DIGITAL FILTERING METHODS FOR CHARACTERIZING PAVEMENT PROFILES

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Obtaining suitable descriptor variables for pavement characterization is a major problem for today's pavement design engineer. Ideally, a set of such variables would provide a way to measure pavement performance and to relate it to pavement distress. With the surface dynamics (SD) profilometer, it is possible to accurately and rapidly obtain road profile information. Pavement serviceability, or performance, and distress are interrelated with pavement profile and, thus, the SD profilometer provides useful data from which various statistics can be obtained for possible use as pavement descriptor variables. One set of such variables is road profile quantities such as amplitude measurements for specific wavelength bands. If it is possible to obtain an adequate model that relates performance to various road profile characteristics as measured by specific descriptors and if various distress manifestations can be related to the same set of descriptors, then pavement performance and distress can be related by means of distress-performance models. This paper discusses possible uses of digital filtering techniques on road profile data in an effort to find a set of ideal pavement descriptors. Included are discussions of current descriptors; digital filtering techniques, including basic definitions; and ways such techniques can be used to obtain better pavement descriptors. The discussions are intended primarily to prompt further investigations into these methods and their trial use in road profile analysis.

•ONE of the major problems in developing improved pavement design methods today is obtaining suitable descriptor variables for characterizing pavement riding quality. An ideal set of such variables should provide a means for obtaining some measure of pavement performance and for relating performance to pavement distress. The surface dynamics (SD) profilometer provides an accurate and rapid means of obtaining road profile information. Pavement profile is interrelated with pavement serviceability or performance and distress and, thus, this device provides data from which various statistics can be obtained for use as pavement descriptors. Road profile quantities such as amplitude measurements for specific wavelength bands are one set of such variables. If a model that relates performance to various road profile characteristics as measured by specific descriptors can be obtained, and, in turn, if various distress manifestations can be related to the same set of descriptors, then pavement performance and distress can be related via distress-performance models.

This paper discusses the possible use of digital filtering techniques on road profile data as a tool in an effort to find such a set of pavement descriptors. The discussion includes comments on initial and current descriptors, i.e., slope variance and power spectral estimates. Digital filtering techniques, including basic definitions, and an

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example application are introduced. How such filtering techniques can aid in obtaining better pavement descriptors is presented. The discussions, which are limited to digital filtering concepts, are primarily intended for prompting further investigations into these methods and their trial use in road profile analysis. The ideas presented are the results of several years of experience in using and analyzing profile data from the SD profilometer.

CURRENT PAVEMENT CHARACTERIZATION METHODS

The SD profilometer provides separate analog profile records for both right- and left-wheel paths for a given pavement section. This record can be converted to equally spaced discrete measurements according to a sampling signal synchronized with the distance traveled. For this paper the digitized profile data are approximately 2 in. (50.8 mm) apart [6 data points/ft (1.8/m)]. For discussion purposes the set of digitized profile data for either the right- or left-wheel paths are $X = x_1, x_2, \ldots, x_n$ where x_i represents the discrete profile values, and n is the section length in half inches.

Roughness index and slope variance statistics were used as the primary pavement characterization descriptors during initial research investigations at the Center for Highway Research and the Texas Highway Department. These two statistics were selected because of their relationship with features that induce forces on the rider and because of their previous acceptance in the highway field. The roughness index is the normalized sum of the vertical deviations of the profile throughout a pavement section, and slope variance is the variance of surface profile slopes calculated for the length of the section. Present serviceability index (PSI) models (3) were developed by correlating these variables along with condition survey statistics.

Several disadvantages of using slope variance as a pavement surface characterization statistic or estimator of pavement serviceability have been noted. First, slope variance as computed at the AASHO Road Test [9-in. (228.6 mm) base] is quite dependent on wheel bounce (5, 7). Consequently, considerable variation in replication measurements for various combinations of pavement roughness and profilometer operating speeds is common. Second, the complexity of a section of pavement cannot be adequately characterized by a single statistic such as slope variance. In fact, the effect of certain wavelengths is completely ignored by this statistic (7). Third, slope variance is somewhat difficult to relate or picture physically and, largely because of the mentioned disadvantages, probably it provides at best a correlation coefficient of about 0.82, and this for profilometer operating speeds of 20 mph (8.94 m/s). (At greater operating speeds, this correlation dropped significantly.) That is, only about 67 percent of the mean rating of the panel's opinion (3) could be explained by slope variance. Roughness index was similarly disadvantaged by these problems, and it exhibited less correlation with the mean subjective ride quality ratings. Adequate serviceability index (SI) prediction models were obtained only after including both condition survey information and slope variance.

Because of the complexities of a road profile, the characterization of a pavement section by its individual wavelength components appears to be much more viable than the use of a single statistic such as slope variance or roughness index. In addition, with wavelength information, various problems such as wheel bounce can be isolated or accounted for to provide more accurate pavement characterizations.

With these shortcomings, the use of power spectral estimates was investigated next as providing more comprehensive descriptor variables. Power spectral estimates like slope variance are statistical quantities, but the power spectrum affords a set of profile descriptors instead of a single measure.

Figure 1 shows the relationship between mean subjective ride quality ratings or PSR and the road profile (64-band) spectral estimates for a large sampling of typical pavements in Texas (3, 7). The power spectral estimates for several frequencies or wavelength bands are shown for various road roughness classes, characterized by PSR. The average spectral amplitudes of 86 pavement sections with various roughnesses (grouped by PSR intervals) were obtained. Generally, the rougher the road was, the greater the spectral amplitudes were (Fig. 1). However, for the higher frequencies

Figure 1. Wavelength versus power spectral estimates (7).

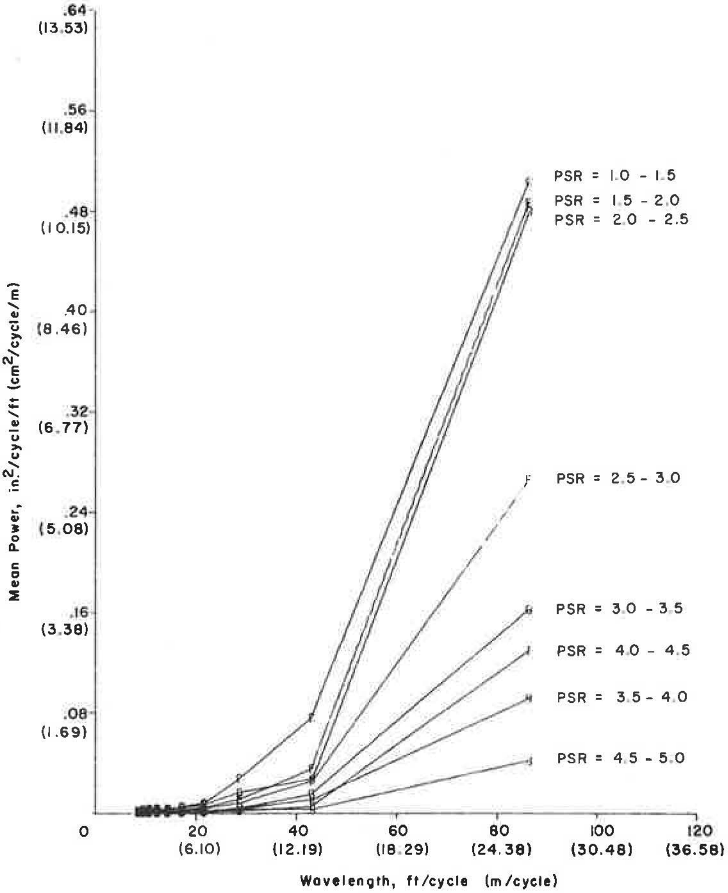
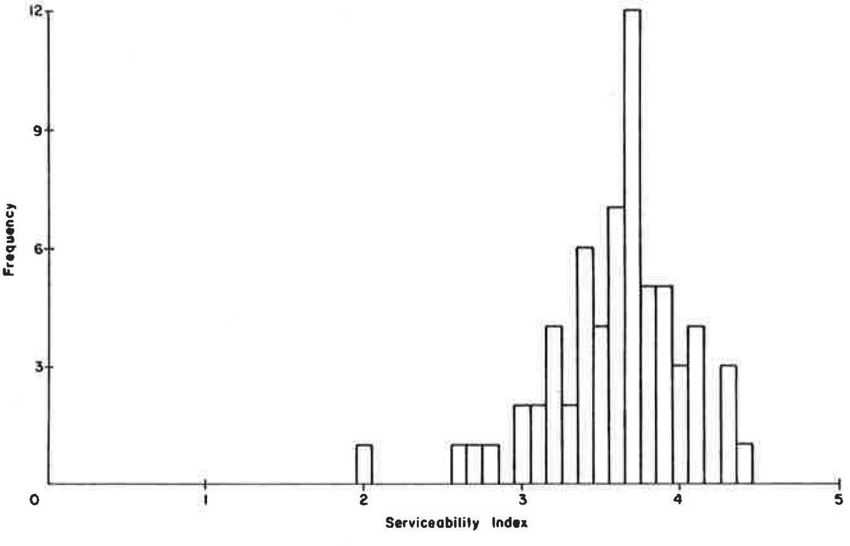


Figure 2. SI histogram for measurements on US-71.



or smaller wavelengths, these groupings are less discriminating as roughness indicators.

Sometimes it is helpful to focus on the amplitude spectrum of a section of road profile rather than its power or covariance spectrum. Such estimates are usually more easily realized physically by the highway engineer than are the power spectral estimates (i.e., the root-mean-square amplitude of the profile irregularities in inches is more easily understood than power in in.^{2}/cycle/ft. Such amplitudes may be obtained from the power spectral estimates from $x_i = \sqrt{2Q_i\Delta f}$ where Q_i is the two-sided power or covariance spectral component for the i th frequency band and Δf is the width of the band containing this variance.

Specific amplitude estimates were highly correlated with pavement riding quality, and a PSI model was developed that was superior to the original slope variance and roughness index models and that has since been extensively used for SI measurement in Texas. In addition, it is also currently being used as the SI measurement standard for calibration with Mays Road Meters (6).

The SI model based on road profile spectral estimates also has a very significant operational advantage over the slope variance or roughness index models in that condition survey information is not required. That is, the SI value is derived only as a function of the spectral estimates, thus permitting more rapid and continuous SI measurements. Figures 2 and 3 show the usefulness of this procedure for obtaining large-scale SI measurements. Figure 2 is useful for computing a SI histogram for several miles of pavements on US-71 south of Austin, Texas, and Figure 3 is useful for providing continuous SI samples for several miles of I-10 east of San Antonio.

There are, however, several problems in using power spectral analysis methods in characterizing road profile data. The primary problem is that the spectral estimate is a mean power estimate for each particular band; thus, the degree of roughness variation within a section is not measured (7).

Assuming that the profile data meet the usual statistical assumptions (Gaussian, stationary, etc.) and enough data are present, this mean provides a good estimate of the real profile amplitude from which a good indication of the characteristics of the individual time or distance ensembles can be obtained. On the other hand, if these assumptions are not met, which is usually the case, then the amplitude estimate can become distorted. In addition, so that reliable spectral estimates can be obtained, pavement sections must be several hundred feet long [1,200-ft (365.76 m) minimum lengths were used]. These constraints thus make it difficult, if not impossible, to get accurate information on localized effects, which must be examined carefully in studies relating distress to performance.

Filtering techniques offer another analysis tool in which the amplitudes of selected wavelength bands can be observed as a function of distance. This permits more localized examinations of the true average amplitude variations. Digital filtering techniques are attractive for analyzing the digitized road profile data because they easily can be developed and applied.

Digital Filtering Definitions

Digital filtering is the process of spectrum shaping by using a digital computer as the basic building block (1). Hence, the goals of digital filtering are similar to those of continuous or analog filtering. Whereas continuous filter theory is based on linear differential equations, digital filter theory is based on linear difference equations.

Digital filters can be applied to the discrete road profile data by convolving these data with the weighing function (impulse response) of a specific filter. The convolution is

$$y_n = \sum_{i=0}^{N} w_i \, x_{n-i} \qquad (1)$$

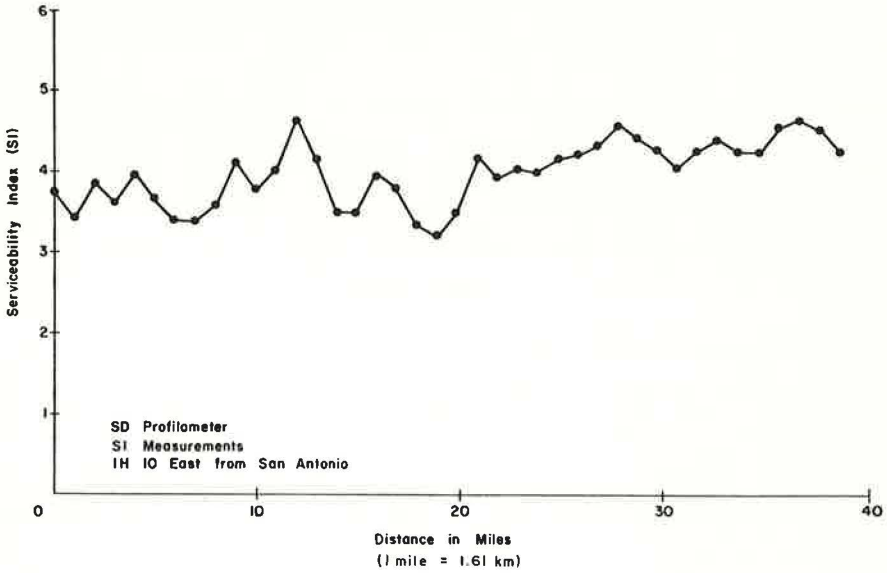


Figure 3. Continuous SI measurements on I-10.

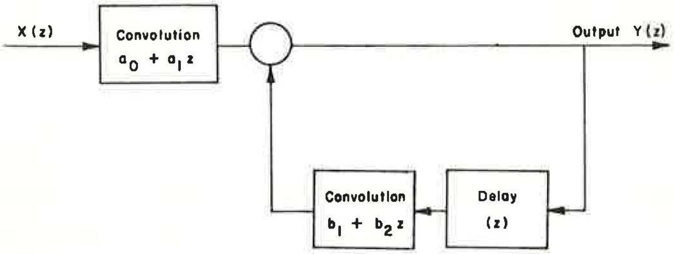


Figure 4. Recursive digital filter (4).

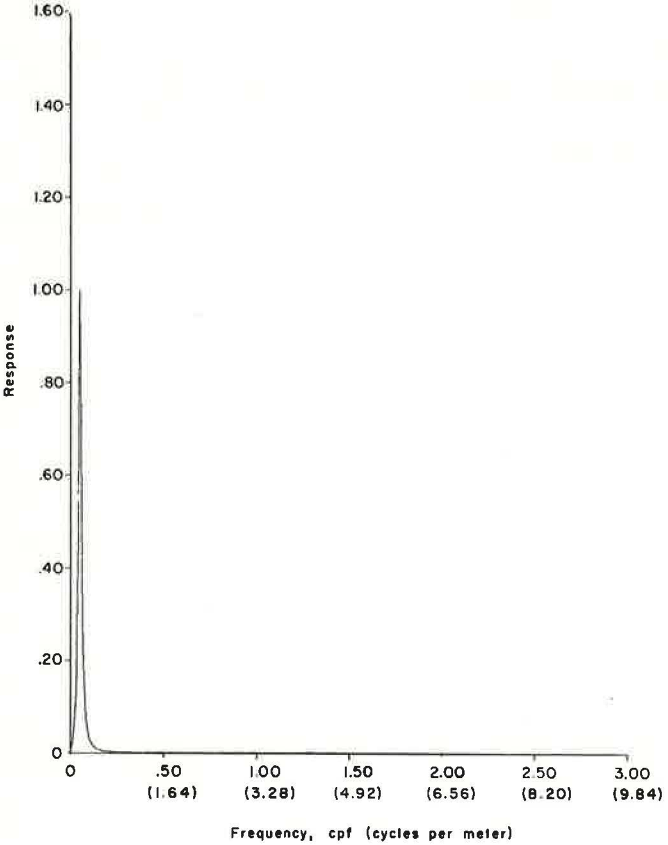


Figure 5. Filter frequency response.

where

$X = \{x_0, x_1, \ldots, x_M\}$ represents M + 1 values of the input series or road profile,
$W = \{w_0, w_1, \ldots, w_N\}$ represents N + 1 values of the filter weighing function, and
$Y = \{y_0, y_1, \ldots, y_{N+M}\}$ represents the N + M + 1 values of the filtered output series.

Equation 1 can also be expressed in terms of its z-transform as

$$Y(z) = W(z)\, X(z) \tag{2}$$

where

$X(z) = x_0 + x_1 z + x_2 z^2 + \ldots x_M z^M$,
$W(z) = w_0 + w_1 z + w_2 z^2 + \ldots w_N z^N$, and
$Y(z) = y_0 + y_1 z + y_2 z^2 + \ldots y_{M+N} z^{M+N}$.

Variable z, which represents the operation of delaying a data sample one sample interval (z^N by N sample intervals), is related to the Laplace variable S by

$$z = e^{-TS} \tag{3}$$

where T is the Δt sample interval.

Some digital filters can also be expressed as a ratio of two polynomials in z or

$$W(z) = \frac{A(z)}{B(z)} = \frac{a_0 + a_1 z + \ldots a_N z^N}{b_0 + b_1 z + \ldots b_M z^M} \tag{4}$$

By using long division (4), w(z) can be expanded into a simple polynomial:

$$\frac{A(z)}{B(z)} = w_0 + w_1 z + w_2 z^2 + \ldots \tag{5}$$

If the filter is stable, the coefficients will converge to zero and, hence, w(z) may be closely approximated by a finite number of terms (i.e., K) or

$$W(z) = \frac{A(z)}{B(z)} \approx w_0 + w_1 z + \ldots w_K z^K \tag{6}$$

This approximation can then be used as a filter by standard digital convolution. If the rational filter

$$W(z) = \frac{a_0 + a_1 z}{1 + b_1 z + b_2 z^2} \tag{7}$$

is used to filter a set of profile data then the standard output Y(z) can be expressed as

$$Y(z) = \frac{a_0 + a_1 z}{1 + b_1 z + b_2 z^2}\, X(z)$$

or

$$Y(z) + zY(z)\,[b_1 + b_2 z] = [a_0 + a_1 z]\, X(z)$$

and thus

$$Y(z) = [a_0 + a_1 z]\, X(z) - zY(z)\,[b_1 + b_2 z] \tag{8}$$

That is, Y(z) is equal to the input convolved with the series (a_0, a_1) minus the output delayed one sample interval and convolved with the series (b_1, b_2).

Figure 4 shows this feedback system, which is realized by the recursive algorithm of Eq. 8. The general recursive equation for rational filters can be expressed as

$$y_n = \sum_{i=0}^{M} a_i x_{n-i} - \sum_{j=1}^{M} b_j y_{n-j} \tag{9}$$

Such filters (1, 2, 4) may be synthesized in the z plane, or standard S plane filters can be converted to such recursive relationships.

Recursive filters may also be used for obtaining zero phase filters by the uses of both forward and reverse recursive algorithms (4).

A Specific Application

As noted before, one advantage in using digital filtering techniques for analyzing road profile data is that a plot of the filtered profile amplitude versus distance can be obtained. Statistical methods that first group similar variances and then obtain more realistic average and extreme amplitude estimates for road sections can then be applied.

Figure 5 shows the frequency response of a simple band pass filter that was applied to about 2 miles (3.2 km) of Texas pavements where nearby swelling clay mounds occurred in 20-ft (6.10 m) wavelengths. The coefficients used in obtaining this filter are given in Eq. 10:

$$\begin{aligned} y_n = {} & (-5.375 \times 10^{-6})x_{n-1} + (5.375 \times 10^{-6})x_{n-5} + 3.954\, y_{n-1} \\ & -5.870\, y_{n-2} + 3.876\, y_{n-3} - 0.9610\, y_{n-4} \end{aligned} \tag{10}$$

for a Nyquist frequency of 2.96 cycles/ft (9.71 cycles/m).

Figures 6, 7, and 8 show the plots of this data before and after filtering where zero phase filtering was performed. Zero phase filtering, which causes no phase shift in the irregularities in the profile corresponding to any frequency, was obtained (4). After the forward recursive algorithm of Eq. 10 was used, the time reverse algorithm of Eq. 11 was applied:

$$\begin{aligned} y_n = {} & (-5.375 \times 10^{-6})x_{n+1} + (5.375 \times 10^{-6})x_{n+5} + 3.954\, y_{n+1} \\ & -5.870\, y_{n+2} + 3.876\, y_{n+3} + 0.9610\, y_{n+4} \end{aligned} \tag{11}$$

The plots in Figures 6, 7, and 8 are useful for showing the results of the filtered data superimposed on the original profile data. The filtered data should be examined, for example, first to segment the pavement section on the basis of amplitude characteristics and then to compute average amplitude statistics.

Digital Filtering for Pavement Surface Characterization

Probably the most important use of digital filtering will be to investigate more localized pavement characteristics. For example, if a large set of amplitude plots for several key wavelengths can be obtained for a specific type of pavement cracking condition at various failure stages, then multivariate analysis techniques, considering the average amplitude variation and the maximum amplitude value of the filtered profile data, might yield a statistical correlation.

Pavement performance has already been somewhat related to specific wavelength amplitudes (7); thus, these same bands might provide initial frequency bands for consideration. Additional rating sessions might also be conducted, and more precise amplitude estimates might be obtained for correlation with the subjective ratings.

Another useful method of applying these filtering methods would be to establish a set of typical upper amplitude levels for construction specifications and control rather than a single number as ⅛ in. (3.2 mm) for 10-ft (3.05 m) wavelengths. So that this

Figure 6. Profile before and after filtering, 0 to 67 ft (0 to 20 m).

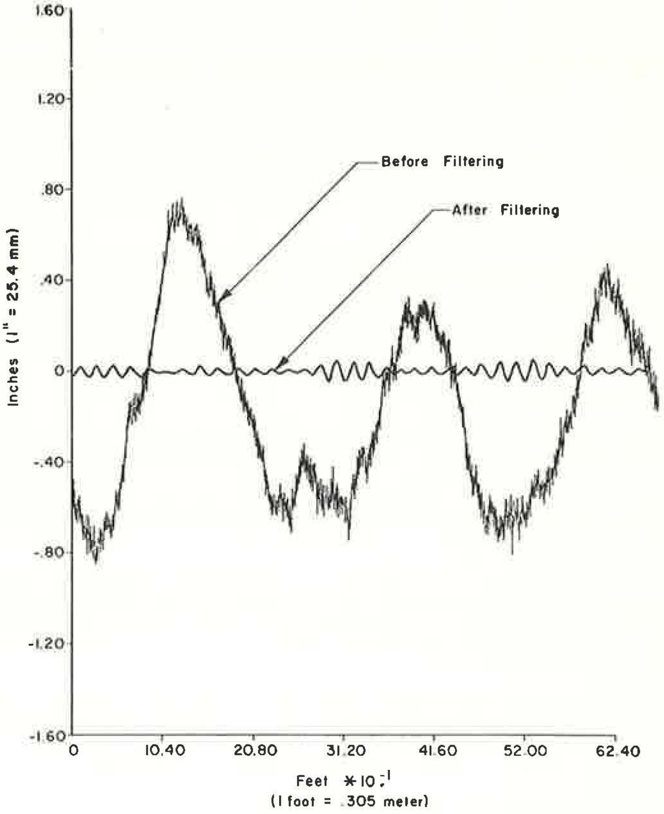


Figure 7. Profile before and after filtering, 67 to 135 ft (20 to 41 m).

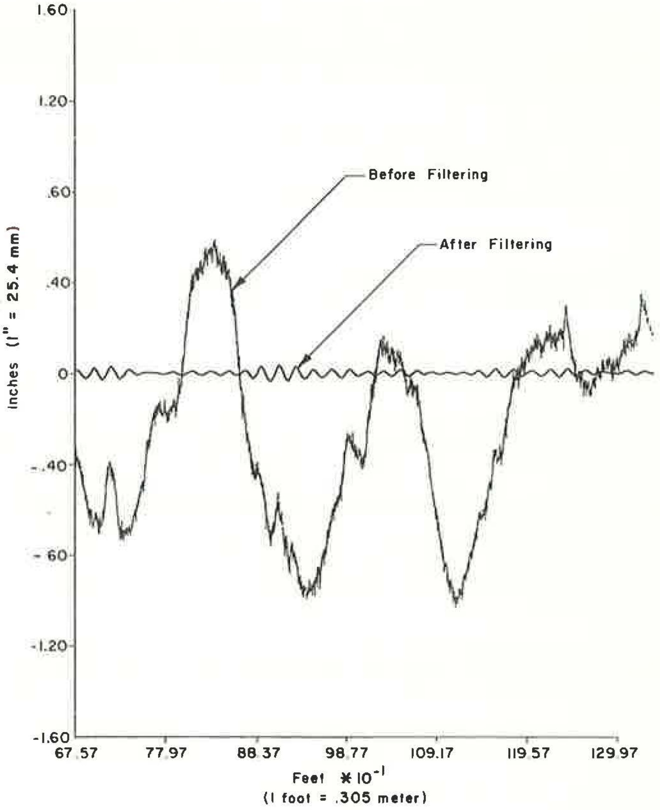


Figure 8. Profile before and after filtering, 135-200 ft (41 to 61 m).

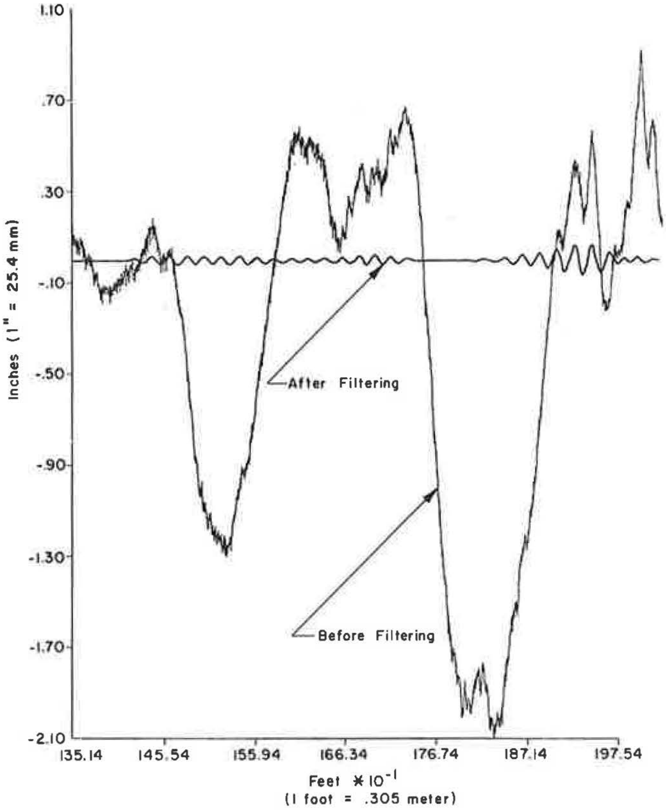
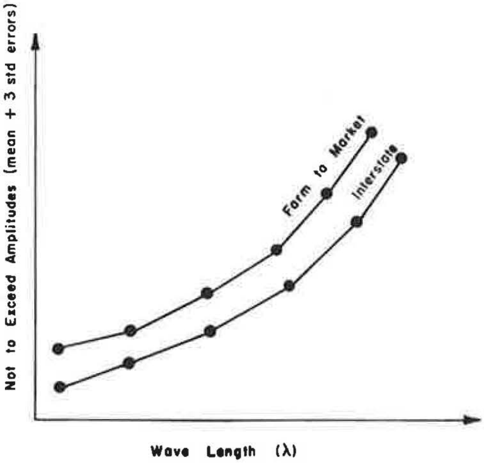


Figure 9. Example of not-to-exceed amplitude levels for construction specifications.



could be done, a representative sampling of profiles from pavements of highly acceptable riding quality could be measured. Band pass filters could then be designed and used on these data to obtain several sets of filtered profile data. Mean and upper amplitude ranges (e.g., three standard errors) could then be established for appropriate roughness regions for each band of these data to establish a set or spectrum of not-to-exceed amplitude regions (Fig. 9). If the mean of the absolute values of the profile elevation deviations at any wavelength exceeds the established threshold value, then the pavement is not satisfactory. Root-mean-square amplitudes could be also used. Initially, filters centered at the bands used in the SI model might be used. Once such ranges are established, the SD profilometer could then be used for evaluation of new or recently overlayed pavements so that areas violating these critical regions could be found rapidly. The use of a small digital controller within the SD profilometer could easily detect such violations immediately during profile measurements.

Of course, the use of digital filters is not without complications. First, which frequency or wavelength bands should be considered for a given application? Second, which statistical or set of statistical methods should be used for summarizing the filtered data? Third, digital filters like analog filters have certain inherent characteristics (e.g., response time, etc.), which must be considered, although the zero phase filter does provide an advantage over analog filtering method.

The numerous combinations of frequency bands can likely be minimized by the power spectral analysis methods discussed, and the numerous data summarizing methods might be limited to those that lend themselves to physical interpretation. This tool, however, should add new dimensions to road profile analysis techniques and perhaps aid in initial solutions relating distress and performance.

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