequency unit with random output down to zero cycles per second.

VI
PROFILE ANALYSIS METHODS

Discussion

Road profiles can be viewed in only two distinct ways; as an elevation map for a narrow strip of terrain, or as a random signal with certain properties in common with all other random signals (see Appendix D). Profile analysis in the first case might consist of inspection to locate pot holes and joint blowups or perhaps a profile workup to estimate quantity of resurfacing material. In other words the profile is used directly with no attempt to characterize it with some average measure. In the second case profile analysis consists of extracting unique values for the properties common to all profiles. In other words, an effort is made to describe or characterize the profile in standard terms which are more meaningful than raw, unanalyzed profile. This second case covers a seemingly broad area extending from rudimentary, single number indices to advanced measures such as power spectral density. In reality there are only four objective measures by which a random signal may be characterized. Of these, only one is a single number index and it provides only rudimentary information about the signal. These measures are:

1) Mean square values also called mean variance, obtained by continuously squaring the signal and dividing by its length. It is a single number measure of average intensity and its square root is often referred to as root mean square or rms intensity.

2) Probability density functions, obtained by noting how long the signal remains at various levels and then plotting these times against the respective levels. It provides an estimate of how much of the time amplitude of a given level occurs in the profile.

3) Autocorrelation functions describe the general dependence of data values at one time, on those at another time. The result is a plot of correlation vertically and baseline difference horizontally. This measure has very little utility in highway work and is important primarily because it provides a route to the next measure through the Fourier transform.

4) Power spectral density functions, which describe the general frequency composition of the signal in terms of the spectral density of its mean square value. The result is a plot of power (variance) in narrow frequency bands on the vertical axis and center frequency (or wavelength) of the narrow bands on the horizontal axis.

Two important questions have arisen concerning the four measures of random signals. First, is measure No. 1 (mean square values) the only single number index applicable to random signals? Not necessarily, since it may be possible to extract single number indices from at least two of the other three measures; this is detailed in a following section. Second, why do these four measures provide the only rational approach to random signal analysis? This question is answered by appeal to an expanding body of work begun in earnest around 1950 to solve problems of random signal analysis (2, 3). In essence, this work reveals that these measures are an optimum blend of statistics and engineering. Engineers need measures that are physically meaningful and that specify the effect of a random signal on other physical systems. Fortunately, these measures are also those for which statisticians can determine sampling requirements and reliability. This is necessary because details about any random processes can only be known in a probabilistic sense and statistics provide a means of estimating those details with a given degree of certainty. Studies in this field have not produced measures other than the four given which provide both meaningful and statistically sound information.

Analysis or, more properly, direct use of the profile is covered in the next section. Next is a section on current roughness measures, specifically inches per mile and slope variance. This is followed by two sections on the four measures described above. The first covers the measures themselves while the second covers possible single number indices derived from them. Finally, the last section provides a handbook approach to profile analysis.

Visual Inspection and Direct Use

For certain applications the profile may be viewed as a wheel path elevation map. The RTP can provide this but some precautions and profile modifications may be necessary. These difficulties arise from scaling problems and from the profile process filter which causes phase shift and attenuation of longwaves, and inserts an arbitrary reference. The result of these problems is often a strip chart plot of RTP profile that doesn't look at all like the actual terrain. The profile is valid but, as shown earlier, only for a specific band of frequencies and with respect to an arbitrary, slowly changing reference. It is therefore helpful visually, and may be vital for certain applications, to tip the profile to a true survey reference as explained earlier. This requires more field work but certainly very much less than would be needed for a precise level survey without the RTP. Extensive operations of this sort are best performed and plotted by digital computer after digitizing the profile and keypunching the precise level data. Once this is done the remaining problem is that of scaling. This can be handled digitally by plotting a filtered profile at high gain to bring out the surface details and a tipped version at low gain to show the longwave trends. Alternatively, the computer can plot tipped profile at high gain in segments that will fit on the plot paper.

The area of direct profile use beyond visual inspection has not been fully explored. The Michigan Highway Research Laboratory has used tipped profiles for pavement inspection and may use them in estimates of resurfacing material quantities.

Current Roughness Measures

Roughness measures in common use today are slope variance measured by the CHLOE instrument, and inches per mile measured by BPR Roughometer devices or rolling straightedges. Both are single number indices that suffer a serious defect because, as shown earlier, they are measured by devices that distort the actual profile. Some wavelengths are sharply attenuated while others are greatly amplified. In terms of the four possible measures of random signals, slope variance is classifiable under mean square values and is a measure of average intensity for the profile's first derivative. Even though this measure is classifiable, it is least powerful of the four and carries no spectral (i.e., frequency or wavelength) information and therefore does not completely specify the random process. Inches per mile is not classifiable under any of the standard measures and is neither physically meaningful nor amenable to statistical sampling and reliability analysis. Despite their low quality, these measures often correlate with other objective and subjective roughness measures. Recent evidence suggests a reason for this which is presented later in this report. Because of this correlation and the large body of work based on these measures, there is reluctance to abandon them even if older profile devices are replaced by the faster and more efficient RTP. Inches per mile and slope variance can be extracted from RTP profiles but the process presents some problems since the RTP returns an undistorted profile over the band of wavelengths sensed by the older instruments. It is necessary to feed RTP profiles into a model of the required traditional instrument simulated in a digital or analog computer. Correlation of the model's index with the actual index is thus determined by accuracy of the simulation.

Need for simulation was not taken for granted at the beginning of this study and the steps to this conclusion provide interesting information about the nature of road roughness and correlation of dissimilar indices. Step one in this study consisted of correlations between the traditional indices and inches per mile extracted directly from RTP profiles with no simulation of either traditional device. The analog computer inches per mile circuit described in reference (1) was used with low-pass filtration to remove high frequency noise. Twenty-two, one-half mile pavement test sections were run simultaneously with the RTP, CHLOE, and Roughometer. These sections included good, average, and poor riding surfaces on rigid, flexible, and overlay pavements. Correlation between RTP inches per mile and the other indices was surprisingly good with fairly low standard errors. Step two in the study was initiated upon discovery that the inches per mile circuit was unsuitable in the form given and that RTP data had been inadvertently overfiltered during step one. When a new circuit was developed and the process repeated with proper filtration the correlations were weak and were accompanied by large standard errors. Step three consisted of feeding the RTP profiles through an analog computer simulation of Michigan's BPR Roughometer. The index extracted was then correlated with Roughometer readings for the twenty-two test sections. The results are seen to be acceptable with a correlation coefficient of 0.966 and a standard error of 13.8 inches per mile. The actual correlation equation for the Michigan Roughometer includes a calibration factor and is:

$$\text{Inches/mile} = \left[\frac{\text{value from model}}{\text{test section length (miles)}}\right] (0.221) + 21.5$$

A more comprehensive simulation of the Roughometer would undoubtedly improve the correlations. A discussion of the present inches per mile extraction process appears in Appendix E. No attempt was made to simulate the CHLOE although this could be readily done in the digital computer.

An important question is raised by the good correlations found in step one. How could two devices with passbands totally unlike the RTP yield indices that correlate so well with a badly distorted index extracted from the RTP profile? A clue to this problem was found in power spectral graphs from a variety of roads analyzed for another study. These graphs show that as roads get rougher, almost all wavelengths increase in amplitude.

This results in groups of spectral graphs that do not cross for most wavelengths. Instead, the whole curve generally moves up for rough roads and down for smooth roads. Under these conditions any measure reflecting amplitude intensity in a given wavelength band will correlate with the same or a different intensity measure from another band. In other words, all that is needed to rank a number of roads in the order of roughness is an intensity measure of any sort from almost any wavelength band. This means that correlation between unrelated roughness indices is probably due to the profile and would not necessarily hold for all roads.

Correlation probably failed in step two of the inches per mile analysis because proper technique brought in shorter wavelength bands. Power spectral graphs did show some crossing at these short wavelengths which would weaken the correlation. In addition, correct technique probably increased the effects of bandpass differences between profile devices causing further weakening of the correlations.

Advanced Analysis

The RTP is perfectly suited to profile analysis based on the four random signal measures discussed previously. All data handling can be quickly and efficiently performed since the profile is available as a varying electrical signal.

A somewhat more detailed explanation of the four measures will aid in understanding their use in profile analysis. To this end, the concept of domains will prove useful. The term domain will refer here to functions of the random signal which result in a graph, as opposed to a single value like mean squares. For purposes of this report a domain will be defined as a region or graphical space bounded by some measured quantity on the vertical axis and some baseline on the horizontal axis. The domain is named for this baseline. Thus, mean squares does not form a domain since there is no baseline. The amplitude distribution with time or number of events vertically and amplitude horizontally is an amplitude domain measure. The autocorrelation function has correlation vertically and time or, for highway work, distance horizontally, and forms a measure in the time or distance domain. The power spectral density function, with power vertically and frequency in cycles per foot horizontally, forms a measure in the frequency domain.

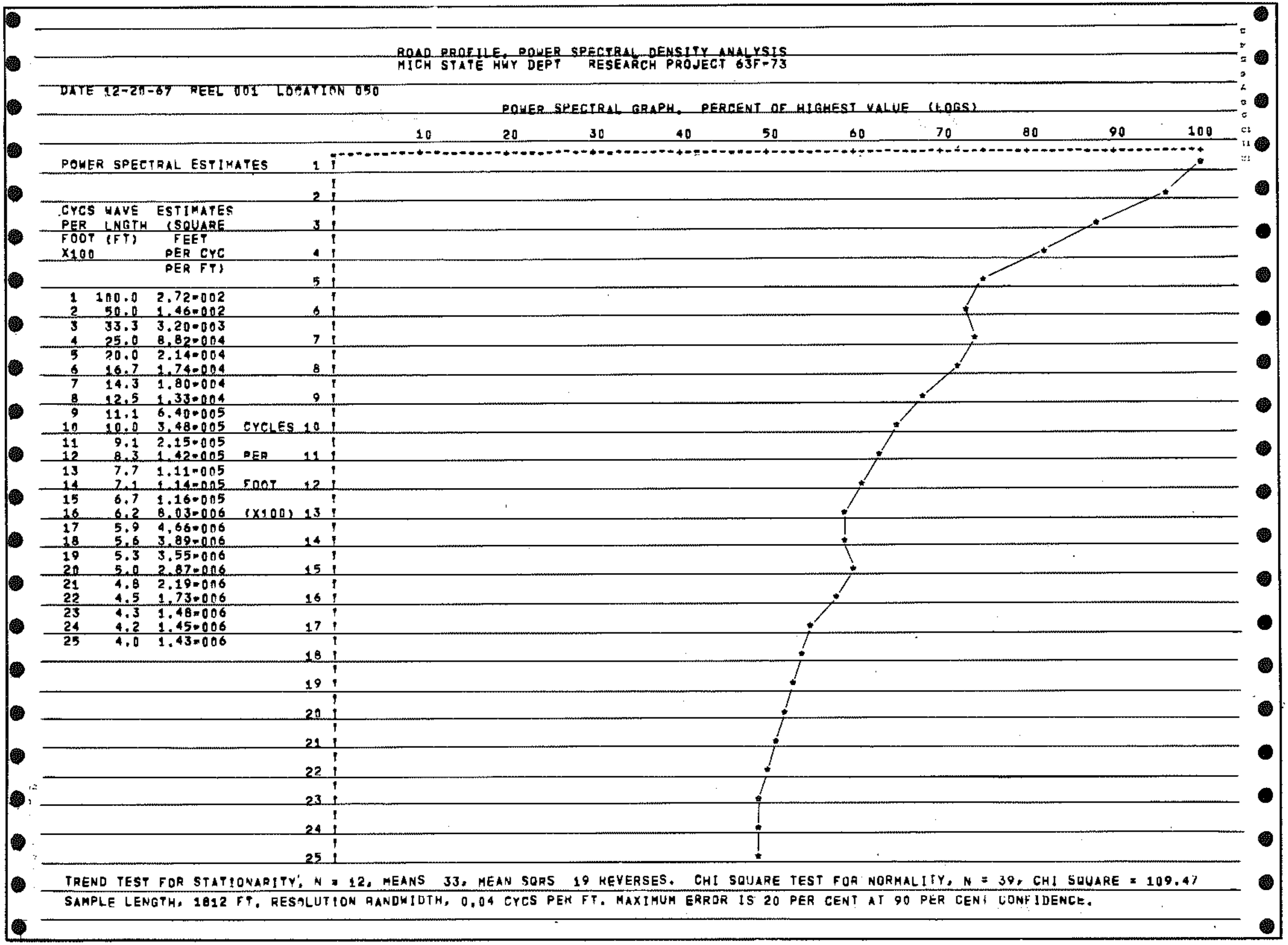
A question now arises concerning just which measures carry the most information about the random signal and what, if any, information about the signal is lost. This can be answered by noting what it takes to define the random signal. To begin with, if nothing is done to the signal no information is lost and its plot is said to completely specify the signal. The signal can be viewed, however, as the sum of an infinite number of sine wave signals, each with its own amplitude, frequency, and phase. A table of these quantities, although infinite in size, would enable the signal to be reconstructed exactly, so these quantities are also said to completely specify the signal. The table can be reduced to finite size if the signal is low-pass filtered so that all data above a given frequency are removed.

The four measures can now be examined to see which of the necessary ingredients, amplitude, frequency, and phase are present. Mean squares specify no individual amplitudes, frequency, or phase. This measure specifies no details about the signal except its general intensity. The amplitude distribution specifies amplitude content of the signal but no frequency or phase information. Autocorrelation specifies amplitude information in the time domain, but frequency is inherent in this domain so this measure may be assumed to specify amplitude and frequency content. This measure does not preserve any phase information. Power spectral density specifies amplitude in the frequency domain and so this measure, like autocorrelation, also specifies amplitude and frequency content; no phase information is retained. The last two measures, then, specify amplitude and frequency content but in different domains. This led to the discovery that autocorrelation and power spectral density form a Fourier transform pair, i.e., a process whereby functions in the time domain can be transformed to functions in the frequency domain and vice versa. Autocorrelation and PSD do not actually specify the signal completely since phase information is lost. They are said to completely specify the signal however, because phase information is not needed for most applications. The point is that PSD provides no more information than autocorrelation but presents it in a more meaningful format. For this reason the autocorrelation function is usually viewed merely as an intermediate computation involved in getting the PSD. For all practical purposes, then, PSD is seen as the measure that completely specifies the random signal. The other measures are embodied in PSD and could be extracted from it if necessary.

Although PSD is usually computed by taking the Fourier transform of the autocorrelation function, this is not the easiest way to understand its meaning. Much more insight is gained by considering an alternate method of computing PSD by analog methods. A typical case involving actual numbers will provide insight into the magnitudes involved. First, assume a profile is filtered to remove all waves longer than 100 ft and shorter than 4 ft. The analysis would then span the range of frequencies from 0.01 to 0.25 cycles per ft or 0.5 to 12.5 cycles per second for an RTP speed of 50 ft per second. This range of frequencies is known as the data bandwidth. To perform the analysis, 25 narrow bandpass filters are constructed with a bandwidth of 2 cps. This is known as the resolution bandwidth. The filter center frequencies are set at 0.5, 1.0, 1.5, 2.0, ...and so on up to 12.5 cps. The filter bandwidths overlap for several reasons beyond the scope of this illustration. Profile signal is then fed simultaneously into the 25 filters. Their function is to break up the profile signal into a spectrum much as a prism breaks up the random signal known as sunlight into its constituent frequencies. The signal emerging from each filter is fed into a squaring network which produces a continuous squared signal. Each of these signals is then integrated, resulting in a fixed positive voltage in each integrator at the end of the run. These values are divided by the profile length which provides a mean square (variance) value for each band. Each value is then divided by the resolution bandwidth, in this case 2 cps, to yield the average variance per cycle in each band. The values obtained are then plotted against the filter center frequencies to form the PSD graph. The units are amplitude squared, divided by frequency on the vertical axis and frequency on the horizontal axis.

The PSD graph presents all salient features of the profile at a glance. It will readily show any narrow band random components in the profile. Improper paving form placement for example, would produce a strong peak at that wavelength. The graph provides intensity of the profile at wavelengths known to cause a bad ride. In addition, the individual spectral estimates forming the graph can be used in a variety of further computations. For example, if both a profile PSD and truck force PSD are known for a given road, it is a simple matter to graph the truck's transfer function. The truck's behavior on any other road can now be determined by obtaining only a PSD for the new road. Figure 8, shows the PSD graph for a typical test section to further illustrate the analysis method. Parameters for this analysis are the same as those for the PSD explanation given earlier. The graph itself is read with the computer output sheet tipped as it appears on the page. Logs of the spectral estimates were computed, then expressed as percentages of the highest value. This provides a plot which remains on the paper but still takes maximum advantage of space. Spectral estimates, included on the printout, are usually replotted since the printout plot is only a crude, quick look at the general spectral shape.

In practice, PSD analysis is a little more complex than this explanation would indicate. Some statistical requirements must be met and the profile must be prefiltered. Longwave, high amplitude signals present in most profiles have plagued investigators using precise level profiles (5, 7). These powerful signals dominate the analysis obscuring subtle power differences



ROAD PROFILE, POWER SPECTRAL DENSITY ANALYSIS
MICH STATE HWY DEPT RESEARCH PROJECT 63F-73

DATE 12-20-67 REEL 001 LOCATION 050

POWER SPECTRAL GRAPH. PERCENT OF HIGHEST VALUE (LOGS)

POWER SPECTRAL ESTIMATES

CYCS PER FOOT X100	WAVE LNGTH (FT)	ESTIMATES (SQUARE FEET PER CYC PER FT)
1	100.0	2.72-002
2	50.0	1.46-002
3	33.3	3.20-003
4	25.0	8.82-004
5	20.0	2.14-004
6	16.7	1.74-004
7	14.3	1.80-004
8	12.5	1.33-004
9	11.1	6.40-005
10	10.0	3.48-005
11	9.1	2.15-005
12	8.3	1.42-005
13	7.7	1.11-005
14	7.1	1.14-005
15	6.7	1.16-005
16	6.2	8.03-006
17	5.9	4.66-006
18	5.6	3.89-006
19	5.3	3.55-006
20	5.0	2.87-006
21	4.8	2.19-006
22	4.5	1.73-006
23	4.3	1.48-006
24	4.2	1.45-006
25	4.0	1.43-006

TREND TEST FOR STATIONARITY, N = 12, MEANS 33, MEAN SQRS 19 REVERSES. CHI SQUARE TEST FOR NORMALITY, N = 39, CHI SQUARE = 109.47
SAMPLE LENGTH, 1812 FT, RESOLUTION BANDWIDTH, 0.04 CYCS PER FT. MAXIMUM ERROR IS 20 PER CENT AT 90 PER CENT CONFIDENCE.

Figure 8. PSD graph and estimates for Test Section one.

in important regions. Various methods, sometimes called detrending, have been tried in order to filter out the long waves. Such filtering is possible with digital techniques but computer time is heavily consumed (8). The RTP solves this problem by automatically filtering out these wavelengths during profile computation. As mentioned earlier, unwanted high frequencies may also be filtered out if the profile is to be digitized. Several new devices have appeared on the market that perform PSD and related analyses. Some of these compute all four random signal measures and are portable enough for field applications.

It should be mentioned that when applying PSD techniques to profile analysis, the same problems are encountered that occur in analysis of all random data. As in any other statistical study, the investigator must include a statement of his statistical decisions. Sample length, resolution bandwidth, data bandwidth, and confidence levels, if clearly stated, will enable other investigators to compare their own work. The profile sample must be long enough to yield stable, reliable estimates of the true PSD since shorter samples produce erratic results. If the sample available is too small to yield a reliable PSD, it will not yield reliable estimates of any other type which attempt to characterize the profile. Appendix D mentions a problem called non-stationarity which occurs in many profiles. This problem can be resolved in many cases but it should be noted that if non-stationarity is bad enough to preclude PSD analysis, any other analysis method will be invalid. Finally, references (2) and (3) are highly recommended for study in this important field.

Single Number Indices

A single number index which characterizes some aspects of the profile may be essential for ride studies, serviceability measures, correlation with other variables, contractor comparisons, etc. The only valid single number index discussed so far is the mean squares value. This index can be obtained much more efficiently, rapidly, and accurately from RTP profiles than from the CHLOE. In addition, it can be computed for the displacement profile or any of its derivatives in any desired wavelength band. Since mean squares is the most rudimentary of single number indices, some possible indices based on amplitude distributions or PSD are presented. It should be emphasized, however, that no single number index can completely specify the profile as does PSD.

Mean squares is considered a rudimentary measure because it carries no spectral (i.e., wavelength or frequency) information. Any other index of interest must, therefore, fulfill two requirements. It must provide more information than mean squares and must be statistically valid. The only additional information that could be supplied is frequency, since phase information is not needed. Also, the best way to insure statistical validity is to derive the index from existing, statistically sound measures. Both requirements will be met if the standard measures, namely amplitude distributions and PSD, are computed either at one frequency or averaged over a small fixed band of frequencies. The result would be single number indices that provide amplitude information in selected frequency regions. The question of which frequency band to choose depends on the investigator's needs. A ride study, for instance, could be based on an index computed from wavelengths known to cause bad riding qualities. Studies of paving form placement error might depend on an index computed from wavelengths equal to twice the paving form length. Usefulness of a given index may not always be known but, in any case, statistical reliability can be determined for those indices derived from the basic measures. Two such indices have been discussed at the Research Laboratory and there may be others.

The first of these indices is obtained from the amplitude distribution. This is an example of an index whose usefulness and even physical meaning has not been fully explored. It is however a statistically valid, single number index that embodies both frequency and amplitude information. This index is obtained as follows.

The profile is bandpass filtered to remove all but a narrow band of desired frequencies. An amplitude distribution of the emerging signal is then formed with amount of time plotted vertically and amplitude horizontally. Those familiar with statistics or physics will be aware that amplitudes of narrow band random data which are bounded by zero and infinity often follow the Poisson distribution. This curve has a peak at the amplitude which occurs most frequently and a long tail asymptotic to the increasing amplitude axis. This reflects the fact that while there are no amplitudes less than zero, there may be a few high ones. Normally, a standard distribution curve such as the normal curve is completely specified by its mean and standard deviation. The Poisson curve however, is completely specified by its mean since its mean and standard deviation are directly related. Thus, the distribution obtained from the filter can be tested by chi-square methods to see if it is a Poisson distribution. If it is, the mean will specify the distribution and is the required single number index.

The second index is obtainable from power spectral density estimates or by a pure analog process. The index desired is total power density in a selected narrow band of frequencies. It is easily obtained from the PSD graph by determining the area under the curve in the frequency band desired.

This can be done by computation, planimeter, or any other convenient method. The analog process is equally straightforward. A profile is narrow-bandpass filtered and the emerging signal fed into the computer's squaring network. The squared signal is then integrated resulting in a fixed positive integrator voltage for the run. This figure is divided by the profile length and filter bandwidth to provide power density in the selected band.

Typical Analysis Procedures

Extensive work with RTP transducer data has provided valuable experience in processing methods. Since it is difficult to find comprehensive treatments of this field in the literature this section suggests some practical processing methods. Before proceeding, however, it should be noted that there is one best method of RTP transducer signal processing. This is all-digital processing which was mentioned earlier but appears here in additional detail. Units required are becoming available and consist of a small, single purpose digital computer with multiplexer, analog-to-digital converter, and digital tape unit built in. This device will scan the necessary data channels, convert the voltage to numbers and write them on digital magnetic tape. Channels scanned would be accelerometer, follower-wheel potentiometer (pot), a vehicle speed signal and one or more information channels. Accelerometer and pot channels would have to be low-pass filtered to remove all data above a preselected frequency. This is necessary to establish a definite rate of digitization which should be about four points per cycle of the highest frequency present. Once the transducer signals are on tape there is no limit to processing techniques. Profile processing of all types is made much more efficient and rapid. In addition the data cannot be contaminated as often happens when analog data processing chains are employed. A full array of outputs, from properly scaled plots to analysis printouts, is made quickly available. The digital data format facilitates specialized techniques such as tipping or complex filtering and simulation. In fact, the digital computer is so valuable that digitization is usually necessary at some stage and is best done in the field. Short of this ideal, there are several combinations of analog methods worth exploring.

If profiles are to be analyzed by analog or analog-digital methods a lab based analog computer is essential. This is true even if the RTP is equipped with the optional analog package since it only computes the profile. The lab based unit provides partial or complete additional processing including prefiltering before digitizing. Digitization may be avoided by use of one of the PSD or amplitude distribution analyzers now appearing on the market. These units accept partially processed data from the analog computer to produce amplitude distributions or PSD graphs. These concepts

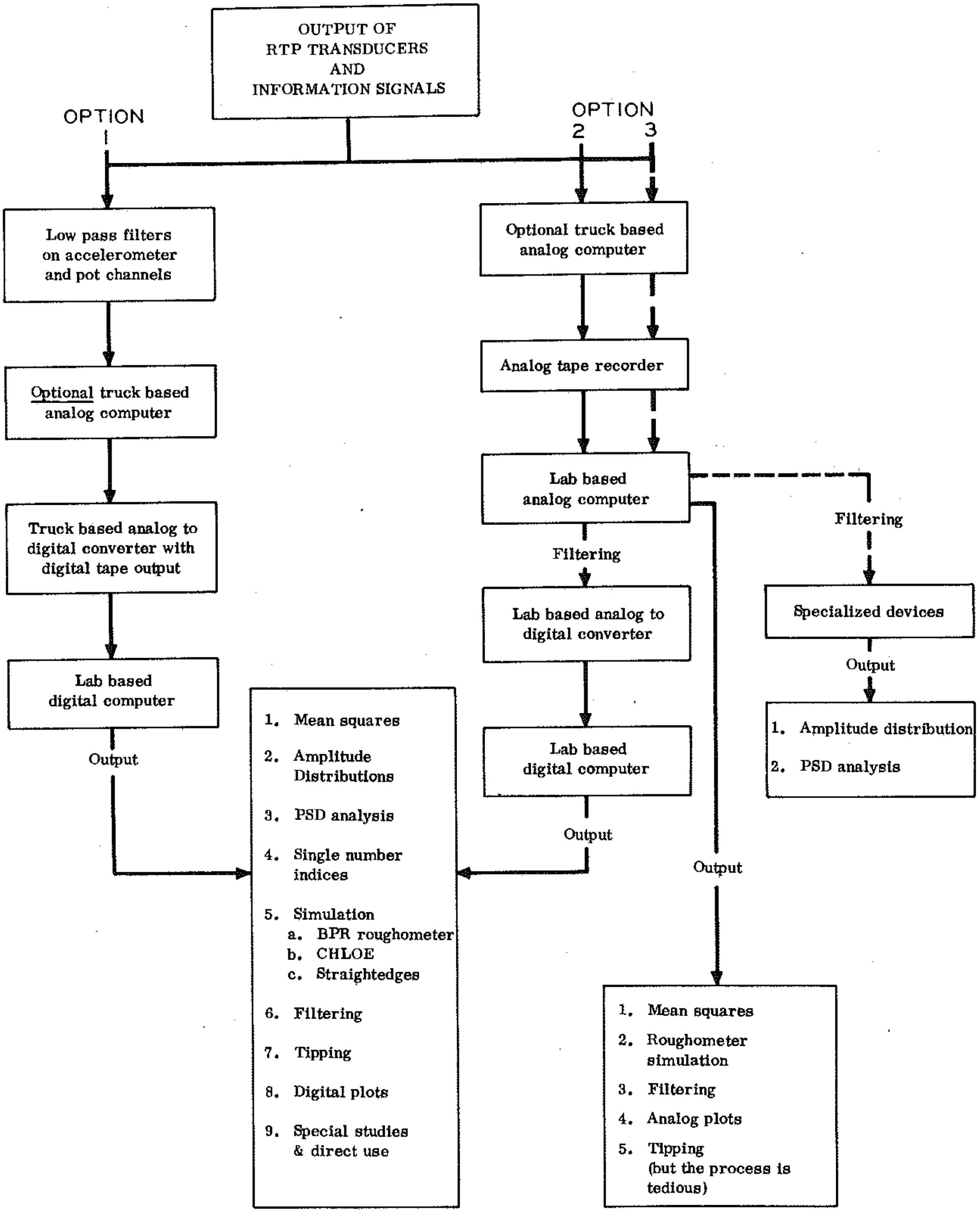


Figure 9. Profile analysis options and associated outputs.

are illustrated in Figure 9 which shows the three data processing chains discussed and the kinds of analysis performed. The blocks are self explanatory but it should be noted that some steps may require partial analysis and storage of intermediate signals on analog tape. These steps are not shown since details of the process will vary for different equipment configurations.

Description of a possible profile analysis run may provide some insight into the practical problems encountered. Assume that a given test section has been profiled and its transducer data recorded on analog magnetic tape. Let three items be required: 1) an inches per mile figure equivalent to the BPR Roughometer, 2) a PSD analysis for a ride study, and 3) a visual plot which has been tipped to restore a survey reference plane. A concise description in steps would be:

1. Select an RTP process filter frequency that will allow 100-ft waves to come through with no phase shift or attenuation. Process the profile and rerecord the results.

2. Synthesize a bandpass filter on the analog computer that removes all waves longer than 100 ft and shorter than 2 ft.

3. Feed the profile from step 1 into this filter then into the digitizer.

4. Send the digital tape, PSD program, tipping program, and keypunched precise level data to the digital computer lab for tipping and plotting to a specified scale and PSD analysis.

5. Partially synthesize a model of the BPR Roughometer on the analog computer, feed in the profile and record intermediate results. (The entire synthesis would be possible on larger machines.)

6. Synthesize the rest of the Roughometer model and feed in the intermediate results to obtain the inches per mile figure.

Two important techniques involved in profile analysis are not comprehensively covered in the literature. The first area, in fact, seems to lack any comprehensive and concise treatment. This is the matter of choosing and manipulating transfer functions and programming them for the analog computer. Knowledge of this area is vital for filtering, differentiating, and integrating profile data. The second area is covered extensively in theory but lacks treatment of applications. This is the problem of setting up and performing the PSD analysis. These techniques are presented in non-rigorous but easily applied form in Appendices F and G. It should be noted that no digital computer programs are included in these Appendices even though many have been written during this study. This is due to the very simple, easy to program algorithms which arise in general signal analysis. Also, the author has observed that data housekeeping operations comprising the bulk of signal analysis programs are unique to each installation. The major problem is understanding the difficult concepts associated with these simple algorithms. There is a third area which is beyond the scope of this report but is extremely important. This is the technique of programming filters for the digital computer. Digital filters can be designed which are far more complex and powerful than can be synthesized on the analog computer.

VII
RELIABILITY, FIELD EXPERIENCE, AND RECOMMENDATIONS

Reliability

With one exception the RTP has been found extremely reliable over 24,000 miles of operation and 6 years of use. The exception is the follower-wheel assembly which is prone to two kinds of failure. The first is potentiometer shaft breakage which usually occurs at the threaded end connected to the wheel bracket. The union is covered by a rubber boot that may hide impending failure. This fitting is now periodically inspected as part of general maintenance. Initially, failure at this point was common, but use of a rigid saddle bracket has reduced breakage to only once in three years. The second problem involves effects of hitting discontinuities in the profile such as faults, pot holes, joint blowups, etc. These are not faithfully recorded because inertial effects of the follower-wheel assembly cause overshoot and bouncing. The worst aspect of this, however, is wear and tear on the follower-wheel tire which can be cut or bruised by such impacts. This limits the RTP profiling speed to some maximum for given road conditions.

Field Experience

Field experience has shown the RTP to be much faster, more efficient, and safer than older profile devices. There are strong reasons for replacing older units with the RTP, e.g., increasing traffic loads and higher average highway speeds. The BPR Roughometer is becoming difficult and dangerous to use at its 20 mph speed; rolling straightedges and CHLOE devices are simply too slow and hazardous. Before long, none of the older devices will be usable without blocking off the lane to be profiled. Another compelling reason to use the RTP is its very high efficiency both in field setup time and data handling. There is virtually no setup time and profiles can be recorded when the test section is reached without leaving the traffic stream. Setup can be performed before leaving the lab and consists merely of operating switches and recording calibration signals. Data processing can be performed entirely by machine once the requisite programs and techniques have been implemented.

Use of the RTP has proven to be very straightforward and, in the author's opinion, routine profiling studies could be performed by non-technical personnel. An operations checklist is basically all that is needed for successful operation. In addition, it is relatively easy to provide training which enables the operator to spot trouble and perform simple repairs in the field. In this connection it should be noted that troubles are mostly mechanical and seldom electronic.

Recommendations

In addition to evaluation, the RTP has been used on a number of actual projects. This extensive study and use has resulted in nine ideas that might expand or improve RTP capabilities. Suggestions two, four, six, and eight have been implemented on the Michigan RTP and are under evaluation at the present time. Feasibility of the remaining suggestions is presently under investigation. The nine suggestions are listed as follows:

1. As mentioned earlier the follower assembly is not only susceptible to damage but also limits profiling speed. In addition the wheel diameter filters out very short waves such as open joints or spalling. A non-contacting distance sensor would solve these problems and probably reduce complexity and setup time. It would permit profiling at any speed and would vastly improve RTP high frequency response while removing overshoot and bounce. At the present time a survey is being conducted to find a non-contacting method such as laser ranging or radar.

2. Ideally, the RTP should employ a servo-drive tape recorder in which tape speed is continuously controlled by vehicle speed. This would eliminate minor vehicle speed variation effects and greatly simplify distance scaling on finished profiles. Such instruments are expensive and add to system complexity. A device has been developed for the Michigan RTP that aids in distance scaling and profile synchronization. It consists of an inductive pickup that senses three metal slugs welded to the follower-wheel. This provides a pulse every six inches of follower-wheel travel. It has also been found advantageous to operate the vehicle at various fixed speeds such as 50, 25, or 12.5 ft per second to aid in distance scaling on the finished profile.

3. The photocell assembly was originally conceived as a crack or joint detector. It has been used, however, as a location marker by placing reflective tape strips on the roadway. This has proved somewhat unsatisfactory since the signal to noise ratio between road features and tape strips is low. This could be eliminated by installing a red sensitive photocell for

example and using red tape markers. This and similar ideas will be explored for the Michigan RTP.

4. A simple oscilloscope, monitoring accelerometer and follower-wheel channels would provide continuous signal quality evaluation. Employment of such a unit would indicate any failures and prevent lost field trips.

5. As mentioned earlier, the tape deck should be in the softest possible shock mounts. This reduces natural frequency of the tape recorder-shock mount system which would prevent much signal contamination. Ideally, the tape deck should float in a well of some kind of foam material. It might be necessary to stabilize the unit with additional holding springs.

6. If a speed indicator box is used, the tachometer generator should be mounted directly at the transmission. It was found that speedometer cable flop noise forced an insensitive setting on the speed control meter. Direct drive to the tachometer generator eliminated this problem and permitted better speed control.

7. One of the problems encountered in synchronizing the RTP profile with the actual roadway has been the matter of longer wave phase shift. Since this phase shift is a function of the profile processing filter, it is natural to ask if there are other filter configurations with less phase shift. There are several types, one of which, the Chebyshev, seems most promising. This filter reduces phase shift at a slight expense in passband flatness. This area needs additional exploration.

8. Elevation difference between right and left wheel paths may be needed for some applications. The optional dual follower-wheel and transducer system does not provide this measure since each profile is measured with respect to its own arbitrary reference. The sophisticated inertial guidance system discussed in suggestion nine would solve the problem but an alternate method is being evaluated at the present time. A heavy semi-circular pendulum with a potentiometer readout has been mounted on the RTP rear axle. A simple calculation involving the regular profile, angle signal from the pendulum, and vehicle geometry produces an imperfect but usable left wheel path profile. Details of the system are not included in this report since evaluation is incomplete at this time.

9. The final suggestion concerns the nature of the entire RTP system. Basically, the RTP is effective for wavelengths up to about 500 ft. This may not be adequate for some applications such as airport runway profiling or some highway applications. Since the RTP is actually a "poor man's"

inertial guidance system it might be possible to obtain very long waves by installing a more sophisticated stable reference. Short of employing a complete inertial guidance system, there would be a vast improvement if long-wave capability of accelerometer tilt error was reduced or eliminated. A gyroscope may supply the accelerometer vertical angle signal necessary to remove this error. The Research Laboratory is evaluating these ideas at the present time.

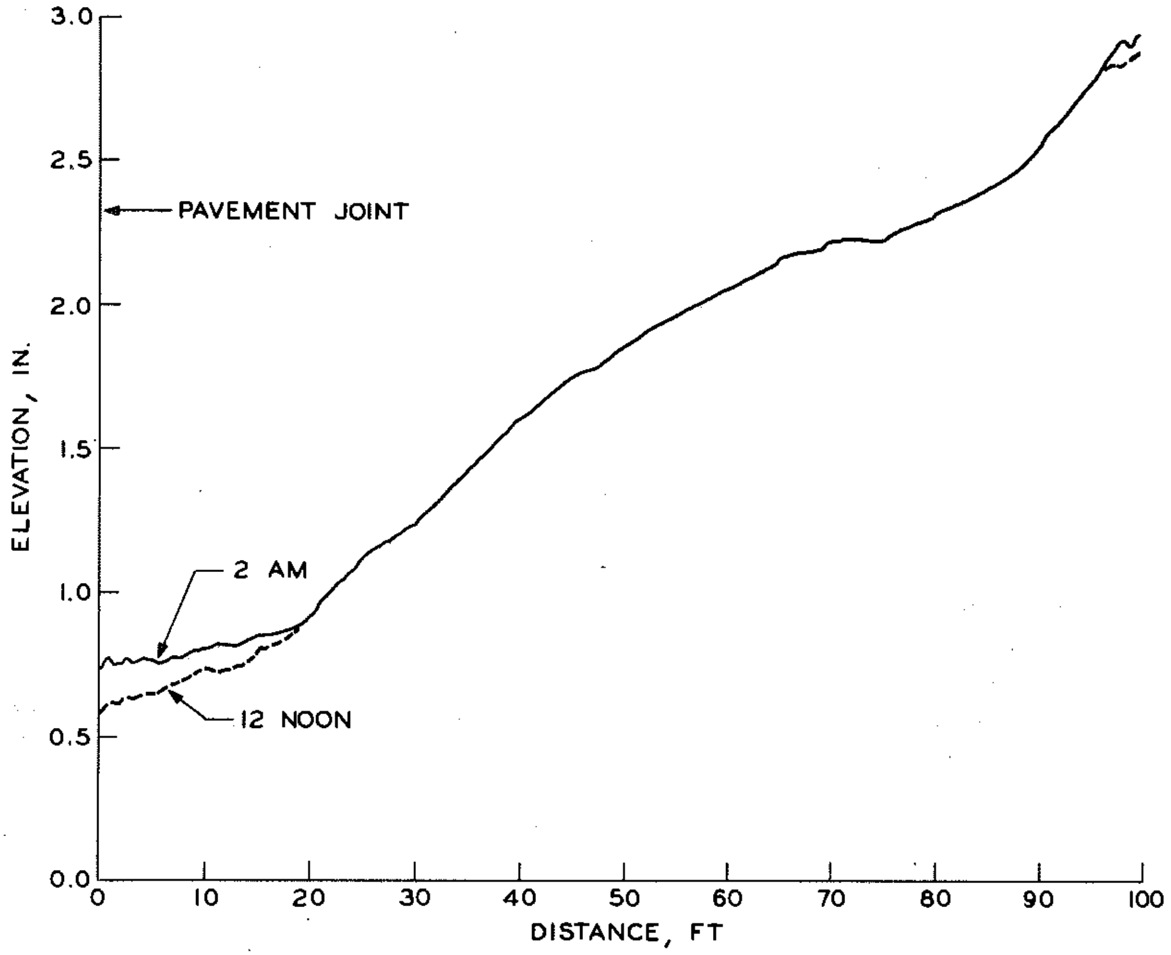


Figure 10. Twenty four hour slab curling study on I-96.

VIII
MICHIGAN RTP APPLICATIONS

The use of RTP profiles in Michigan highway studies is increasing rapidly. Profiles have been analyzed by many methods including power spectral density, analog computer simulations, and visual inspection. A digital computer "roughness package" program is being considered. It will compute all possible indices, power spectra, and other desired measures. Some examples of early and current studies will indicate the diversity of work involving RTP profiles.

1. It has been known for some time that due to temperature and moisture differential, pavement slabs curl. Slab ends tend to curl upward at night when the surface is cooler than the interior, and downward in daytime when surface temperatures are higher than interior levels. The RTP was used to profile selected test sections known to be susceptible to curling. The study was continued for 24 hours and the amount and change in curl are clearly visible. Figure 10 shows one of the joints examined.

2. Expansion of pavements in hot weather often causes the familiar maintenance problem of joint blowups. One of the problems associated with repairing these joints is how much pavement around the damaged joint is heaved up and must be repaired. The RTP has proved valuable in these cases by clearly showing the extent of the damaged area. Figure 11 shows the profile of a joint blowup and the extent of slab heaving in the vicinity. These joints had temporary bituminous patches to limit severity of the fault.

3. Freshly poured concrete bridge deck surfaces were previously finished by hand or with transverse finishing equipment. RTP profiles have been used to compare these methods with a more recent method utilizing a longitudinal finishing machine. Comparison was based on visual inspection of the profile only, although power spectral analysis could be used.

4. A major Research Laboratory effort involved automatic weighing of vehicles in motion by an electronic scale system. The weighing units consist of four platforms as shown in Figure 12. The roadway and platform wheelpath profiles have provided valuable insight into weighing difficulties arising from profile-induced oscillations of the vehicle.

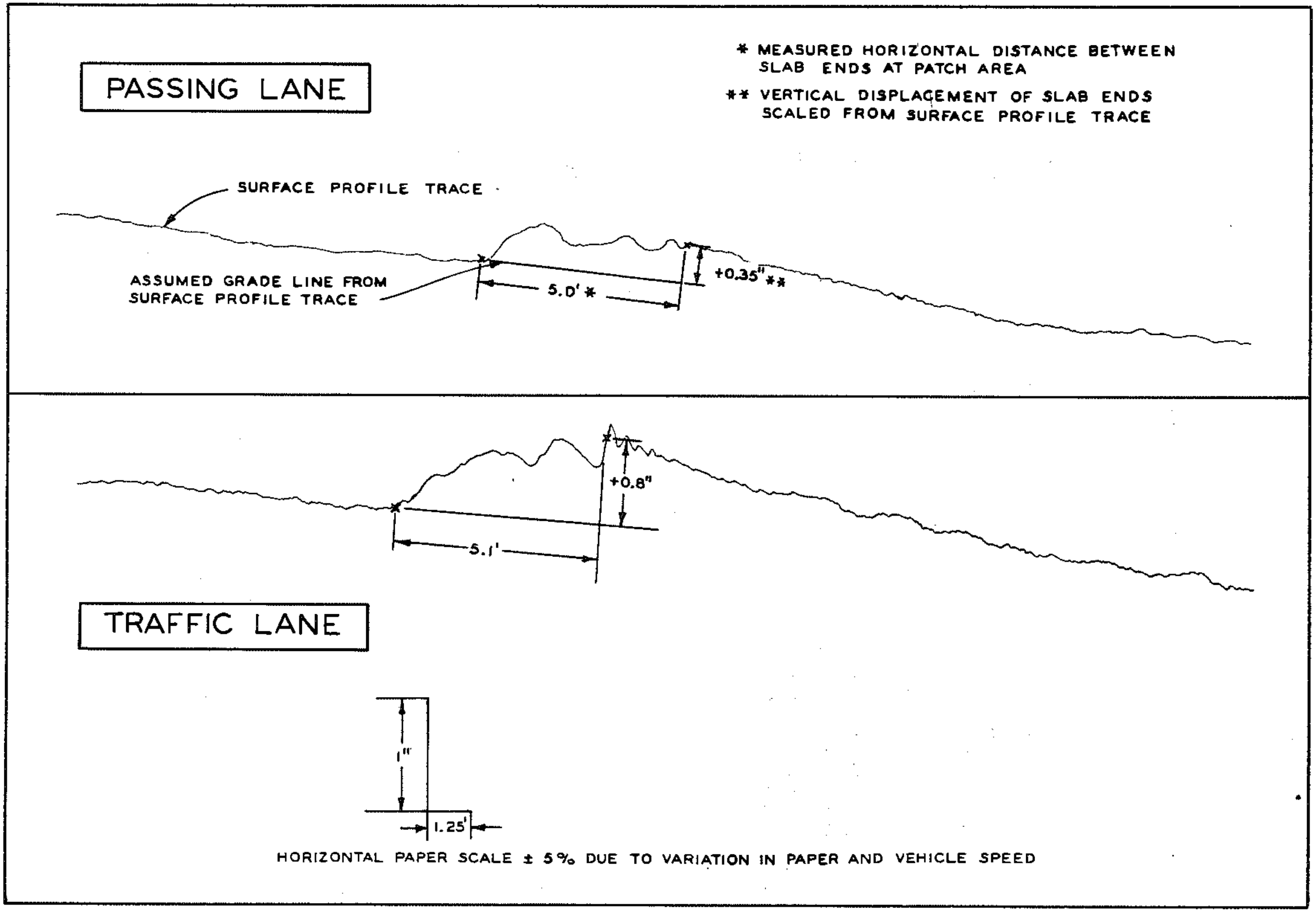


Figure 11. RTP profiles of a blown up joint showing extent of damage.

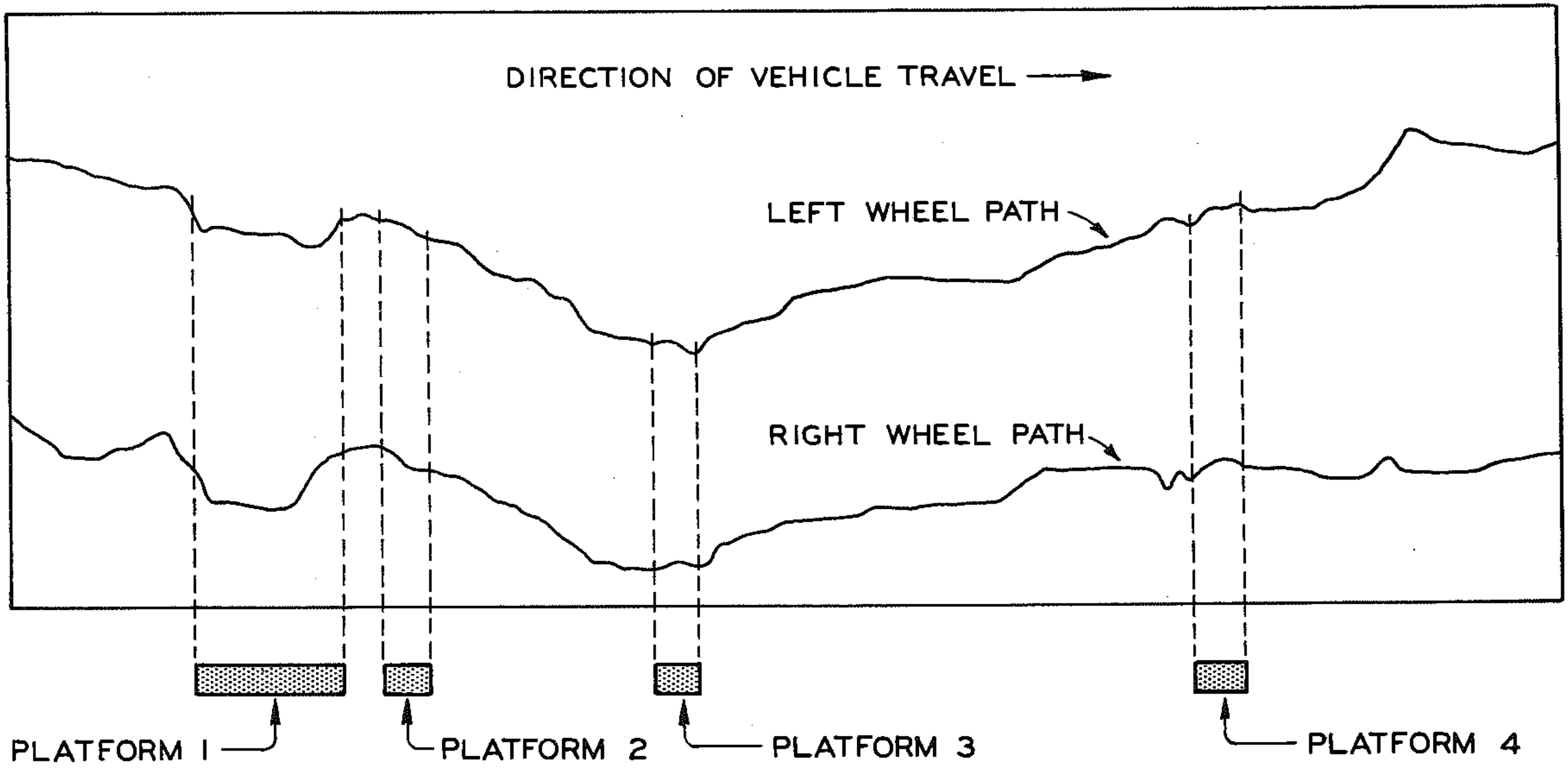


Figure 12. RTP profiles of the Electronic Scale approaches and platforms.

5. Heavily used airport runways are difficult to profile by conventional methods but RTP profiles have been obtained in an effort to spot areas needing repair. The RTP has been limited to maintenance jobs however, since most distressed areas of runway are short enough to be faithfully recorded by the RTP. A complete power spectral evaluation of the runway for aircraft use cannot be performed since aircraft respond to longwave components not recordable by the RTP.

6. Profiles are being recorded on a periodic basis from a series of experimental pavements. Data are merely being stored at this time since analysis methods which will clearly show progressive changes have not been determined. The study covers a number of pavement variables such as continuous reinforcement, no load-transfer dowels, styrofoam insulated subgrade, and asphalt stabilized subgrade.

7. Estimating amounts of bituminous material needed for road resurfacing is difficult and usually inaccurate. Preliminary results indicate that RTP profiles of the inner and outer wheel paths and a digital computer simulation of the paving machine will yield close estimates of material needed. In this case the inner and outer profiles must be recorded with the correct relative elevation. Direct recording of the two wheel paths is not possible with a one wheel path RTP system, so the inner wheel path profile is estimated. This is done by attaching a heavy semicircular pendulum to the rear axle and estimating the inner profile from vehicle geometry and rear axle angle.

8. In some areas, highway construction specifications call for removal of crown upon entering a superelevated curve and restoration of crown when leaving the curve. Since this is done by manual operation of the screed, there has been some concern about changes in general roughness over the transition region. Profiles of the transition regions were compared with profiles of adjacent segments of regular pavement and indicated no significant differences in roughness.

9. An application still in the exploratory stage is use of the RTP accelerometer alone to determine remote displacements. For this application the accelerometer is removed from its mount in the truck and placed on the surface to be displaced. The accelerometer will sense all displacements resulting in 0.002 g's or more acceleration. This technique has been successfully applied to bridge deck oscillations and truck-induced earth tremors.

IX
CONCLUSIONS AND OBSERVATIONS

Conclusions

Five major conclusions have resulted from evaluation and use of the RTP and are listed below.

1. The system does return an accurate profile but accuracy must be interpreted as the report indicates. That is, the profile is completely accurate in the frequency domain but only over a selected band of frequencies. It is also an accurate elevation map for a strip of terrain but, again, this must be qualified. Not only is the profile reference arbitrary but it is linear only over specified lengths. In addition, waves longer than one-tenth the longest wave recorded will be shifted ahead of their actual location and attenuated.

2. There is no question that the RTP is faster, safer, more reliable and efficient than current profile devices. This is very important due to rising work loads for profile devices and increasingly hazardous traffic conditions.

3. Remarkable reductions in profile data processing time and labor are made possible by the RTP. Analyses which were too tedious to apply are now easily performed. A very small work force could handle complete profiling programs.

4. Accuracy, efficient data format, and prefiltering are RTP qualities that permit computation of the standard random signal measures. These are, mean square values, amplitude distributions, and power spectral density.

5. Most reservations about the RTP concern the follower-wheel assembly. As discussed earlier, it places restraints on profiling speed and RTP high frequency response. In addition, it is the one component likely to present a reliability problem. It is useful to stress again the conclusion that a non-contacting distance sensor would be highly desirable in place of the follower-wheel.

All of the objectives set forth in the original study proposal have been accomplished except for the last, i.e., "To write complete specifications on the finally evolved and evaluated system and make a cost analysis."

Considerable effort would be required to accomplish this objective and in the opinion of the investigators the effort expended would serve no useful purpose. General Motors Corporation and their licensee, K. L. Law Engineers, Inc. of Detroit, have cooperatively developed plans, specifications, and costs, and are marketing the system.

Costs for such systems would have little meaning because of the great number of instrumentation options available to prospective users. However, any agency interested in procuring such a system should anticipate a minimum system cost of approximately $50,000 and, depending upon their anticipated application and data processing and recording needs, a maximum of $85,000.

Observations

Extensive use and evaluation of the RTP have generated four observations which are listed below.

1. Evidence suggests that the inertial reference principles embodied in the RTP are natural for profiling work. It seems safe to assume that future profile devices of all sorts will adhere closely to these principles. Advances in transducers and miniature electronic systems will probably lead to a variety of portable and less expensive inertial platform profilometers which may even replace the rod and transit.

2. Experience indicates that there may be strong pressure from highway departments and other potential users to obtain much longer waves than canbe recorded by the RTP. This is particularly true when using the profile as a terrain map. It is often confusing to potential profile users to find known hills and landmarks tipped the "wrong" way. In many cases roadway features such as joint blowups or pot holes are obscured or overemphasized by the non-survey, arbitrary reference. Precise level shots, which solve this problem, may be avoided by an RTP system based on a better inertial platform.

3. Maximum utilization of the RTP requires complete understanding of its capabilities and limitations. Subtleties of the device and its application are such that potential users should anticipate an extensive grounding in theory even though the RTP itself is easy to operate. Serious study of

the device and concepts involved will provide the highway engineer with a very valuable tool.

4. Since traditional profile devices produce inaccurate profiles under inefficient conditions, there has been very little application of profile data to highway problems. It is to be hoped that use of the RTP will extend beyond mere repetition of the limited objectives of present profiling programs. A largely unexplored area is that of direct profile use in problems such as bituminous resurfacing quantity prediction and road maintenance.

ACKNOWLEDGMENTS

This project was supported by the Bureau of Public Roads and--materially and technically--by the General Motors Technical Center. The support and advice of J. B. Bidwell, E. B. Spangler, and W. J. Kelly of the Technical Center contributed substantially to the success of this work.

The author wishes to thank Paul Milliman, designer and supervisor of the project; and Leo DeFrain for his help in the latter part of the project. M. J. Fongers, also of the Highway Research Laboratory, is to be commended for his work in assembling the measurement system, prooftesting and "debugging" it, and for system field operation and data processing throughout the study.

REFERENCES

1. Spangler, Elson B. and Kelly, William J., "GMR Road Profilometer Method for Measuring Road Profile." General Motors Research Publication GMR-452.

2. Bendat and Piersol, Measurement and Analysis of Random Data. J. Wiley and Son, 1966.

3. Marshall, James L., Introduction to Signal Theory. International Textbook Company, 1965.

4. W. N. Carey, Jr., H. C. Huckins and R. C. Leathers, "Slope Variance as a Measure of Roughness and the CHLOE Profilometer." The AASHO Road Test Special Report 73, publication No. 1012 National Academy of Sciences-National Research Council.

5. Hutchinson, B. G., "Analysis of Road Roughness Records." Department of Highways, Ontario, Canada, Report No. 101, 1965.

6. Quinn, B. E. and VanWyck, R., "A Method for Introducing Dynamic Vehicle Loads into Design of Highways." HRB Proceedings 40, 111-122, 1961.

7. Quinn and Zable, "Evaluating Highway Elevation Power Spectra." Highway Research Board Record No. 121, 1965.

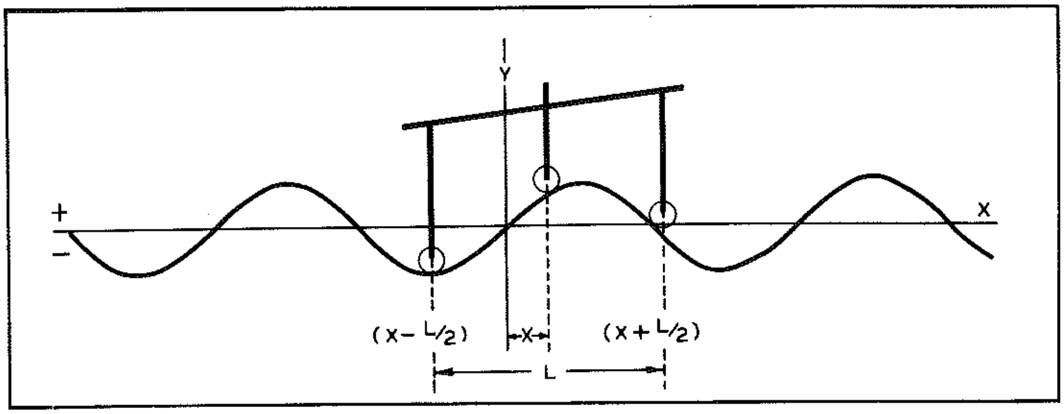
8. Blackman, R. B., Data Smoothing and Prediction. Addison Wesley, 1965.

APPENDIX A
TRANSFER FUNCTION FOR ROLLING STRAIGHTEDGES ON SINE SURFACES

Any linear system that accepts an input and produces an output can be described by a differential equation or graph known as a transfer function. This function specifies the output for any input in terms of a ratio of output-to-input magnitudes. Typical cases might be displacement in -- force out; or acceleration in -- displacement out; or displacement in -- displacement out, etc. A particularly useful presentation of the transfer function is known as a Bode plot. This is a graph with magnitude ratio plotted vertically and input frequency or wavelength plotted horizontally. It shows at a glance which frequencies are being amplified, attenuated or left unchanged by the given system. The Bode plot is usually obtained by feeding a sine wave of known amplitude and frequency into the actual system or its equivalent mathematical or analog computer simulations. The peak output is then divided by the peak input and the ratio plotted against frequency to form one point. This process is repeated for all frequencies of interest resulting in a complete plot.

Since the Bode plot for the RTP is known, it was thought valuable to obtain them for the rolling straightedges, CHLOE, and BPR units to aid in system comparison. The rolling straightedge plots were obtained analytically; the CHLOE plot was obtained by analytical and simulation techniques; and the BPR plot by analog computer simulation. CHLOE analysis is discussed in the next Appendix (B) and the BPR simulation shown in Appendix E. Development of the straightedge Bode plots is given below.

Consider a straightedge profilometer situated on a pure sine wave profile as shown:



An equation is sought that will give the output displacement of the center wheel as a function of profilometer geometry, profile frequency, and distance along the roadway. The transfer function will then be obtained by dividing the output equation by the input equation. To do this, the following quantities are defined:

A - peak sine wave amplitude

n - number of cycles per foot (this frequency in radians = $2\pi n$)

L - distance between front and rear wheels of straightedge

x - any distance along the x axis

O - output of the center wheel

T - transfer function for the profilometer.

It is evident that displacement of the center wheel is affected by elevation of the end wheels as well as the elevation being measured. It can be deduced from the drawing that displacement of the center wheel due to sine wave amplitude under the left wheel is given by $-1/2\ A \sin 2\pi n(x-L/2)$. Displacement of the center wheel itself is given by $A \sin 2\pi nx$. Finally, displacement of the center wheel due to sine wave amplitude under the right wheel is given by $-1/2 A \sin 2\pi n(x+L/2)$. Total displacement of the center wheel (output) is found by summing these three displacements:

$$O = A \sin 2\pi nx - A \sin 2\pi nx \cos \pi nL; \text{ and then,}$$

$$O = (1 - \cos \pi nL) A \sin 2\pi nx$$

If the last equation is divided by the input amplitude under the center wheel the result is:

$$T = \frac{(1 - \cos \pi nL) A \sin 2\pi nx}{A \sin 2\pi nx} = 1 - \cos \pi nL$$

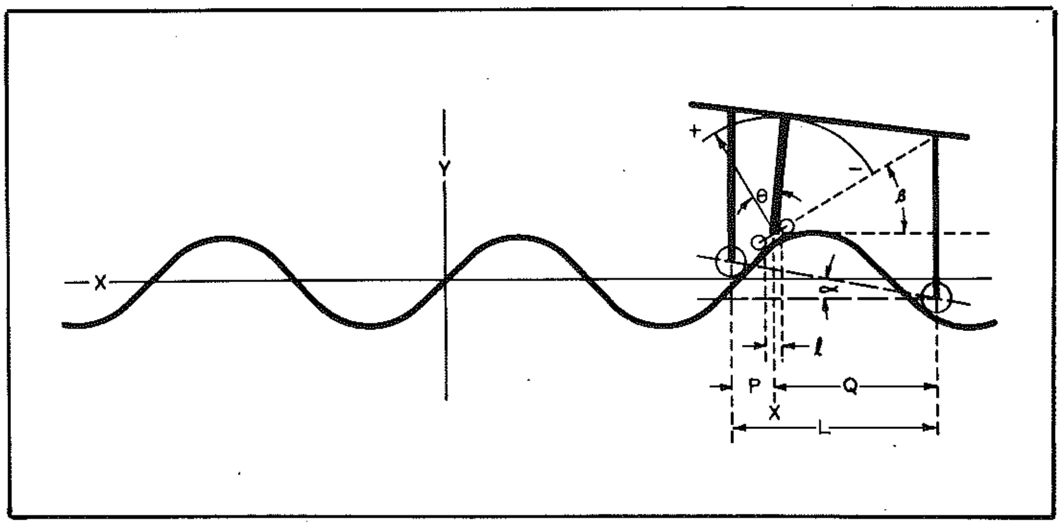
$T = 1 - \cos \pi n L$ is the transfer function for any rolling straightedge and gives the ratio of output to input as a function of sine wave frequency and profilometer length. For a given profilometer length, the Bode plot can be obtained by evaluating the transfer function for all frequencies of interest and plotting the results. This can be rather tedious, however, and close inspection of the transfer function reveals two features that allow a Bode plot to be sketched directly. First, the function reaches a maximum of 2 when the product nL is an odd integer and a minimum of 0 when even. Next, the function ceases to oscillate and descends asymptotically to zero when n is less than 1/L.

This analysis is based on a profilometer with simple end wheels (bogey wheels). Most profilometers have complex bogey wheel arrangements designed to reduce the effect of bogey displacement on the center wheel. Although the analysis could be worked out for any bogey wheel arrangement, it was felt unnecessary since the output will always be affected by the end-point elevations. Moreover, complex bogey arrangements may defeat their own purpose if wheel path differences sensed by the various bogey wheels more than offset the improvement.

APPENDIX B
TRANSFER FUNCTION FOR CHLOE DEVICES ON SINE SURFACES

The preliminary remarks concerning transfer functions found in Appendix A apply equally to analysis of the CHLOE device. In this case, however, the output is an angular quantity rather than displacement. An equation is sought that will provide the angular output of a wiper arm attached at the center of a dolly carrying two closely spaced sensing wheels. Although the angularity signal is normally converted to a quantity similar to the profile's first derivative, a transfer function based on angularity will adequately specify system response. Analysis of the CHLOE is essentially the same but more complex than that for the straightedge. Relationships among various angles of the CHLOE are provable by geometric methods but are given here by inspection.

Consider a CHLOE type device situated on a sine wave profile as shown:



The following definitions apply to this analysis:

θ - output angle sensed with respect to the CHLOE frame

α - angle formed by difference in elevation between front and rear wheels measured with respect to the zero line

β - angle formed by difference in elevation between front and rear sensing wheels measured with respect to the zero line

A - peak sine wave amplitude

n - number of cycles per foot (frequency in radians = $2\pi n$)

x - any distance along the x axis

L - spacing between front and rear wheels of the CHLOE

l - spacing between the CHLOE angle sensing wheels

P - distance from center of sensing wheels to rear axle

Q - distance from center of sensing wheels to front axle

Geometry of the CHLOE is such that:

$$\theta = \alpha + \beta$$

θ is the angular output fed into the CHLOE computer. Expressions for the angles α and β can be derived by the rule "...the tangent is equal to rise over run." In this case, rise is difference in elevation between wheels, and run is spacing between axles. This leads to the following expressions for α and β

$$\alpha = \tan^{-1} \frac{A \sin 2\pi n\,(x - P) - A \sin 2\pi n\,(x + Q)}{L}$$

$$\beta = \tan^{-1} \frac{A \sin 2\pi n\,(x + l/2) - a \sin 2\pi n\,(x - l/2)}{l}$$

The output function $\theta = \alpha + \beta$ does not simplify readily and it is evident that the transfer function would remain a function of profile amplitudes as well as frequency and CHLOE dimensions. This difficulty was avoided by evaluating the function with a digital computer and the maximum angle for a number of wavelengths found. It can be shown that the true maximum angle (ψ) is given by subtracting the angle of a line at right angles to the profile wave at zero, from 90 degrees ($\pi/2$ radians). The equation is derived by taking the arc tangent of the reciprocal of the maximum profile derivative from $\pi/2$ radians. That is:

$$\psi = \frac{\pi}{2} - \tan^{-1} \frac{1}{2\pi n A}$$

The CHLOE maximum angle for each wavelength was divided by the true maximum angle to provide the Bode plot shown in the report. Changes in the sine wave amplitude (A) had very little effect on the amplitude ratio, so analysis was confined to A = 1.5 inches.

The analysis given may depart somewhat from the actual device since there are mechanical details not accounted for. Nevertheless, this should be a close approximation since essentials of the system cannot be changed extensively by mechanical means.

APPENDIX C
DYNAMIC ACCURACY ANALYSIS CRITERIA

The piecemeal analysis of dynamic accuracy results from problems caused by several features common to most road profiles. Analysis of the RTP using profile data is entirely analogous to testing an amplifier frequency response using an input with extreme difference in volume between low and high frequencies. The low frequency sounds would come through very loudly making the weak high frequency sounds virtually inaudible. Such is the case with most road profiles. The longer wave, hence low frequency features have amplitudes much greater than shorter wave, high frequency features. The analogy with amplifiers is even more realistic because the difference in decibels between low and high frequency profile features is comparable to that between program material and high frequency noise in a good amplifier, usually 40 db or more. It is obvious that amplifier noise is completely drowned out even by quiet records.

Profiles exhibit another feature, however, which establishes the points of change from one analysis type to another. Considering the profile as a composite signal with different "loudness" at each frequency, it is usually found that the "loudness" changes in three distinct patterns. First, the "loudest" signals occur at the longest wavelengths (lowest frequency). As frequency goes up, the "volume" falls less rapidly over a larger span of frequencies until the shortest wave (highest frequency) region is reached. From this point the "volume" again falls rapidly as the wavelengths go down to a few inches. These regions of change generally occur as follows:

1. Very rapid drop in intensity from 100- to 50-ft waves.
2. Slower drop in intensity from 50- to 10-ft waves.
3. Rapid drop in intensity from 10- to 1/2-ft waves.

This effect is highly visible on plots of profile survey data. If the big hills and valleys stay on the paper, almost no surface details are visible, because their amplitudes are so small in comparison.

With these facts in mind, the analysis rationale can be readily demonstrated. To begin with, it may be recalled that the coherence function, which expresses the correlation between two signals in a narrow frequency band, is the best measure to use for the entire analysis. It was noted, however, that the rapidly falling profile power spectrum precluded use of the coherence function for all wavelengths. It was possible to use direct, pointwise correlation for wavelengths from 100 to 50 ft for two reasons.

1. The wavelength band of 100- to 50-ft waves is in fact a narrow frequency band. The frequency range is 0.01 to 0.02 cycles per foot, which is exactly one octave. An octave is defined as any band over which the frequency doubles.

2. The great difference in strength between low and high frequency data gives the same effect as if all wavelengths shorter than 50 ft had been filtered out of the profile. The shortwave amplitudes were so low in fact, it was unnecessary to filter them out by artificial means. This fortuitous pair of facts exactly satisfy the requirements for pointwise correlation. It is the same as doing one narrow-band region of the coherence function by itself.

The coherence function was used from 50- to 1-ft waves because the profile power spectrum fell off less rapidly over this region. In this case, however, it was essential to filter out the powerful low frequency signals consisting of 100- to 50-ft waves. This was done by synthesizing filters on the analog computer and feeding the profile through these before digitization. This was actually done in two steps with the coherence function computed for 50- to 12.5-ft waves, then for 12.5- to 1-ft waves. This further reduced biasing effects of the falling profile power spectrum. The regions 50- to 12.5-ft and 12.5- to 1-ft waves are not narrow frequency bands so direct correlation could not be substituted for coherence analysis.

The region from 1- to 1/2-ft waves is again a narrow frequency band of one octave so direct correlation could be used if all wavelengths longer than 1 ft were filtered out. This frequency region could not be included in the coherence analysis from 12.5 to 1 ft because there was some difficulty in getting these very shortwave features in phase with the precise level profile. Neither method was needed, however, since it is easy to simply construct a known waveform and use direct-fit comparison as was done for this study.

APPENDIX D
THE NATURE OF PROFILE RANDOMNESS

Road profiles are referred to as random signals in this report and this view may require some elucidation. The following remarks about the nature of profile randomness are based on the author's experience with profile signals examined during the course of this and other studies. Statistically valid statements about the nature of profile randomness will require a definitive and probably extensive study. Before proceeding, it may be well to point out that the profile is considered a signal for two reasons:

1. The profile is an actual input signal to the wheels of a vehicle moving over the surface.

2. The signal viewpoint allows application of powerful frequency domain analysis techniques.

A vehicle "sees" the profile in terms of frequency in cps which is a function of speed and profile wavelength. The profile is viewed in terms of cycles per foot for other frequency domain analyses. Vehicle speed is the only parameter needed to make the simple transition between cycles per foot and cycles per second. It should also be noted that reference to a random signal being composed of "frequencies" is based on the "Fourier viewpoint." This view holds that any signal, random or not, which meets certain criteria can be reproduced by summing an infinite number of pure sine waves. Each sine wave has a specific amplitude, frequency, and phase to reproduce a given signal.

Four general remarks about random signals will clarify the discussion of road profiles. A very good intuitive grasp of random data is obtained by considering pure "white noise" and doing some analog manipulations of this signal. First of all, pure white noise would be very difficult to handle if it actually existed. This is because it would have to contain a finite amount of power at all frequencies. This would be an infinite amount of total power since there are infinitely many frequencies. A plot of such a signal with respect to time would be strange indeed. Since infinitely high frequencies would be present there could be no visible transitions from one amplitude to another no matter how much the time scale was stretched out. Clearly, such a signal is impossible in the real world. This illustrates the concept of band limited or "pink noise." In reality, all so called white noise is pink or band-limited noise. Band limited means that a signal has some power over a given band of frequencies and has no power outside that band. Instead of white noise or pink noise it is better to speak of broad band or narrow band noise. An interesting feature of this concept is that there is no limit to narrowness of the band. Thus,the following procedure is perfectly valid. A broad band random noise generator feeds its signal into a very narrow bandpass filter centered at 30 cps for example. Assume further that the filter bandwidth extends from 29.99 to 30.01 cps. The signal from the random generator emerging from this filter will tend to look like a 30 cps sine wave! It is, nevertheless, a random signal and a close watch will reveal slight shifts in frequency and amplitude as time goes on. This concept of narrow band random phenomena will illuminate important features of the profile signal.

The second property of random noise also needs some clarification. This is the matter of the amplitude probability distribution. If a random process is the result of a number of different random processes the Central Limit Theorem predicts a normal (Gaussian) distribution of amplitudes. In other words, the result of combining a number of different random amplitude operations is a random process with normal amplitude distribution no matter what the individual amplitude distributions were. Although proof is beyond the scope of this discussion, it should be noted that the distribution type is not unduly important in highway work and furthermore places no restrictions on shape of the power spectrum.

A third property of a random signal is its power or strength at various frequencies. All frequencies in a random signal need not have the same strength. This difference in power at various frequencies is described by the power spectral density function and is probably the most important characteristic of any random process. Narrow band random components of the signal often have power different from adjacent frequencies which makes them highly visible on the power spectral graph as sharp peaks or valleys.

The fourth observation about random processes concerns the concept of stationarity. Broadly speaking, a stationary random process has the same average amplitude and amplitude variance at all times. In the profile case this would mean that the mean and variance of the profile amplitude would remain the same no matter which piece of a given test section is examined.

These four concepts, narrow band noise, amplitude distribution type, power differences, and stationarity allow a description of the kind of randomness found in typical road profiles. Two aspects of road profiles can be immediately explained. First, the amplitude distribution of most profiles does seem to be roughly normal. Departure from this ideal seems to be caused by extremely powerful longwave components which fall in a narrow frequency band. It was noted previously, however, that this is not too important for profile analysis. Second, most profiles are not stationary and in fact both the mean and variance of the profile amplitude change for different parts of the test section. On newer concrete and bituminous pavements, however, the variance is quite constant even though the mean changes. This matter of stationarity is important in profile analysis and is discussed again in Appendix G.

The remaining properties, power change and narrow band noise are important characteristics of profile randomness. First of all it has been generally observed that the rate of fall in power as wavelength shortens is about 20 decibles per frequency decade; this is equivalent to 6 decibels per octave. It is interesting to note that this rapid drop in power is roughly the same as that caused by a first order low-pass filter. It has also been noticed that the power curve merely moves up as a unit for rough roads and down as a unit for smooth roads without changing its general shape or rate of power loss. If the spectral shape is found to be constant for most roads it may be possible to compute a relatively simple but comprehensive roughness index based on the general power level.

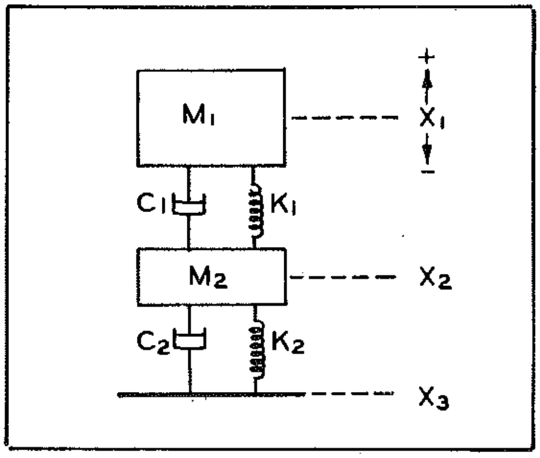
The final observation about profile randomness concerns the existence of narrow band random components in the broader band profile signal. If, for example, irregularities in placing adjacent paving forms were prevalent, a corresponding narrow band random component would manifest itself as part of the general random signal. This would appear as a sharp peak on the power spectral curve at a wavelength equal to twice the paving form length. Examples of other processes causing narrow band random components might be out-of-round paving finisher wheels or interactions of bituminous resurfacing machines with certain profile frequencies. Power spectral graphs for a number of roads of all types have not shown widespread existence of these narrow band components. Occasionally there are broad peaks showing higher power levels across fairly broad bands and one or two narrower peaks have been found. In general however, the drop in power is fairly uniform as the wavelength goes from 100 to 4 ft.

In closing it should be mentioned that the power spectral density program developed at the Laboratory includes a non-parametric test for randomness which is applied to each profile processed. Invariably this test has shown that the profile signal indeed stems from a random process.

APPENDIX E
SIMULATION OF THE MICHIGAN BPR ROUGHOMETER

Extraction of the BPR Roughometer, inches-per-mile index from the RTP profile illustrates the contrast between analog and digital simulation. Simulation of the BPR Roughometer on a digital computer would be difficult to program and time consuming to run. It is relatively straightforward for the analog computer but requires an extensive computer to achieve a complete model. A complete model would also require transport delay equipment to provide the time shifted profile seen by successive wheels. The simulation presented here is an approximation of the true Roughometer since the Laboratory analog computer is a small scale, twenty amplifier unit. Even this rough approximation, however, requires a pass through each of two circuits with storage of intermediate results on analog tape. The recorded RTP profile is first passed through a model of the BPR Roughometer and relative displacement between axle and frame recorded. This signal is then passed through a filter and a circuit which duplicates action of the Roughometer integrating clutch. The integrating clutch circuit is noteworthy since an electronic diode with near perfect characteristics has been developed. This was necessary since even high quality computing diodes are non-linear and have a 0.3 volt forward drop which introduced unacceptable error. The Roughometer model given here is based on actual measured parameters from Michigan's unit. It is probably necessary to measure these parameters for each Roughometer simulated. Although correlation between model and Roughometer is high and standard error small, the model returns a much higher numerical value. This does no harm since the Roughometer measure is normally estimated from the RTP measure by means of a regression equation which must be determined for each Roughometer simulated. This characteristic can be attributed to incompleteness of the model and unknown tire effects.

The circuit is straightforward except for differentation of the profile which is combined with second order, low pass Butterworth filtration set at 30 cps for a playback speed of 50 feet per second (See Appendix F). Another feature of the model is a provision to adjust its response curve for any profile playback speed. Since the Roughometer normally operates at 20 miles per hour the model response curve must move up or down the frequency scale if the profile is played in at higher or lower speeds. The model response rate can be increased or decreased by multiplying the input to its integrators by factors greater or less than one. Thus, an additional gain of two for each integrator was preceeded by a potentiometer set at 0.50 giving a net gain of one and leaving the model unchanged. Setting the four pots at 1.000 however, speeds the model up by a factor of two which enables a profile play-in speed of 40 mph. In the case at hand, the profile is played in at 34.1 mph which is 1.71 times faster than 20 mph. The pots are set at 0.855 to give a net gain 1.71 to each integrator. Three other features of interest are: 1) pots 7 and 19 which remove the gain of 20 and convert feet to inches prior to recording the models output for the next step, 2) the use of common mode rejection which has been found very necessary, and 3) a scaling pot for adjusting the model using calibration signals representing one inch. Development of the model follows and it is assumed that the reader is familiar with analog computer program development. The system equations are based on the following mechanical model.



where:

M_1 - mass of the Roughometer frame

C_1 - viscous damping coefficient between frame and axle

K_1 - spring constant between frame and axle

M_2 - mass of the wheel and axle assembly

C_2 - viscous damping coefficient between tire and ground

K_2 - tire spring constant

X_1 , X_2 , and X_3 - absolute displacement of the frame, axle and profile respectively

The system equations result from summing forces on each mass and are:

$$M_1 \ddot{x}_1 - C_1 (\dot{x}_2 - \dot{x}_1) - K_1 (x_2 - x_1) = 0 \text{ for } M_1$$

and:

$$M_2 \ddot{x}_2 - C_1 (\dot{x}_1 - \dot{x}_2) - C_2 (\dot{x}_3 - \dot{x}_2) - K_1 (x_1 - x_2)$$

$$-K_2 (x_3 - x_2) = 0 \text{ for } M_2.$$

The constants were obtained by measuring the Michigan BPR Roughometer and are:

M_1 = 22.9 slugs

C_1 = 24.0 lb-secs/ft

K_1 = 3492 lbs/ft

M_2 = 2.02 slugs

C_2 = 34.4 lb-secs/ft - tire damping has little effect on the system but was included for completeness

K_2 = 21600 lbs/ft

The maximum profile displacement (x_3) was assumed equal to 0.5 ft. The undamped natural frequency of M, is;

$$\omega_{n_1} = \sqrt{\frac{K_1}{M_1}} = 12.3 \text{ radians/sec}$$

For M_2

$$\omega_{n_2} = \sqrt{\frac{K_1 + K_2}{M_2}} = 11.4 \text{ radians/sec}$$

Maxima for the derivatives based on 0.5 ft maximum displacement are:

$$\dot{x}_1 = x_1\,\omega_{n_1} = (0.5)\,(12.34) = 6.17 \text{ ft/sec}$$

$$\dot{x}_2 = x_2\,\omega_{n_2} = (0.5)\,(111.4) = 55.70 \text{ ft/sec}$$

$$\ddot{x}_1 = \dot{x}_1\,\omega_{n_1} = (6.17)\,(12.34) = 76.14 \text{ ft/sec}^2$$

$$\ddot{x}_2 = \dot{x}_2\,\omega_{n_2} = (55.7)\,(111.4) = 6204.9 \text{ ft/sec}^2$$

$$\ddot{x}_3 = x_3\,\omega_{\text{profile}} = (0.5)\,(188.4) = 94.2 \text{ ft/sec}$$

This leads to a scaling for the variables and their derivatives as follows:

$[20x_1]$, $[\dot{x}_1]$ and $[\ddot{x}_1/10]$

$[20x_2]$, $[\dot{x}_2]$ and $[\ddot{x}_2/500]$

$[20x_3]$ and $[\dot{x}_3/10]$

The system equations are now re-written with the scaled variables, rearranged and adjusted to maintain proper scaling.

$$\left[\frac{\ddot{x}_1}{10}\right] = \frac{10\,C_1}{10\,M_1}\left[\frac{\dot{x}_2}{10}\right] - \frac{C_1}{10\,M_1}\left[\dot{x}_1\right] + \frac{K_1}{200\,M_1}\left[20\,x_2\right] -$$

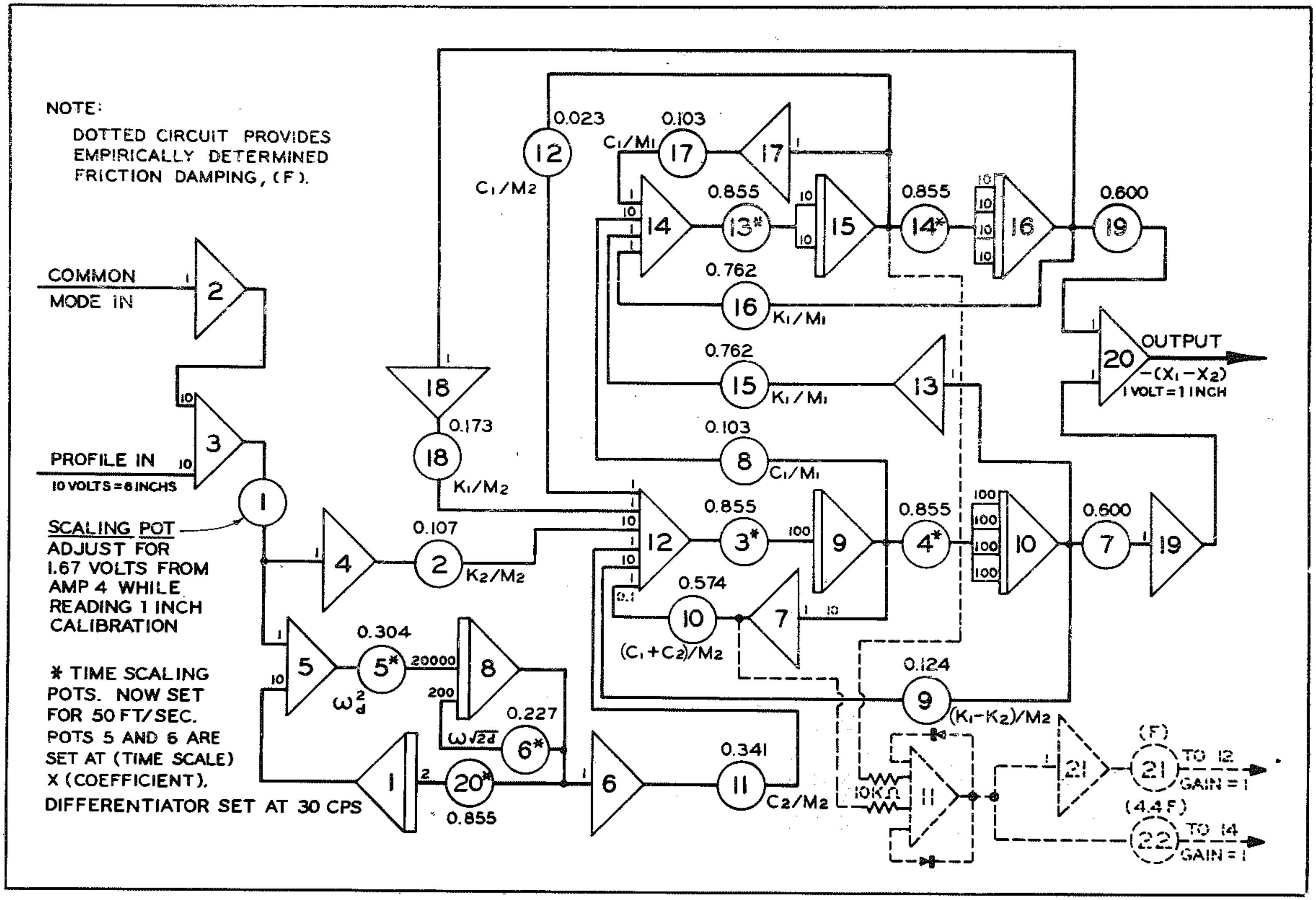
$$\frac{K_1}{200\,M_1}\left[20\,x_1\right] \qquad \left[\frac{\ddot{x}_2}{500}\right] = \frac{C_1}{500\,M_2}\left[\dot{x}_1\right] - \frac{10\,(C_1 + C_2)}{500\,M_2}\left[\frac{\dot{x}_2}{10}\right] +$$

$$\frac{10\,C_2}{500\,M_2}\left[\frac{\dot{x}_3}{10}\right] + \frac{K_1}{10000\,M_2}\left[20\,x_1\right] - \frac{K_1 + K_2}{10000\,M_2}\left[20\,x_2\right] +$$

$$\frac{K_2}{10000\,M_2}\left[20\,x_3\right]$$

These equations lead to the circuit in Figure A which also includes the additional features mentioned earlier. The recorded RTP profile, computed such that 100-ft waves are retained, is played into this circuit and the output $[-(x_1 - x_2)]$ recorded.

The next step duplicates action of the Roughometer integrating clutch to obtain the inches per mile index. Recorded output of the model is played at 50 ft per second into a second order, low pass Butterworth filter set at 20 cps. Common mode rejection is also used at this stage. The filter output goes to a circuit that combines differentiation with third order, low pass Butterworth filtration set at 30 cps. This combination was chosen empirically to give the most consistent agreement between the model and Roughometer. The differentiated signal goes to the electronic diode which was developed here to replace conventional computing diodes. The circuit is straightforward and works as follows. Amplifiers 9 and 10 are extremely unstable with respect to polarity of the input. Any slight voltage will slam amplifier 9 up to 0.3 volt and amplifier 10 up to 0.6 volt which is the maximum allowed by the computing diodes in feedback mode. This level is amplified up to about 9 volts and is fed with alternate polarity to the FET gates. This turns one FET on hard and the other off hard. The original differentiated signal passes through the turned on FET and is integrated to provide action of the Roughometer integrating clutch. Note that polarity of the positive signal component is reversed to provide a negative signal to the integrator at all times. At the end of a run the integrator will contain a voltage equal to the total number of displacement inches in one direction between axle and frame of the model. This number is to be divided by length of the test section to give the inches per mile figure. Capacity of the integrator is 1,000 in. which is adequate for most runs. The final number must be multiplied by 0.824 to compensate for a calibration difference between the Michigan Roughometer and its model. This number will probably differ for each Roughometer. The circuit diagram is given in Figure B.

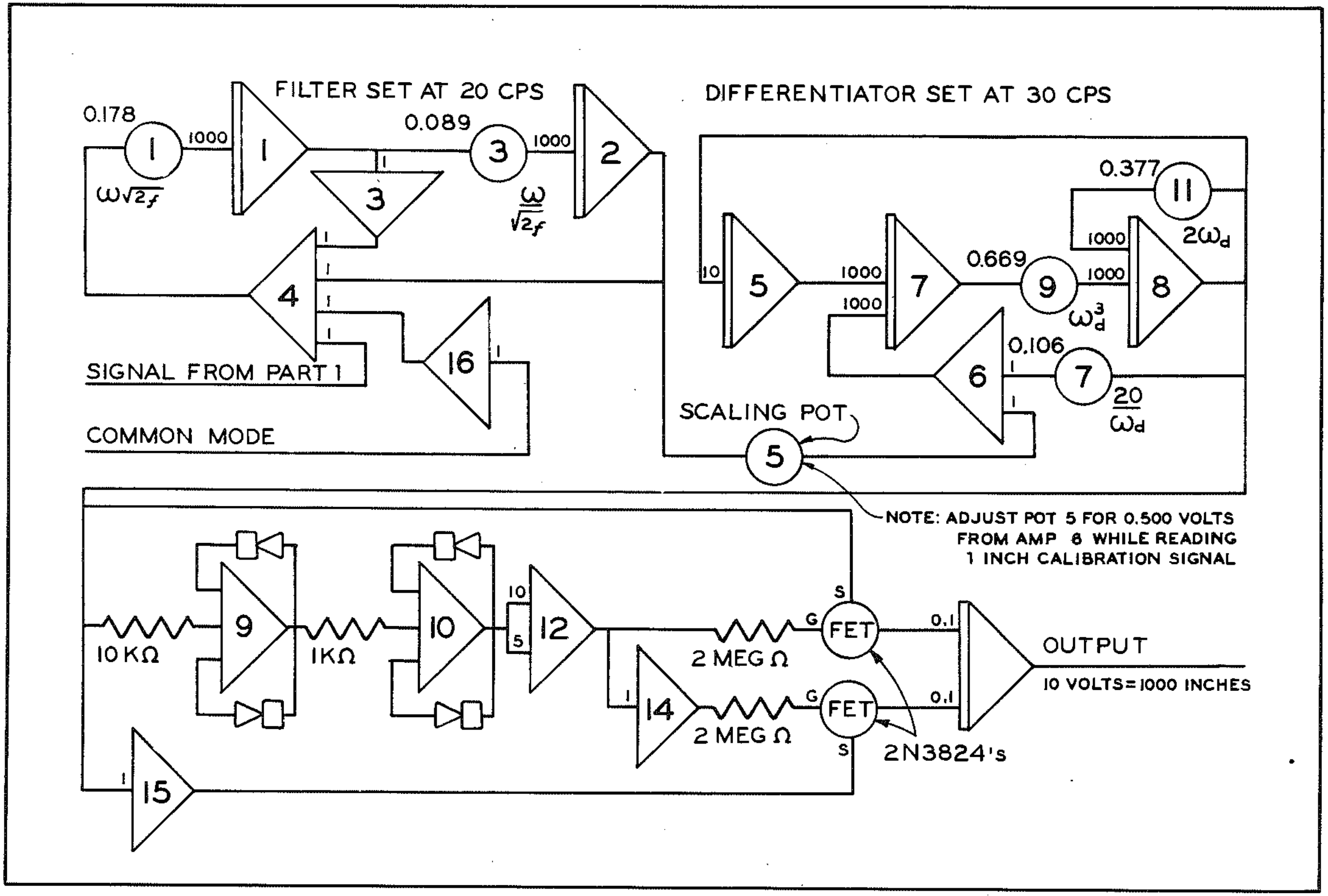


NOTE:
DOTTED CIRCUIT PROVIDES EMPIRICALLY DETERMINED FRICTION DAMPING, (F).

SCALING POT
ADJUST FOR 1.67 VOLTS FROM AMP 4 WHILE READING 1 INCH CALIBRATION

* TIME SCALING POTS. NOW SET FOR 50 FT/SEC.
POTS 5 AND 6 ARE SET AT (TIME SCALE) X (COEFFICIENT).
DIFFERENTIATOR SET AT 30 CPS

Figure A. Analog computer simulation of the Michigan BPR type Roughometer.



NOTE: ADJUST POT 5 FOR 0.500 VOLTS FROM AMP 6 WHILE READING 1 INCH CALIBRATION SIGNAL

Figure B. Filter, differentiator and electronic diode comprising remainder of the Roughometer simulation.

APPENDIX F

TRANSFER FUNCTION SYNTHESIS FOR ANALOG COMPUTERS

The lab based analog computer has been found indispensible for pre-processing profile information prior to digitization. So far, pre-processing has been confined to filtration, integration, differentiation, algebraic operations and simulation. Pre-processing provides two important advantages. First, analog filtration permits a rational approach to digitization. The number of digital samples needed to reconstruct a continuous function is at least two and preferably four points per cycle of the highest frequency in the signal. Filtration of unwanted high frequency components such as profile texture, analog tape hiss and general high frequency noise can greatly reduce the sampling rate and save large amounts of digital computer time. The second value of pre-processing is the ability to perform some operations that would be difficult to program and time consuming for the digital computer.

Three related and important areas of analog computer use are not concisely covered in the literature seen to date. This is the matter of writing and programming transfer functions on the analog computer to perform filtration, differentiation, and integration. These operations are related because differentiation and integration cannot be successfully performed on the analog computer without combining the operations with filtration. This problem arises because low and high frequency noise components which are always present, are greatly amplified by integration and differentiation respectively. Thus, when integrating, a high pass filter is needed to suppress low frequency noise. Differentiation requires suppression of high frequency noise with a low pass filter. Moreover, the problem cannot be solved by filtering first then integrating or differentiating. The filtration must be combined with and occur simultaneously with the desired operation. These operations are combined by multiplying the filter and desired operation transfer functions together and programming the product.

Filtration, integration, and differentiation canbe described by differential equations in operator form using the Heaviside operator $P = d/dt$, where t is time. Px would be the first derivative of amplitude (x) with respect to time, $P^2 x$ the second derivative and so on. Integration is denoted by x/P, integration twice by x/P^2 and so on. The "order" of an operation is determined by the highest power of P appearing in the equation. Thus, x/P is a first order operation as is Px. There is an important relationship between the order of these operations and the rate at which they amplify or attenuate various frequency components of an input signal. It can be shown that P (differentiation) amplifies a signal at the rate of 6 decibels per octave (20 db per frequency decade) for all frequencies above one radian per second and attenuates at the same rate below one radian. Integration (1/P) has precisely the opposite effect. Double integration or differentiation twice are second order operations which attenuate and amplify at the rate of 12 db per octave (40 db per decade). Each additional order attenuates and amplifies 6 db per octave more than the last. Thus, differentiation four times would amplify and attenuate at the rate of 24 db per octave. Filters also change the input amplitude at the rate of 6 db per octave per order but are not restricted to work around one radian or to both attenuate and amplify as do integration and differentiation. The low pass filter for instance, passes all frequencies from zero cps to some selected frequency with no change in amplitude. Above this point, the filter attenuates at the rate of 6 db per octave per order. The high pass filter does precisely the opposite. The bandpass filter acts like a low pass filter followed by a high pass filter to remove all frequencies above and below selected frequency points.

It may be recalled from the report that transfer functions describe the response of a system or process in terms of a ratio of output to input. Thus, the transfer function for a time derivative would be: $\dot{x}/x = P$ where $\dot{x}$ is the time derivative of x. Likewise, the transfer function for integration would be $x/\dot{x} = 1/P$, where the input is written x to show that it is the derivative of the desired result. There are an infinite number of transfer functions that describe the action of an infinite number of filters but only four types are presented here. These are the second and third order high pass and low pass configurations. The first order filter is not included because its 6 db per octave attenuation rate is too low for most applications. Orders higher than three are not included because the necessary number of computing components is too high for most small scale computers when other operations are being performed. The transfer functions are:

ORDER	LOW PASS	HIGH PASS
2	$\frac{x_f}{f} = \frac{\omega^2}{P^2 + \omega AP + B\omega^2}$	$\frac{x_f}{f} = \frac{P^2}{P^2 + \omega AP + B\omega^2}$
3	$\frac{x_f}{x} = \frac{\omega^3}{P^3 + \omega AP^2 + \omega^2 BP + \omega^3 C}$	$\frac{x_f}{x} = \frac{P^3}{P^3 + \omega AP^2 + \omega^2 BP + \omega^3 C}$

where:

x_f means x filtered

ω = $2\pi f$, is the filter breakpoint or frequency at which the filter begins to attenuate.

The signal will be 3 decibels down or 0.707 of its original amplitude at this frequency.

The constants A, B, and C determine the filter characteristics. These constants are very important and are the subject of extensive literature spanning years of investigation. For general profile work there are only several useful sets of these constants, the best of which were developed around 1930 by S. Butterworth, a British engineer. They are tabulated below.

Second Order: $A = \sqrt{2}$ $B = 1$

Third Order: $A = 2$ $B = 2$ $C = 1$

The rest of this discussion describes the mathematical operations needed to rewrite, program, and combine these transfer functions for the analog computer. It is assumed that readers of this Appendix are familiar with analog computer program diagrams. Also note that bandpass filtration can be obtained by first using a high pass filter set at the lower breakpoint followed by a low pass unit set at the higher breakpoint. The second order, high pass Butterworth filter will be considered first. The transfer function:

$$\frac{x_f}{x} = \frac{P^2}{P^2 + \omega\sqrt{2P} + \omega^2}$$

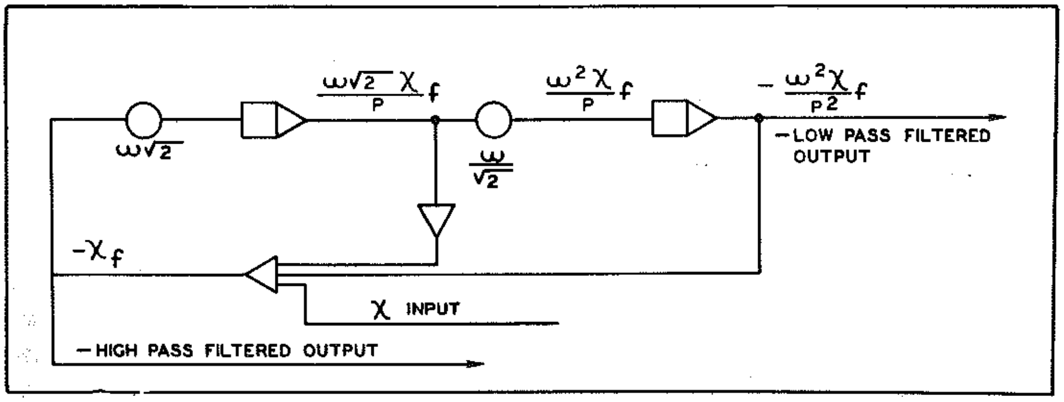
is rearranged to:

$$P^2 x_f + \omega \sqrt{2}Px_f + \omega^2 x_f = P^2 x$$

then to:

$$x_f = x - \frac{\omega \sqrt{2}x_f}{P} - \frac{\omega^2 x_f}{P^2}$$

This converts the differentiations to integrations which are more stable on the analog computer. The analog computer circuit for this transfer function is:

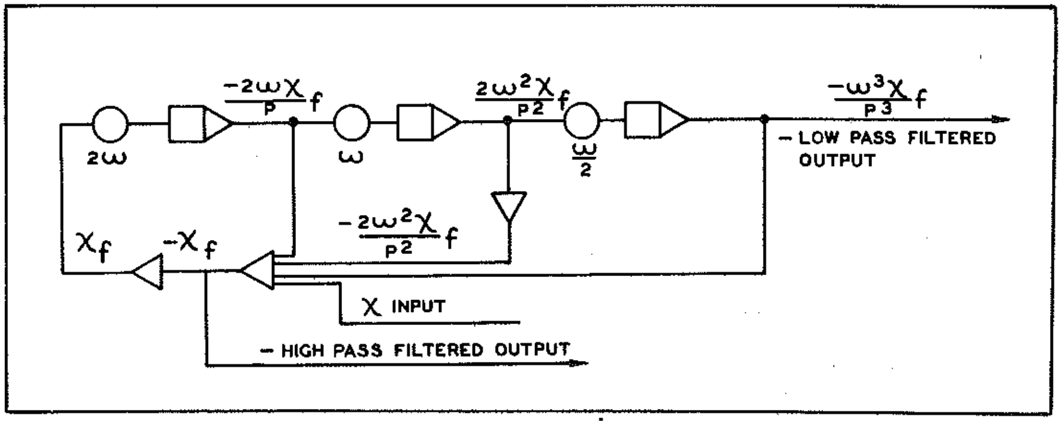


the term $-\dfrac{\omega^2 x_f}{P^2}$ is the low pass filtered version of the input signal although proof will not be included here. This circuit therefore, provides both high and low pass filtration as desired. This is also true for the third order case which follows. The transfer function:

$$\frac{x_f}{x} = \frac{P^3}{P^3 + \omega 2P^2 + \omega^2 2P + \omega^3} \qquad \text{is rearranged to:}$$

$$P^3 x_f + \omega 2P^2 x_f + \omega^2 2PX_f + \omega^3 x_f = P^3 x \quad \text{and then to:}$$

$$x_f = x - \frac{\omega^2 x_f}{P} - \frac{\omega^2 \cdot 2x_f}{P^2} - \frac{\omega^3 x_f}{P^3}$$ which yields the following circuit:



The third order filter provides 18 db per octave attenuation and would be the filter of choice in all applications where enough components are available. The second order unit is ideal when equipment is limited and is a very good general purpose configuration. It is interesting to note that the empirically determined damping factor of 0.5 used for the original third order, high pass, RTP profile process filter (1) fortuitously yields the Butterworth coefficients.

Transfer functions for integration and differentiation are multiplied by high and low pass filter transfer functions to yield pseudo integration and differentiation transfer functions. These allow integration down to a given frequency and differentiation up to a given frequency. The order of filter chosen must be at least one higher than the number of integrations or differentiations desired. This rule arises because each integration or differentiation contributes one order of noise amplification. The filter requires an additional order to provide at least first order reduction of the low or high frequency noise. It would be better in fact, to use a filter two orders higher than the operation desired to provide second order noise suppression. Double integration for instance, required at least third order, high pass filtration as is the case for the RTP profile process filter. Since integration is usually performed twice to go from acceleration to displacement the RTP profile process filter is recommended. The follower-wheel signal input is merely left open and the signal to be double integrated fed into the accelerometer input.

Differentiation is used in the inches per mile and BPR Roughometer simulations in Appendix E. Differentiation combined with second and third order low pass Butterworth filtration is given below. The third order case is best but the second order uses less equipment. The product of differentiation and a second order, low pass Butterworth transfer function is:

$$\frac{\dot{x}_f}{x} = [P]\,\frac{\omega^2}{P^2+\omega\sqrt{2}P+\omega^2}$$

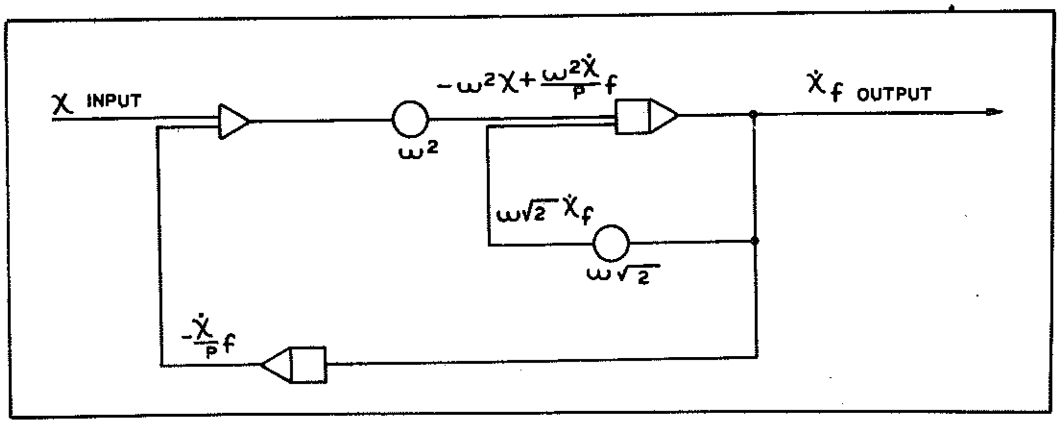
which is rearranged to;

$$P^2\dot{x}_f+\omega\sqrt{2}P\dot{x}_f+\omega^2\dot{x}_f=\omega^2 Px$$

and then to;

$$\dot{x}_f=\frac{\omega^2 x}{P}-\frac{\omega\sqrt{2}\dot{x}_f}{P}-\frac{\omega^2\dot{x}_f}{P^2}$$

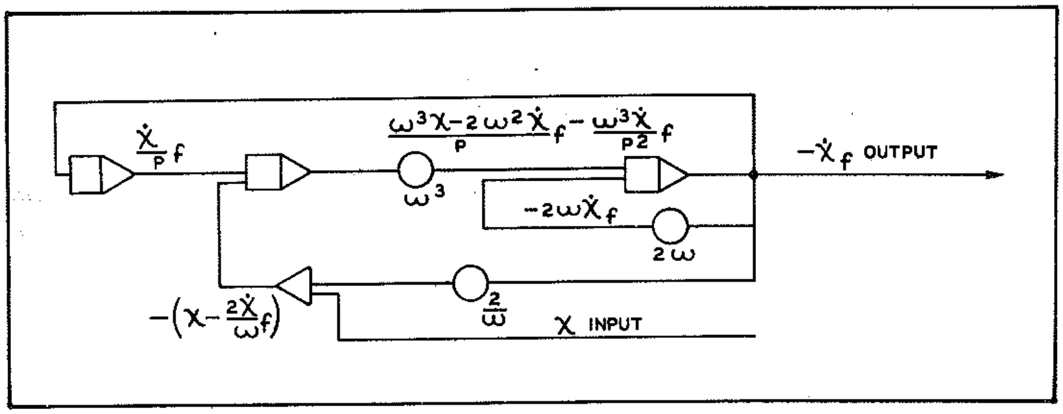
which yields the circuit:



For differentiation combined with third order low pass Butterworth filtration the transfer function is:

$$\frac{\dot{x}_f}{x} = [P]\,\frac{\omega^3}{P^3 + 2\,\omega P^2 + 2\,\omega^2 + \omega^3}$$ and this is rearranged to;

$$\dot{x}_f = \frac{\omega^3\,x - 2\,\omega^2\,\dot{x}_f}{P^2} - \frac{2\,\omega\dot{x}_f}{P} - \frac{\omega^3\,\dot{x}_f}{P^3}$$ which yields the circuit:



APPENDIX G
POWER SPECTRAL DENSITY ANALYSIS

It would be impossible for this Appendix to improve on the excellent presentation of random signal analysis given in reference (3). Some observations about highway PSD analysis are worth passing on, however. Each observation is headed by a phrase indicative of the area discussed.

Statistical Reliability

Statistical reliability is an area of great concern in the random signal analysis field. It was also a problem for all earlier methods of profile analysis but was not generally recognized as such. The problem is stated as follows. How large does a sample from a random process have to be to insure that inferences drawn from that sample are correct for the entire process? Restated for highway applications the question would read: Given a very long stretch of uniform new construction for example, how much of it must be profiled so that measures extracted from this sample apply correctly to the entire highway? Normally the size of sample needed depends on the PSD resolution bandwidth, highest frequency present and the desired level of confidence in the results. This confidence is stated as a percentage of test sections run, for which the measure will be a given percent correct. A typical confidence statement for road profiles might read; Nine out of ten properly chosen test sections from this highway will yield a PSD that is within ten percent of the true PSD.

The highway case is different in a respect that essentially eliminates this confidence concern. In Most cases the highway investigator will profile the entire section of roadway in which he is interested. In statistical terms this is the same as sampling the entire process or sample universe as it is called. Measures extracted from this total sample will estimate the true values with 100 percent reliability 100 percent of the time since the complete process has been specified. In a sense the PSD for a given road or stretch of road is a "roughness print" for that particular section. This does not mean that there are no sampling requirements at all, but it does imply a less restrictive view of sampling requirements. It will not be demonstrated here, but the sample need only be about ten times longer than the maximum lag distance used in computation of the autocovariance function. The maximum lag value is in turn determined by the PSD resolution bandwidth employed. For example, the PSD for a 500-ft bridge deck could be resolved into 0.02 cycles per foot bandwidth segments since this requires a 50-ft maximum lag if the analysis is to extend down to 4-ft wavelengths. If the investigator is interested in the PSD for a very long project however, the standard sample requirements will have to be observed if he does not wish to profile the entire section.

Stationarity

This is another problem of great concern in analysis of random signals. It also presents a danger to all older methods of profile analysis but has received little attention. Most random signal analysis methods are based on the premise that the signal under investigation is the result of a stationary process. A stationary process can be broadly defined as one whose mean amplitude and amplitude variance do not change with time. Restated for highway applications the definition would read: A stationary highway profile has the same mean and variance for any piece of the test section. A change in the mean is usually referred to as a change in general elevation while changes in variance are known as changes in general roughness. It is evident that many profiles are non-stationary in both mean and variance. It should be noted here that the RTP removes non-stationarity of the mean through the profile process filter which forces the entire profile to work around a mean of zero. Therefore, non-stationarity for RTP profiles refers only to variance.

The problem with non-stationarity is that no statements can be made which are true for any specific region of the test section. In other words a PSD or roughness index derived from a non-stationary profile will not truly represent any particular piece of the test section. A roughness index, for instance, would be too high for the smooth regions and too low for the rough regions.

For many applications this problem can be ignored by a change in viewpoint. First, the view that a measure specifies some property of any region from the test section is dropped. Instead, the measure is viewed as an overall averaging of the rough and smooth regions. Again, this is the "roughness print" idea expressed earlier. A PSD analysis would represent the overall condition of a specific test section without regard to local variations within the section.

Filtering

A signal can be difficult to analyze if it contains very powerful components at some frequencies and weaker components at others. Basically, this problem arises because there is no such thing as a perfect filter. Neither digital filters, as used in PSD analysis, nor analog filters completely remove all frequencies beyond their breakpoints. A high quality filter for instance, might attenuate an adjacent frequency by 48 decibels. This does little good however if the adjacent frequency is 46 decibels higher than the frequency of interest. The unwanted signal would be suppressed only 2 db below the desired data which means that much of the adjacent signal would flood over into the region of interest. This has resulted in chapters on "detrending" and "prewhitening" in the literature on PSD analysis. These are attempts to remove the offending signal components or give them all equal strength before analysis.

In the highway case the powerful components are always long waves. These are neatly removed by the RTP profile process filter so that PSD analysis can proceed with no difficulty. It is a matter of choosing the longest wave desired in the PSD analysis and adjusting the profile process filter to remove all longer waves. In addition, it may be recalled that high frequencies were also filtered out to aid in digitizing the profile. In practice these two operations are efficiently performed by passing the broadband profile through a bandpass filter synthesized on the analog computer. An example will illustrate the process. Assume that a profile has been processed such that 200-ft waves are retained and the result re-recorded for storage. Later on, a PSD analysis is desired extending from 100- to 4-ft waves. At a playback speed of 200 feet per second this represents a frequency range of 2 to 50 cycles per second. Third order high and low pass Butterworth filters are synthesized on the analog computer to remove all frequencies below 2 and above 50 cps and the emerging signal digitized. PSD analysis can now be performed with few difficulties. However, the following minor difficulty should be recognized. If PSD estimates are computed at wavelengths of 100 and 4 feet, the end points of the PSD graph will be somewhat incorrect. This arises because the PSD resolution bandpass filter centered at 100 and 4 feet will extend into a region that has been prefiltered. There seems to be no completely acceptable method of eliminating this effect except by extending the analysis slightly and then ignoring the PSD end points or by applying an empirically determined correction factor to the end points.

Sampling Rate

Most of the literature on PSD analysis states that a continuous function will be represented well enough for statistical purposes if it is sampled at two points per cycle of the highest frequency present. Experience with highway profiles indicates that four points per cycle of the highest frequency is a better choice. It was found that this promoted greater stability and repeatability in the PSD computations. This presents a slight problem however, since books like reference (3) usually give the PSD analysis formulas based on two points per cycle of the highest frequency. The problem is easily solved by merely assuming a highest frequency equal to twice the actual highest frequency. The standard formulas for the two point case will now apply to the four points per cycle case. The only difference is that PSD estimates will be computed only up to one half the assumed highest frequency. An example will illustrate. Assume that a PSD is desired from 100- to 4-ft waves. This is 0.01 to 0.25 cycles per foot. If the upper frequency is assumed to be 0.50 cycles per foot the two points per cycle equations will apply. Two points per cycle of 0.50 frequency will actually be four points per cycle at 0.25 cpf which is the desired sampling rate. This setup would normally call for 50 PSD estimates extending up to 0.50 cpf. Instead, only 25 PSD estimates will be computed at frequencies 0.01, 0.02, 0.03, ..., 0.25 cpf. All other mathematical operations would be the same as those based on analysis up to 0.50 cpf.

GLOSSARY

AUTO- AND CROSS-CORRELATION. These are statistical techniques, which show the correlation of signal amplitude with itself (auto-correlation), or with another signal (cross-correlation), for various distances along the signal.

BANDPASS. The term bandpass, applied to a system, refers to its frequency response. Bandpass characteristics are often presented on a graph known as a Bode plot, showing those frequencies that are passed by the system and those which are attenuated or amplified. Such plots appear in Figure 2 of the report.

COHERENCE FUNCTION ANALYSIS. A statistical technique that expresses correlation of two signals at all frequencies of interest. Such an analysis would indicate any frequencies not passed by the RTP but present in the precise level profile.

CROSS POWER SPECTRAL DENSITY ANALYSIS. A technique similar to PSD analysis except that covariance between two signals is used instead of variance for one signal.

FILTERS. A filter is a process, device or electrical network designed to transmit, block or attenuate specific frequencies of any signal applied to the filter. Filtration used with the RTP can be described by linear, third order differential equations; hence the terms linear, third order found in the text. Second order filtration refers to second order differential equations and so on. Each order implies a certain attenuation rate beyond the filter cutoff frequency, such as 60 db per frequency decade for the third order filter. In addition to order, the filter type must also be specified. Highpass filters attenuate all frequencies below a certain value and pass all those above. Lowpass filters provide the opposite characteristic. Bandpass filters attenuate frequencies above and below given values and pass all frequencies between.

FILTER CENTER FREQUENCY. This phrase applies to bandpass filters and is that frequency upon which the filter is centered. A typical bandpass filter might be centered at 10 cps and pass all frequencies from 8 cps to 12 cps.

HYBRID PROCESSING SYSTEMS. A data processing system consisting of linked analog and digital computers. Analog data can be fed into the analog section of the system from magnetic tape. These data can then be partially processed by analog techniques, such as filtration, simulation, etc. Partially processed data are then moved to the digital section for further processing and digital printout.

POWER SPECTRAL DENSITY. A statistical technique which breaks down the total amplitude variance (mean square value) of a signal into variance associated with any specific frequency or wavelength band. Thus, power spectral graphs show the amplitude densities for the wavelengths found in road profiles. A road found to be rough riding, for instance, would exhibit high amplitude densities at wavelengths known to cause vehicle bounce.

PROFILES

Road or Actual. The term road profile has reference to road surface elevation variations. It includes all elevation changes--small surface texture variations up through those changes caused by the curvature of the earth.

Precise Level. These are plots of elevations, obtained from road surfaces with a precise level, rod and target. For evaluation of the RTP, readings were taken at one to five foot intervals depending on rapidity of change in the surface. Values between the sampled elevations were estimated by simple linear interpolation.

Raw Profile. Refers to RTP transducer data consisting of accelerometer and follower-wheel potentiometer signals recorded on magnetic tape. These data are partially filtered by inherent limitations of the system and will be further filtered when processed by analog computer.

Computed or RTP Profiles. These are finished profiles computed from raw profile data. During this computation the investigator may remove any undesirable long wave data such as that resulting from pavement design grades, vertical curves or earth curvature. Therefore, the term RTP profile normally means all road surface elevation changes up to some stated maximum wavelength of minimum frequency.

RESOLUTION BANDWIDTH. Each value on a road profile PSD graph can be considered the result of "looking" at the profile through a narrow bandpass filter. The range of frequencies passed by this filter is called the resolution bandwidth. The PSD spectrum will be increasingly resolved as the filter bandwidth is made smaller, but more profile will be needed to maintain a fixed statistical confidence in the result.