A Progress Report on the Evaluation and Application Study of the General Motors Rapid Travel Road Profilometer

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This paper is primarily concerned with evaluation of accuracy, reliability, and applicability of the General Motors rapid travel profilometer (RTP) for highway purposes. Details of the measurement system itself are very limited, having been excellently covered in an earlier report by General Motors.

The report comprises four sections: theoretical and experimental accuracy, profile analysis methods, reliability and field experience, and a brief discussion of use of the RTP on Michigan projects.

Comparison study of RTP profiles and precise level survey profiles demonstrates RTP accuracy. Thousands of miles of use have proved the system to be rugged and consistently reliable. Furthermore, field experience has shown the system to be easily usable for determining the surface profile of any type of highway surface. In addition, the magnetic tape medium and FM format of recorded field data permits and facilitates electronic data processing machine computation.

The results and rationale of correlation studies between the RTP index and slope variance (CHLOE), and the RTP and a BPR-type roughometer, are presented and are considerably better than would be theoretically surmised. Also, the frequency reponse of the RTP is compared to various length rolling straightedges and to a BPR-type roughometer and is found greatly superior in this respect to either of these devices.

A considerable portion of the report is devoted to the various methods of profile analysis permitted by the device's output format. It lends itself to analog, digital, or hybrid processing. Power spectral density analysis is investigated and suggested as a superior method of profile analysis and presentation.

•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 ". . . study, field evaluate, and determine the applicability to pavement and bridge surface roughness measurements, of the presently evolving (1963) General Motors Corporation, Rapid Travel Profilometer." The proposal was subsequently approved by the Bureau, and the Laboratory proceeded to procure the necessary components and to assemble a system identical to the GM unit.

At the time the proposal was submitted the GM device was still under development. Its evolution, however, had advanced sufficiently to indicate that it would prove to be the first practical, accurate, high-speed road profilometer.

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This report includes a very cursory description of the measurement system. The device was in existence prior to this study and has been adequately described by Spangler and Kelly (1), the GM personnel instrumental in its development. This report principally covers an evaluation of the system's profile measuring capabilities and its applicability to highway work.

In theory, the General Motors rapid travel profilometer (RTP) is capable of reproducing a surface profile while so-called rolling straigntedge profilometers, of any practical length, produce distorted profiles. The RTP represents a new concept in profilometry by utilizing inertial principles and hardware to establish its reference plane. Evaluation of this new instrument by the Department has confirmed its theoretical capability and demonstrated that it meets or exceeds expectations. In addition to obvious advantages such as accuracy, speed, and safety, the RTP provides many unexpected, but important, benefits. One example is the provision for adjustable profile filtering prior to power spectral analysis. Another is the flexibility in processing stored field data to enhance or attenuate specific profile features. Magnetic tape profile storage enables direct analog, digital, or hybrid processing and eliminates the need for manual data reduction. RTP attributes of greatest importance appear to be efficiency in use, faithful reproduction of all significant wavelengths, and data storage on magnetic tape.

Correlations obtained between the RTP and other profile devices are discussed and a short summary of RTP applications to Department problems is also included. Prior to presenting a final HRP report on this project to the Bureau of Public Roads, further study will be performed on system accuracy by computing the coherence functions between RTP profiles and closely sampled level profiles. Additional work will be necessary to derive other profile indexes from the RTP data.

Profiles and profilometers have traditionally been described in the spatial domain. In this domain, distance and elevation characterize profile features, while profilometers are usually described in dimensional terms (straightedge length, wheel size, etc.). Analysis of profiles, the RTP, and ride phenomena in general, is greatly facilitated in terms of the frequency domain. This is a viewpoint from which profilometers and vehicles are described by their response to road profile frequencies. Also in this domain, profiles are seen as complex signals with specific statistical properties. The profile's effect on ride can be analyzed by modern frequency domain techniques as explained by Marshall (2) and Bendat and Piersol (3). It will aid the reader to bear in mind the relationships between profile wavelength, vehicle speed, and frequencies induced in the vehicles. For example, a 20-ft wave traversed at 60 mph will produce a 4.4-cps signal while the same wave traversed at 20 mph will produce a 1.5-cps signal. This concept, though elementary, is important to an understanding of high-speed profilometry.

Figure 1. Michigan's GMR-type rapid travel profilometer.

RAPID TRAVEL PROFILOMETER

For the benefit of readers unfamiliar with the RTP, or as a review for those requiring it, a brief and greatly simplified system description is given.

Figure 1 shows Michigan's version of the General Motors RTP. The device is relatively simple. It consists of a small truck with a spring-loaded pavement follower wheel mounted underneath. An accelerometer is secured to the truck body at a point directly over a linear potentiometer which is connected between the follower-wheel axle and the vehicle body.

To obtain a surface profile, the system traverses the surface and during the run, potentiometer and accelerometer signals are recorded. If the accelerometer signal is then double integrated to produce a body displacement signal, and this displacement signal is summed algebraically with the potentiometer signal, the resulting signal will comprise the wheel movement, or the surface profile. This assumes, of course, that the accelerometer is linear and of correct frequency response, that all signals are properly scaled, and that the vehicle speed was not so great as to cause the wheel to leave the surface.

Also, at the option of the operator, it is feasible to perform the integration and summing functions as data are being sensed and then record only the profile signal. This approach, however, precludes any further processing with raw data signals and limits the flexibility of processing techniques. This matter will become clearer to the reader as he progresses further into the report.

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.

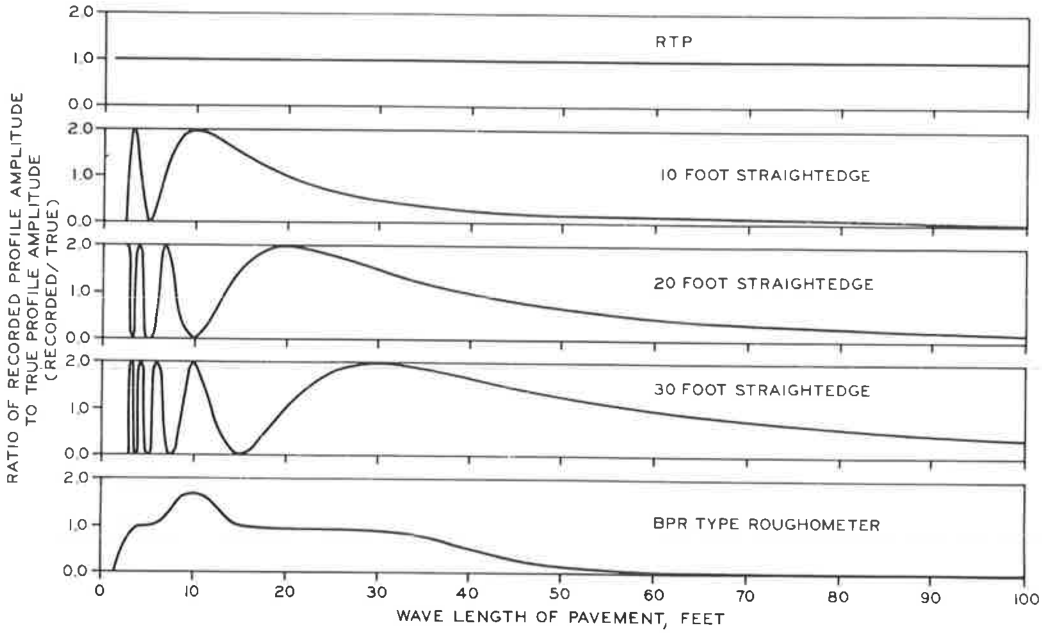


Figure 2. Theoretical differences between RTP, rolling straightedges, and seismic roughometers.

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 and simulation. 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 1 to 5 ft 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.

ACCURACY STUDIES

Theoretical Accuracy

In theory, a profilometer of the RTP type should exhibit accuracy superior to that of any other current road profiling or roughness measuring device. It has much greater usable frequency range, being limited on the high end only by the size (6 in.) of the measuring wheel and on the low end by the quality of electronic equipment used. Accuracy of the system is relatively unaffected by vehicle properties such as suspension, tires, and weight changes. Wavelengths of from 3 in. to 1200 ft have been successfully measured and reproduced with the RTP during this study.

Profile resolution with the RTP is primarily a matter of recorder scaling. Obviously, on any conventional recorder, it is not possible to simultaneously obtain a scaling which will sense pavement grade changes of many feet and at the same time resolve small surface bumps. Those familiar with instrument calibration and sensitivity adjustments will immediately recognize that high signals will overload an instrument set at high sensitivity and that low signals will be lost when recording at a low sensitivity setting.

Figure 2 shows the theoretical differences between the RTP and other surface measurement devices. These are amplitude ratio (bandpass) plots for the RTP, 10, 20 and 30-ft rolling straightedges, and a typical BPR-type roughometer. A ratio of output to input amplitude equal to 1.0 indicates no error. Ratios of 2.0 and 0.0 indicate plus and minus 100 percent error, respectively. Analysis for a rolling straightedge on a sine wave profile is given in the Appendix. A realistic combination of spring, mass, and damping factor was used for the theoretical BPR roughometer bandpass plot.

Bandpass plots for slope variance devices (CHLOE) should be similar to straightedge plots with suitable modifications for sense wheel geometry. Validity of this assertion is demonstrated by noting that integration of the slope profile should yield an ordinary straightedge profile. Since length of the device is the determinant of straightedge bandpass characteristics, no improvement in accuracy is gained by taking the profile's first derivative.

Arguments that roads are not composed of pure sine waves and, therefore, would not cause such distortion of straightedge data are not tenable. Distortion would occur in the power spectrum of a straightedge profile taken from a completely random road

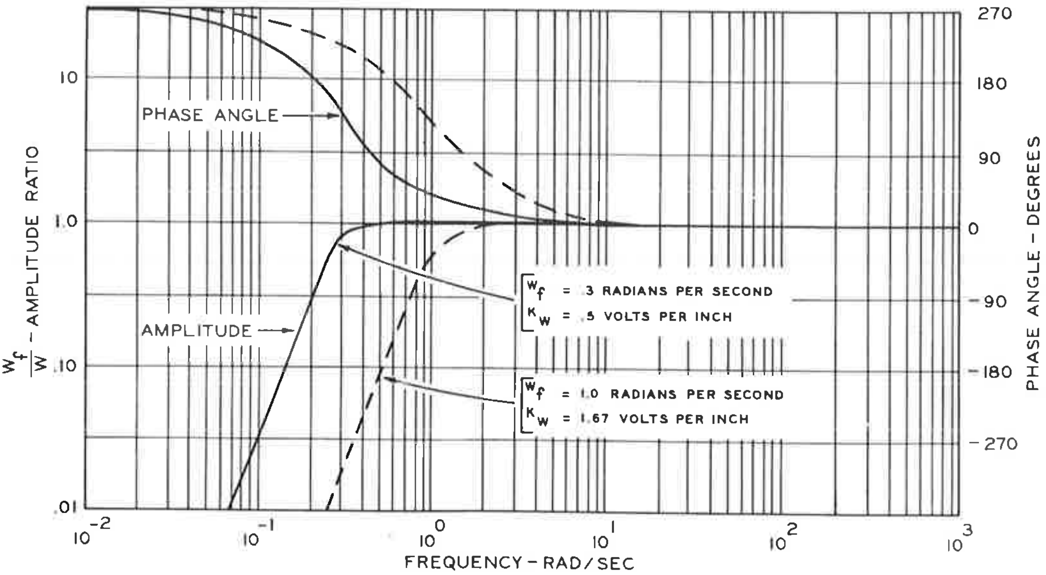


Figure 3. Filter attenuation rates and phase shift.

surface. This would indicate that, on the average, the straightedge would amplify or attenuate random data in a given frequency band just as it did for sine waves.

RTP amplitude ratio does begin to roll off for wavelengths shorter than 3 in. due to the finite size (6 in.) of the measuring wheel. Long-wave reproduction is primarily a function of the quality of electronic equipment used.

Reference Problems

Acceleration and follower-wheel data from the RTP transducers are converted to pavement profile by analog computation. This computation, whether in RTP or laboratory-based computers, inserts an arbitrary reference from which the profile is measured and allows filtration of specific wavelengths.

Analog computation of the profile provides adjustable third-order, high-pass filtration. The purpose of this filtration is twofold. First, reasonable recorder and computer scaling for low-amplitude data does not permit writing the high-amplitude, long-wave data found in most profiles. Consequently, this long-wave information is attenuated by filtration, thus reducing the frequency range but eliminating computer or recorder overload. Second, double integration greatly amplifies small, low-frequency drifts in the electronic system. Filtration of low frequencies eliminates such drift effects and thereby stabilizes the computation process. So-called open loop integration without some filtration is possible only with highly sophisticated equipment.

The filtration process has several effects on RTP profiles. By definition, third-order, high-pass filtration attenuates at a rate of 60 db per frequency decade for frequencies below the filter cutoff point. Thus, as wavelength increases indefinitely, amplitude is reduced to zero. Lag in presenting a wave in the computed profile (phase shift) approaches 270 as the wavelength increases. Figure 3 illustrates both of these characteristics. It should be noted that effects of filtration are also a function of RTP speed. As the RTP speed increases, the frequency sensed from a given surface will increase, i. e., fixed wavelengths are traversed in a shorter time period. Various combinations of RTP speed and filter frequency provide a wide range of profiling options. For instance, by profiling at 68 mph and commuting at 0. 3 radians per second a 1400-ft wave could be reproduced.

Introduction of a mechanical model for the filter used in profile computation will facilitate explanation of the computed profile appearance and reference problems. Third-order filtration of the profile which is inherent in the analog computation circuit can be viewed as a mechanical system into which the profile is fed. For simplicity, a second-order system will be described which behaves similarly to a third-order system but only attenuates at 40 db per decade instead of 60 db. Since the unfiltered profile from RTP transducers is fed into this filter, it is equally valid to view the filter model as actually traversing the profile. The filter model thus replaces the entire RTP and computational system.

The filter model is constructed as follows.

Consider a large mass, say 6400 lb, supported by a spring of 20 lb per foot rate and a viscous damper of ratio 0. 5. A small wheel is attached to the damper and spring opposite the mass. The device is run down the road on this small wheel, and displacement measured between wheel and mass, to yield the profile. The model has a natural frequency of 0. 3 rad/sec, one of the standard filters used in profile computation. If such a device could be built, it would function as a perfectly valid profilometer. As the model rolls along, it is clear that shortwave features will be measured faithfully since plus and minus excursions of the wheel occur too rapidly for movement of the heavy mass. Undesired long waves, on the other hand, will be filtered out since they tend to move the entire system, which results in little relative displacement between wheel and mass.

Explanation of reference and profile appearance problems is now intuitive. It is easy to see that the profile is measured with respect to position of the mass which forms an arbitrary reference plane. Moreover, the road profile may excite the system to oscillate near its natural frequency, thus continuously changing the reference plane. Clearly, position of the reference mass at a given time is a function of all profile

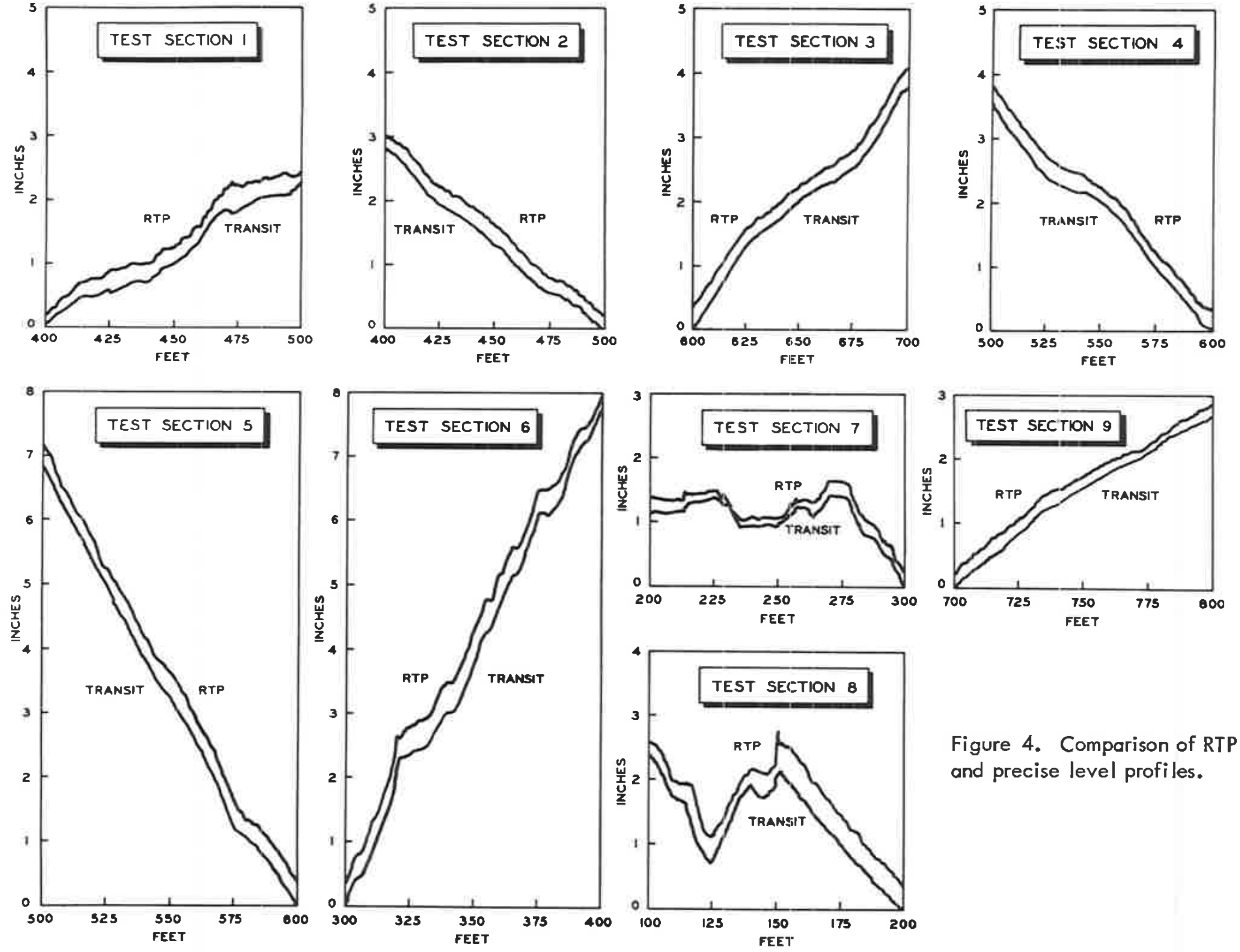


Figure 4. Comparison of RTP and precise level profiles.

previously encountered on the run. This explains the seeming paradox that two different but equally valid profiles can be obtained from the RTP by running a test section in opposite directions. That is, when the model arrives at spot x on the roadway, the position of its reference mass may differ from its position when arriving at spot x from the opposite direction. However, the two profiles can be made to match each other or conform to a fixed transit reference by a process called "tipping," explained in the section on analysis methods. A qualified statement of RTP accuracy would say that the profile is accurate with respect to an arbitrary reference for a given frequency band.

Pre-Test Stabilization Runs

Another problem readily explained in terms of the hypothetical filter model is the need for a stabilizing approach run whenever a profile is taken. Vehicle accelerations causing wide swings in the recorded signals at the start would appear, during profile computations, as violent oscillations of the "filter mass." To prevent this occurrence a short run is necessary before entering the test zone allowing these perturbations to fade. The 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-rad/sec filter frequency might be 500 ft. At 1.0 rad/sec 100 ft would suffice. In any event, the longest pre-run consistent with possible filtration choices should always be used. It should be noted that profile recorded after a short pre-run would still be accurate; it would merely be measured with respect to a rather unsettled filter model reference. This would cause overloading of the analog computer or recorder not scaled for such large signals.

RTP and Precise Level Profiles Compared

Field tests were set up to experimentally verify theoretical RTP accuracy. RTP profiles were taken on nine 1000-ft pavement test sections of various surface materials and roughness. Precise level readings on these sections were made every 1 to 5 ft, depending on profile detail, and subsequently plotted by digital computer. RTP profiles were computed such that wavelengths up to 100 ft suffered no attenuation or phase shift and several 100-ft lengths from each test section were electronically tipped to match the precise level reference plane (pavement grade). Precise level and tipped RTP profiles were then plotted together for comparison.

Visual inspection of the selected 100-ft lengths (Fig. 4) shows close aggreement between RTP and precise level profiles despite sampling gaps in the precise level data. To statistically quantify the relationship of the two profiles, each pair of traces was sampled at 2-ft increments and a linear correlation computed. Excellent correlation resulted—the 95 percent error intervals (1.96 standard deviations) are very small and slopes are near 1.0 (45°), as desired (Table 1).

Table 1
LINEAR CORRELATIONS BETWEEN
RTP AND PRECISE LEVEL PROFILES

Test Section	Slope	One Standard Error (in.)	Correlation Coefficient
1	0.97	0.050	0.997
2	0.98	0.034	0.999
3	1.00	0.046	0.999
4	0.97	0.031	0.999
5	1.01	0.044	0.999
6	1.02	0.074	0.999
7	0.99	0.056	0.982
8	1.01	0.096	0.986
9	1.05	0.027	0.999

Unfortunately, simple linear correlation of simultaneous points from two or more signals such as these can be misleading in that it may be insensitive to differences in frequency content. Consider two signals, with similar high-amplitude low-frequency trends, such as the profiles in question. If only one of the signals also contained higher-frequency low-amplitude data, correlation might still be good, because high correlation of long waves might obscure or negate the lack of correlation at shorter wavelengths. To preclude this possibility each signal could be filtered to a narrow band of frequencies, and linear

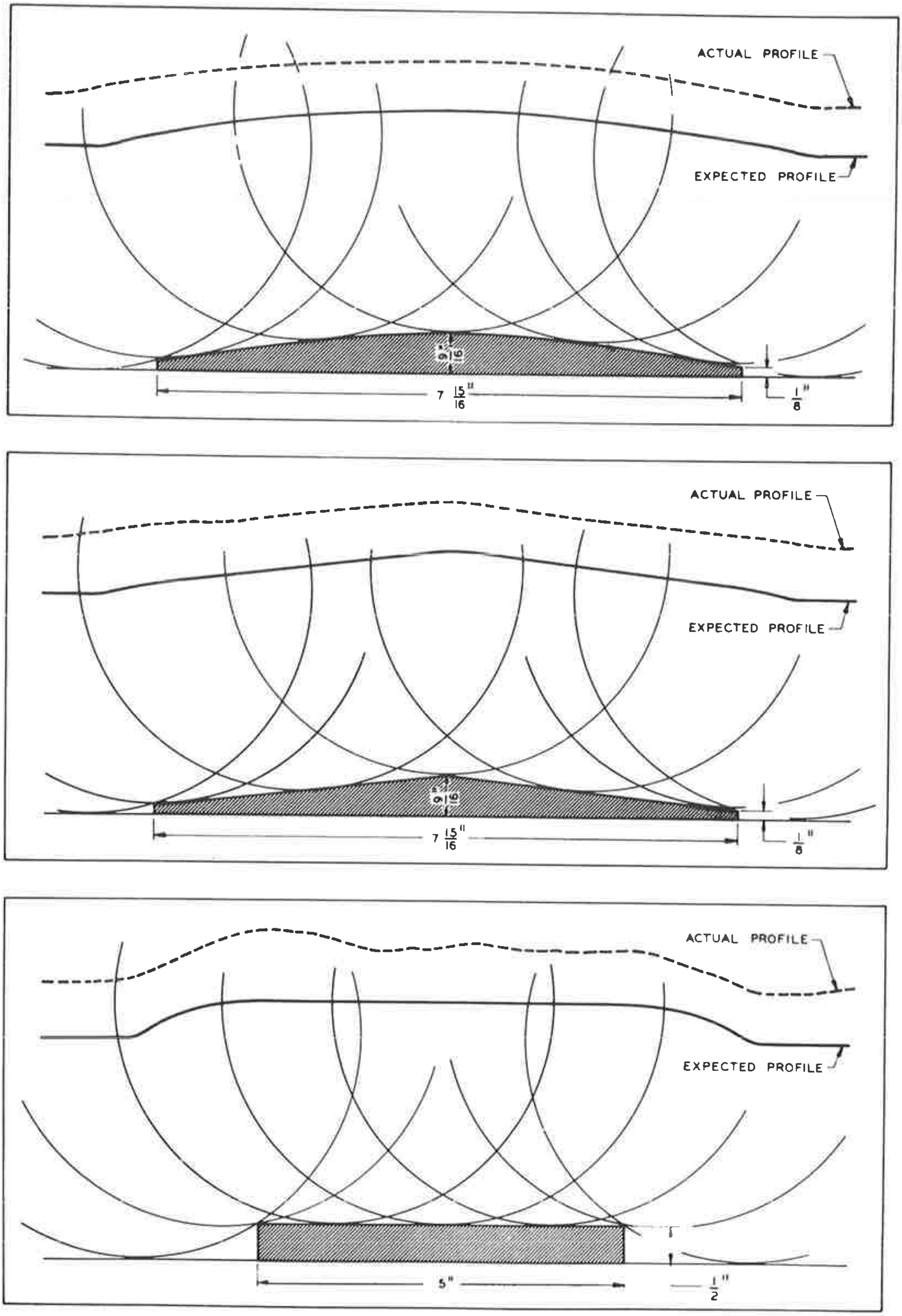


Figure 5. Profiling known waveforms.

correlation of the data would then be more meaningful. One would then consider correlation in each frequency band, e.g., 0-1 cps, 1-2 cps, etc.

A technique which performs such a correlation mathematically is the coherence function. 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). The result is a graph showing correlation (0 to 1) for all wavelengths in question.

Coherence function analysis of RTP and precise level data is in process but is incomplete at this time. Uniform and closely spaced precise level readings are needed for a test section containing large amounts of data at all frequencies. Sections of precise level profile will have to be digitally tipped to match the arbitrary reference of RTP data, and computer programs will be needed to compute coherence functions from RTP and modified precise level profiles.

Profiling Known Waveforms

Correlations obtained to date confirm the RTP's capability for accurate reproduction of profile wavelengths of 50 to 100 ft. This observation is supported by noting that high correlation is maintained down to any 50-ft region. Although correlation information is lacking for middle wavelengths, several profiles were made of variously shaped shortwave objects. Three waveforms that would be increasingly difficult to profile, the semicircle, triangle and rectangle, were fabricated from steel plates, secured to a pavement surface and then profiled. These three shapes, in the order presented, required increasingly better RTP high-frequency response for faithful shape reproduction. (Frequency response in this sense means ability to pass increasingly intense high-frequency terms found in the Fourier decomposition of these waveforms.) From the results obtained it appears that the mass of the follower arm and wheel is the major limitation to RTP high-frequency response. The metal waveforms were profiled at 12.5 ft/sec since higher speeds caused considerable follower-wheel bounce. Figure 5 shows the expected and actual profiles superimposed. Expected profiles are axle paths of the 6-in. follower wheel over the waveforms. Except for the follower-wheel bounce over the rectangle, agreement of the traces is so close that quantitiative comparison is deemed unnecessary.

ANALYSIS METHODS

Magnetic Tape Recorders

A word about magnetic tape recorders is in order before discussing methods of profile analysis. Most meaningful analysis will require raw data storage on magnetic tape. This is true whether data are computed by the RTO analog package, processed in lab-based analog equipment, or digitized for numerical analysis. Departmental experience indicates that a highly portable IRIG standard FM deck, using 1-in. tape, is highly desirable. It should be of highest instrumentation quality and, for efficient use with digitizers, be capable of at least a four-to-one speed change.

Visual Inspection

An obvious method of profile analysis is visual inspection. Adjustable filtering during profile computation is advantageous for this and other types of analysis. Profiles filtered at high frequency will contain only low-amplitude short-wave detail which can be amplified for greater clarity. At low filter frequency, long-wave high-amplitude features will dominate the profile. As the profile is computed from raw data it can be simultaneously recorded on a spare tape track for subsequent analysis. Information data must be re-recorded with the profile to maintain synchronization.

Since road profiles are normally thought of with respect to a plane perpendicular to gravity, it may be disturbing to find the profile tipped the "wrong way." A gravity reference can be restored by taking precise level shots at intervals equal to the longest unfiltered wave. Computed profile can then be electronically tipped, section by section, to match the precise level points. This is actually a process of reinserting previously filtered low-frequency data.

All of the RTP profiles shown in Figure 4 have been electronically tipped to match the true pavement grades. The Department has found that a two-pen "x, y" plotter is indispensible for visual profile displays of this type. These servo-driven plotters have a large "y" axis range allowing a plot of terrain elevations while retaining considerable surface detail.

Analysis Equipment

Any analysis beyond visual inspection will require analog or digital computation, or both. Profile computation can be performed by an optional analog computing package built into the RTP. Analog analysis beyond this level, however, will require a lab-based analog computer of at least the 20-amplifier class. It should be equipped with at least 10 integrators, a comparator, an x^2 unit and a multiplier. Digital computations will require an analog-to-digital converter. This unit need not be very elaborate due to the low frequencies involved. Most digitizers sample very rapidly so that profile playback speeds, of four or even eight times normal, result in efficient use of computer memory and time. Coupled analog and digital computers, called hybrid systems, greatly facilitate profile analysis but are not in widespread use. Choice of analog or digital methods depends, to some extent, on depth of analysis desired.

Single Number Indexes

Profile analysis begins by recasting the data into terms more meaningful than computed profile. The first and least powerful technique is to characterize the profile by a single number index. A particularly dubious index is inches per mile. An analog computer program has been developed to accumulate vertical excursions of the profile. These excursions are summed and divided by test section length to yield the average inches-per-mile index. This index provides little information since it does not relate to particular wavelengths nor does it express the distribution of amplitudes. Digital or analog methods can be used to obtain the average and variance of the profile or its derivatives. Again, these single number indexes provide no information about wavelength content.

It is perhaps more meaningful to obtain these quantities in a narrow frequency band rather than overall frequencies. This can be accomplished by synthesizing a narrow bandpass filter on the analog computer. Profile data are then passed through the filter and any desired index is computed from the emerging signal. This process may be repeated for all frequency bands of interest. An estimate is thus obtained linking each index to a particular wavelength band. Such indexes might be relevant to vehicle behavior or indicate the nature of pavement distress.

Simulation of Other Profile Devices

Assuming correctness of RTP profiles, one can compute actual slope variance, inches per mile, and other indexes directly. There is interest, however, in obtaining these indexes as measured by existing profile devices. Since these devices (BPR roughometers or rolling straightedges) have passbands totally unlike the RTP, it is necessary to synthesize a model of each device in analog or digital terms. RTP profiles are then fed into these models and the appropriate index computed from the emerging signal. Although analog simulation of a BPR roughometer is fairly straightforward, the rolling straightedge is not. Simulation of the latter device on the analog computer requires transport delays to shift the profile to that seen by successive wheels. (Transport delay tape decks or analog computer delay packages are commercially available.) Straightedges are, however, relatively simple to synthesize on the digital computer.

Correlation of the RTP and Other Profile Devices

A shortcut to prediction of CHLOE and MDSH-BPR type roughometer indexes from RTP data was tried with rather unusual results. Twenty-two ½-mi 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. Since the CHLOE slope variance and roughometer inches per mile are numeric indexes, the RTP profiles were converted to inches per mile. Simple linear correlations between RTP, CHLOE, and roughometer indexes are given in Table 2. The good correlations obtained were not expected. How could three devices with radically different passbands, and in two cases differently computed indexes, correlate so well? It was also discovered that the RTP data had been inadvertently overfiltered during processing, thus removing all but the longest waves. Apparently, a frequency band strongly sensed by the RTP was correlating well with the outputs of two devices which very weakly sensed this same frequency band.

This would indicate that intensity of the higher frequencies sensed by CHLOE and the roughometer correlates with intensity of lower frequencies sensed by the RTP. Apparently the intensities of both these bands are higher on rough roads and lower on smooth roads. Under these conditions, any parameter reflecting amplitude dispersion computed from one frequency band will correlate with the same or a different dispersion parameter from the other band. What the correlations very likely show is not an ability to directly predict various indexes from RTP data, but a correlation among various wavelengths in the selected test sections. Such intra-profile correlation, if universally found, would permit indirect prediction of traditional roughness parameters from RTP data.

To validate the above hypothesis would require a major experimental effort. Consequently, the computation of indexes from RTP data is probably most safely done by simulation techniques as previously discussed.

Advanced Analysis

The RTP makes possible new methods of characterizing road profiles in highly meaningful terms. Flat bandpass, ability to pre-filter, and magnetic tape storage are prerequisites to use of high-powered analytical techniques. Such techniques began to appear about two decades ago but their application to highway work has been very limited (4, 5). Known broadly as time-series methods, they include auto- and cross-correlation, power spectral density, cross power spectral density, and coherence functions.

Table 2
LINEAR CORRELATIONS BETWEEN
RTP, CHLOE, AND MDSH-BPR ROUGHOMETER INDEXES

Correlation of RTP in. per mi with:	Pavement Type	Correlation Coefficient
CHLOE, slope variance	Combined Types	0.917
MDSH-BPR, in. per mi	Combined Types	0.830
MDSH-BPR, g's per mi	Combined Types	0.778
CHLOE, slope variance	Flexible	0.907
CHLOE, slope variance	Rigid	0.918
CHLOE, slope variance	Overlay	0.984
MDSH-BPR, in. per mi	Flexible	0.910
MDSH-BPR, in. per mi	Rigid	0.896
MDSH-BPR, in. per mi	Overlay	0.989
MDSH-BPR, g's per mi	Flexible	0.980
MDSH-BPR, g's per mi	Rigid	0.906
MDSH-BPR, g's per mi	Overlay	0.992

Of these, power spectral density analysis currently appears most promising for highway work.

Power Spectral Density Methods

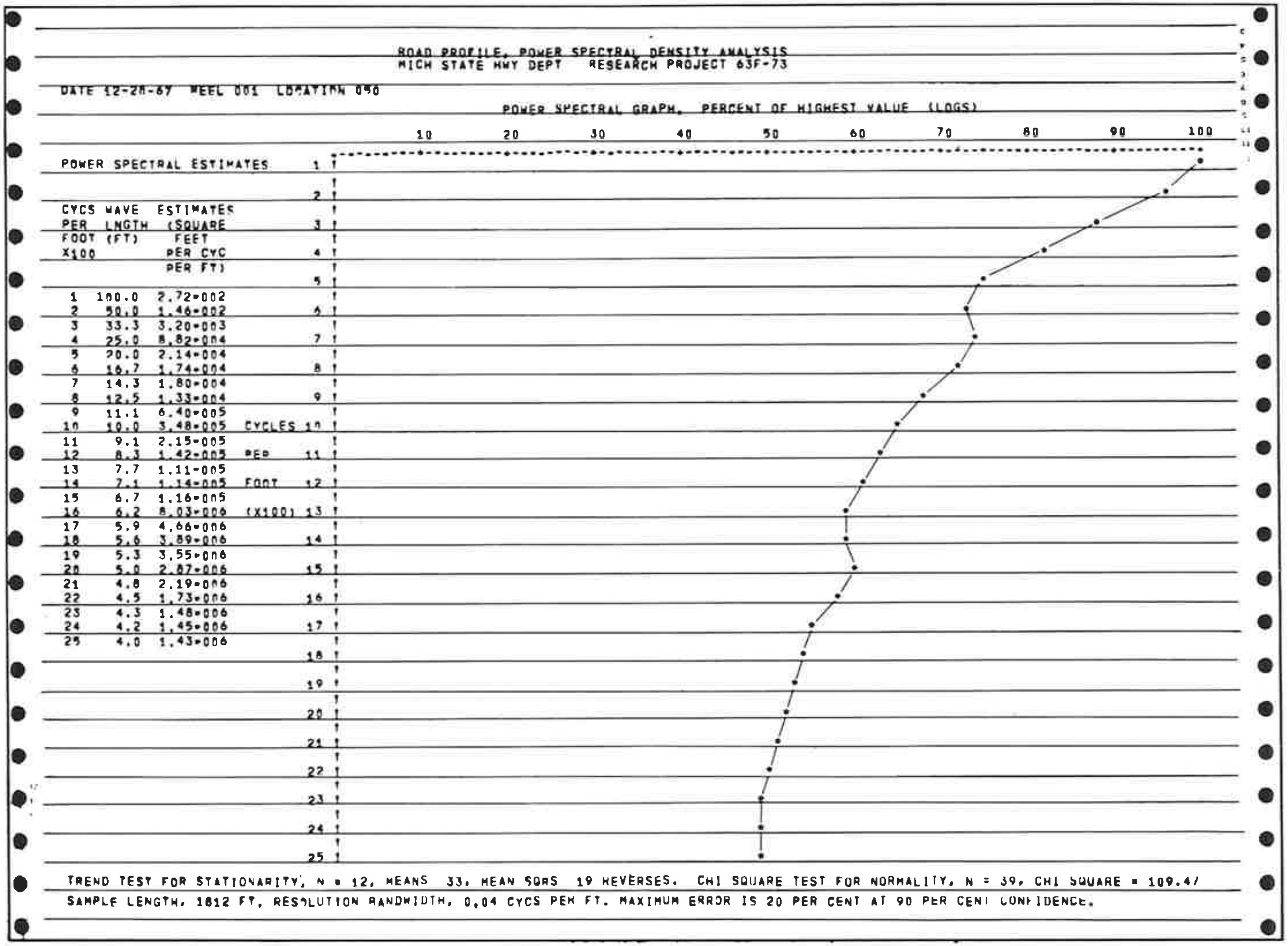
The power spectral density function (PSD) is best described by a possible analog method of computation. Consider a number of narrow bandpass filters of bandwidth B_e' (B_e being resolution bandwidth) selected such that their center frequencies are uniformly distributed over the frequency range of interest. Apply the profile signal as input to this array of filters. Square the output of each filter and accumulate the squared outputs over the profile length. Divide each accumulation by the profile length thereby obtaining the mean variance of each frequency band. Then divide each mean variance by B_e to form an average over the frequencies passed by that particular bandpass filter. These are PSD estimates and form the PSD graph when plotted against bandpass filter center frequencies. The units are amplitude^2/frequency on the "y" axis and frequency on the "x" axis.

In practice, PSD analysis is more complex than its explanation would indicate. Fairly stringent statistical requirements must be met and the profile must be prefiltered. Long-wave, high-amplitude signals present in most profiles have plagued investigators using precise level profiles (6). These powerful signals dominate the PSD analysis obscuring subtle power differences in important regions. Various methods, sometimes called detrending, have been tried to filter out these wavelengths. Such filtering is possible with digital techniques but computer time is heavily consumed (7).

The RTP resolves this problem by automatically filtering out these long waves during profile computation. Filtration of unwanted high frequencies may also be necessary if the profile is to be digitized for PSD analysis. This filtration can also be readily performed on the analog computer prior to digitizing. Recently, several firms have marketed analog devices specifically designed to do PSD and related analysis. This equipment may prove adequate for profile analysis programs and is sufficiently portable to be used in the field.

PSD graphs and estimates for two typical test sections appear in Figures 6 and 7. Each 1-ft sample of an 1812-ft profile was digitized and PSD estimates were then computed for frequencies of 0.01 to 0.25 cycles per foot, in 0.01-cycle increments. This corresponds to wavelengths of 100 to 4 ft. Frequencies above and below these wavelengths were filtered out. Assuming statistical assumptions are met, the estimates from the sample are within 20 percent of the true value for the entire highway 90 percent of the time. The resolution bandwidth was 0.04 cycles per foot. Logs of the estimates were taken and then expressed as percents of the highest value. This provides a plot which remains within the boundaries of the paper but takes maximum advantage of space. It is read with the page in normal position and primarily shows shape of the spectrum.

It should be mentioned that when applying PSD techniques to profile analysis, the same problems are encountered that occur in analysis of most 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 make comparisons with their own work. Length of the profile sample must be chosen to yield stable, reliable estimates of the true power spectrum since shorter samples will produce erratic results. If the sample available is too small to yield reliable PSD estimates, it will not yield reliable estimates of any other type which attempt to characterize the profile. Often, when large samples of profile are taken, a problem known as non-stationarity appears. This is due to changes in the statistical properties of the profile as the sample is traversed. Techniques for analysis of such data have been given by Bendat and Piersol (3). In this connection, it must be noted that if the non-stationarity is bad enough to preclude PSD analysis, any other analysis method will be equally invalid. Random data, at best, are difficult to analyze but PSD techniques, if applicable, offer the only coherent, fully developed method of attack. If PSD analysis cannot be applied, very little can be said statistically about the profile.



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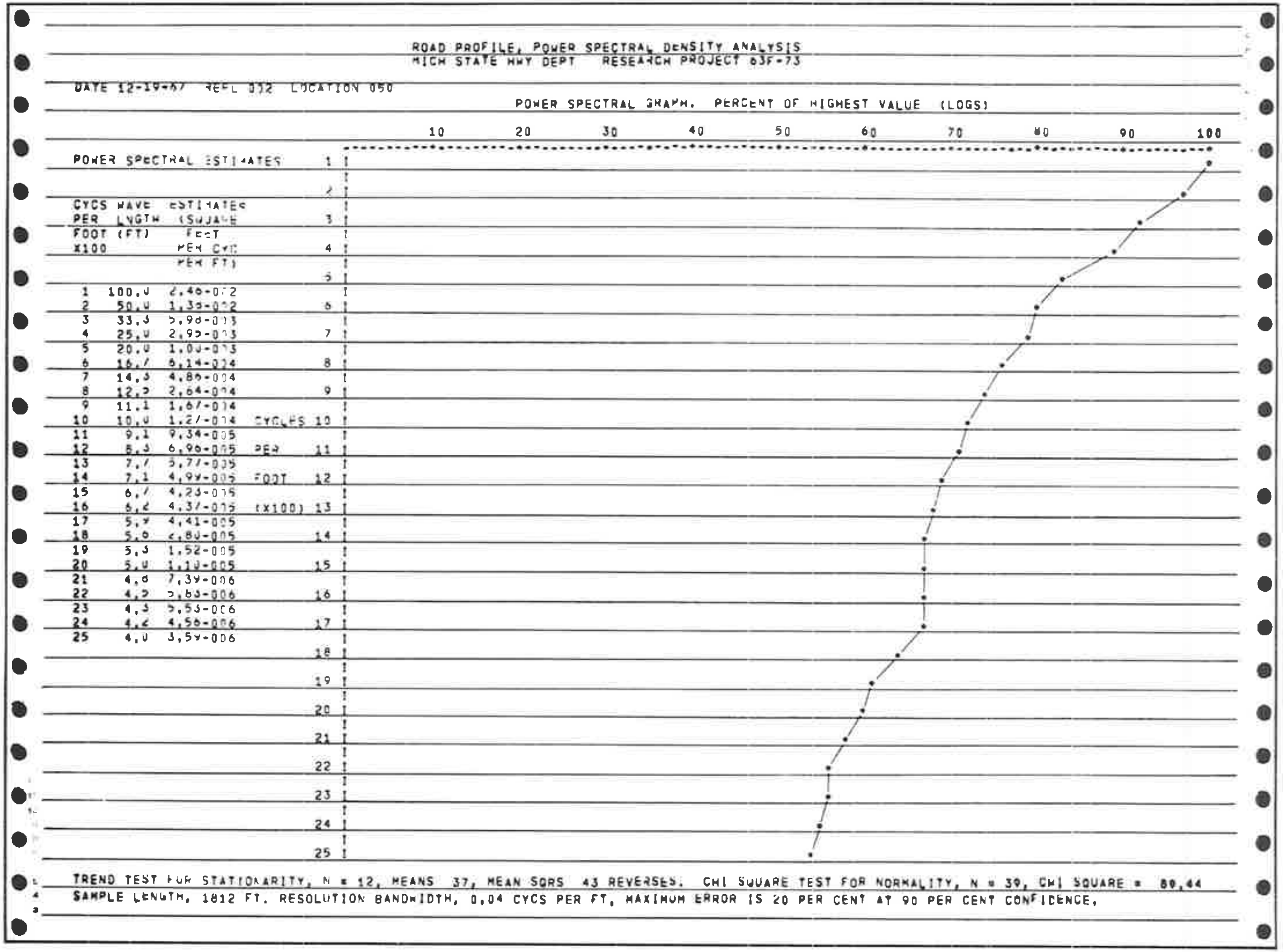
                                   ROAD PROFILE, POWER SPECTRAL DENSITY ANALYSIS
                                   MICH STATE HWY DEPT   RESEARCH PROJECT 63F-73
DATE 12-28-67  REEL 001  LOCATION 050
                                         POWER SPECTRAL GRAPH,  PERCENT OF HIGHEST VALUE  (LOGS)
                               10    20    30    40    50    60    70    80    90   100

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



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                              ROAD PROFILE, POWER SPECTRAL DENSITY ANALYSIS
                              MICH STATE HWY DEPT   RESEARCH PROJECT 63F-73
DATE 12-19-67  REEL 032  LOCATION 050
                                        POWER SPECTRAL GRAPH.  PERCENT OF HIGHEST VALUE  (LOGS)

POWER SPECTRAL ESTIMATES

CYCS  WAVE   ESTIMATES
PER   LNGTH  (SQUARE
FOOT  (FT)     FEET
X100           PER CYC
               PER FT)

  1   100.0  2.46-002
  2    50.0  1.35-002
  3    33.3  5.98-003
  4    25.0  2.95-003
  5    20.0  1.00-003
  6    16.7  6.14-004
  7    14.3  4.86-004
  8    12.5  2.64-004
  9    11.1  1.67-004
 10    10.0  1.27-004
 11     9.1  9.34-005
 12     8.3  6.96-005
 13     7.7  5.77-005
 14     7.1  4.99-005
 15     6.7  4.23-005
 16     6.2  4.37-005
 17     5.9  4.41-005
 18     5.6  2.80-005
 19     5.3  1.52-005
 20     5.0  1.10-005
 21     4.8  7.39-006
 22     4.5  5.83-006
 23     4.3  5.53-006
 24     4.2  4.56-006
 25     4.0  3.59-006

TREND TEST FOR STATIONARITY, N = 12, MEANS  37, MEAN SQRS  43 REVERSES.  CHI SQUARE TEST FOR NORMALITY, N = 39, CHI SQUARE =  80.44
SAMPLE LENGTH, 1812 FT. RESOLUTION BANDWIDTH, 0.04 CYCS PER FT, MAXIMUM ERROR IS 20 PER CENT AT 90 PER CENT CONFIDENCE.
```

Figure 7. PSD graph and estimates for test section seven.

Uses of power spectral density analyses are too many and varied for inclusion here. Some applications to highway work have been by covered by Hutchinson (4), Quinn and VanWyck (5), and Quinn and Zable (6). PSD and cross-PSD estimates are used in coherence function computations mentioned earlier. An interesting use in determination of vehicle transfer functions by modifying the process is also covered (5, 6).

Miscellaneous Analysis Methods

Two additional types of profile analysis should be mentioned for completeness. Amplitude distributions are easily formed from RTP profiles by analog or digital methods. Such characterization of the profile is not complete since it carries no wavelength information. Usefulnes of this measure probably lies somewhere between indexes and PSD analysis. Another analysis method uses the profile as direct input to a simulated vehicle. Problems of what to do with the output, however, still remain.

RELIABILITY AND FIELD EXPERIENCE

RTP reliability has been fully demonstrated during many miles of profiling. Several minor initial difficulties have been eliminated. Solid-state electronics minimizes instrumentation failures. Several minor improvements have been incorporated and are available in commercial models of the RTP.

A weak link in the system from the reliability and profiling viewpoint is the follower-wheel system. The wheel is subject to wear and despite 300 lb of holding-down force will bounce on sharp rises. Detailed profiles of severely distressed surfaces (faulted joints) are difficult with the present system. Nevertheless, wheel wear is not rapid and sharp obstructions are rare in general profile work.

Field experience has led to several refinements in operating procedures:

1. Ideally, such systems would use a servo-drive tape recorder where tape speed is continuously controlled by vehicle speed. This would eliminate minor vehicle speed variation effects and greatly simplify distance scaling on finished profiles. However, such instruments are expensive and add to system complexity. The Michigan RTP does not include such a recorder. Its tape unit has a number of fixed speeds. To facilitate distance scaling on the finished profiles, it has been found advantageous to operate the vehicle at various fixed speeds such as 50, 25 or 12.5 ft per sec.
2. A detailed operations checklist assures uniform profiling techniques and is a valuable teaching aid.
3. Remote control of profilometer electronics permits one-man (driver) operation where necessary.
4. Magnetic tape dropouts can cause violent perturbations of the "filter mass" and invalidate a test. A device designed by the Laboratory's electronics personnel monitors critical channels during testing, and signals if a dropout occurs. This is a serious problem only when computing the profile from tape.

MICHIGAN RTP APPLICATIONS

Michigan's use of RTP profiles is increasing rapidly. Most analyses to this time have been visual. Advanced analysis techniques will be used in a forthcoming study linking profiles with dynamic axle forces. A digital computer "roughness package" program is being considered. It will compute all possible indexes, power spectra, and other desired profile information. A few examples of initial studies will indicate the diversity of use:

1. A study of 24-hr slab movement recording actual slab curling;
2. A study of blowups clearly showing the cross-section profile;
3. A comparison of hand, transverse and longitudinal bridge deck finishing;
4. Examination of approaches and platforms for an electronic scale project;
5. Profiles of an airport runway to aid in resurfacing operations; and
6. Profiles of a number of experimental pavements as the first of a series of periodic

profiles to study progressive changes. These include pavement variables such as continuous reinforcement, no load transfer dowels, styrofoam-insulated subgrade and asphalt-stabilized subgrade.

CONCLUSIONS AND OBSERVATIONS

1. This study has shown that the General Motors rapid travel profilometer is a rugged, fast, reliable, and easily utilized system for profiling highway road and bridge surfaces. It is superior to any other known highway profilometer in that it provides an accurate, "true" profile of the surface being measured.
2. The magnetic tape recording medium facilitates computer processing. This in turn permits (a) controllable filtering to enhance or attenuate specific profile features, (b) various types of statistical processing, (c) simulation of other surface measurement devices, and (d) calculation of single number numerical indexes for correlation with CHLOE, BPR-type roughometer, rolling straightedges, and other such instruments. Of course, in addition to all these is possible the most common mode of use—visual examination of the profile in areas of interest such as joints, patches, rough areas, and distressed areas.
3. Maximum utilization of the RTP, as with any instrument, requires complete awareness and comprehension of all of its capabilities and limitations. The subtleties of the device and its application are such that potential users should anticipate an extensive familiarization and break-in period. Serious study of the device and the involved concepts will reward the highway engineer with a very valuable tool.
4. To achieve an RTP system of superior accuracy and resolution it is essential that the two transducers, the magnetic tape recorder, the signal conditioning and calibration electronics, and the analog computer all be of highest instrumentation quality.
5. The pavement follower arm and wheel currently constitute the RTP's major limitation to high-speed (50 to 70 mph) operation and thereby high-frequency response. Development of a sensitive non-contacting distance transducer would eliminate this problem and permit profiling of any surface, at any speed.

ACKNOWLEDGMENTS

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M. J. Fongers of the Highway Research Laboratory is to be commended for his excellent work in assembling the measurement system, for proof-testing and "debugging" it, and for system field operation and processing of data throughout the study.

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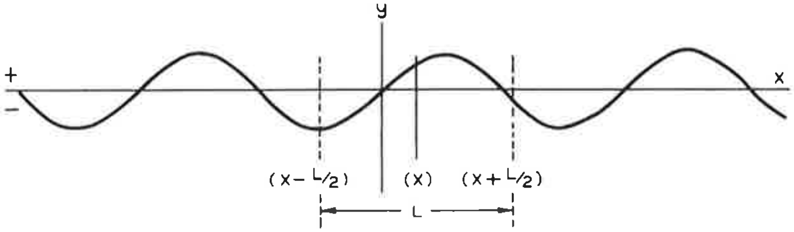
Appendix

Transfer function for rolling straightedges on sine surfaces. Consider the sine wave profile shown:



For displacement of the measuring wheel on a straightedge we have:

$$y = -1/2\,A \sin 2\pi n\,(x - L/2) + A \sin 2\pi n x - 1/2\,A \sin 2\pi n\,(x + L/2)$$

where:

A = amplitude
n = number of cycles per foot
L = length of straightedge
x = distance in feet

Noting that $\sin (A + B) + \sin(A - B) = 2 \sin A \cos B$ we can write:

$$y = A \sin 2\,\pi n x - A \sin 2\,\pi n x \cos \pi n L, \text{ and}$$
$$y = (1 - \cos \pi n L)\,A \sin 2\,\pi n x$$

If $A = 1$ ft, $(1 - \cos \pi n L)$ is the output amplitude and also the amplitude ratio or transfer function (T). Inspection of T reveals maxima when the product nL is an odd integer and minima when even. Note that for $n < 1/L$, T ceases to oscillate and descends asymptotically to zero.