USE OF PROFILE WAVE AMPLITUDE ESTIMATES FOR PAVEMENT SERVICEABILITY MEASURES

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For a number of years, engineers were interested in developing objective criteria for designing and maintaining highways on the basis of pavement performance, i.e., riding quality. The development of the serviceability performance concept by Carey and Irick provided a method for developing such criteria. Although this method may seem rather crude to some, it is still the best method available of those that consider the subjective riding-quality measurements of highway users. Several classes of instruments have been used for obtaining the objective measurements required for this concept; one is the slope-variance measuring device. Serviceability index models were developed based on slope variance of road profile data obtained with the surface dynamics profilometer. Subsequently, a serviceability index model was developed based on profile wave amplitude estimates of the road profile data. This latter model has been found to be superior to the slope variance model and has now been used extensively for providing measurements in Texas. This paper describes this model and some of the results of its uses in field operations.

•FOR A number of years, engineers have sought an objective measure of the riding quality of highways in order to establish better highway design and maintenance procedures. Various measuring devices have been proposed and tried in attempts to provide objective data to indicate a pavement's riding quality. The problem was further complicated in these initial attempts because there were no means of calibrating these roughness data when they were obtained; e.g., How rough is rough, or how smooth is smooth? Finally, during the planning for the AASHO Road Test, Carey and Irick (4) developed a serviceability concept that serves as a basis for most current pavement rating systems and is based on a subjective evaluation of the road user's opinion of the pavement at any given time.

Because this concept requires correlation between objective physical measurements of pavement characteristics and subjective measurements of the pavement, the development of reliable serviceability index (SI) prediction models is not a trivial task, for it requires some type of an adequate statistically designed highway rating experiment for the subjective measurements and some type of roughness measuring device for the objective measurements.

The availability of the surface dynamics profilometer (SDP) provided a profile-measuring device with which roughness characteristics could be obtained. The Texas Highway Department purchased the first such profilometer (15). In subsequent research (12), a large-scale pavement rating experiment was conducted in which a panel of typical road users riding in typical American automobiles expressed their opinions on the riding quality of a group of pavements. The sites selected for the rating sessions represented different topographical areas of Texas. The road profiles of these test site pavements were measured with the SD profilometer, and pavement deterioration (con-

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Publication of this paper sponsored by Committee on Pavement Condition Evaluation.

dition survey) information was obtained. Roughness index and slope variance statistics computed from those data were then used for characterizing the pavement sections.

The roughness statistics and the condition survey information were correlated to the mean panel present serviceability rating (PSR) to get pavement SI prediction models (12, 16).

Because of the complexities of a road profile, a much better possibility of characterizing a pavement section appears to be by its power spectrum or wavelength components than by a single statistic such as slope variance. With wavelength information, various problems such as profilometer sensor wheel bounces can be isolated or accounted for to provide more accurate pavement characterizations.

It would also appear that a predictor of riding quality at least as good and probably better could be obtained by correlating the effects of individual frequencies with PSR through multiple regression analysis techniques. By this method, only those frequencies that are found to be highly correlated with PSR could be included, and the rest could be discarded.

SI MODEL DEVELOPMENT USING PROFILE WAVE AMPLITUDE ESTIMATES

To predict a pavement serviceability index as a function of profile wavelength, the following linear model is considered:

$$SI = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \ldots + \beta_N X_N + \epsilon \tag{1}$$

where

β_i = linear model parameters, and
X_i = average wavelength amplitude.

Average wavelength amplitudes are considered the independent variable, for these values obviously affect the riding quality or roughness of a pavement and are more easily realized physically by the highway engineer than are, say, the power spectrum estimates. Such amplitudes may be obtained from the power spectrum estimate from

$$X_i = \sqrt{2Q_i \Delta f} \tag{2}$$

where Q_i represents the 2-sided power or variance spectrum component for the ith frequency band, and Δf is the frequency containing this variance.

In the development of the model, the original rating session data (12) were reexamined by using the mean panel ratings from 86 representative test sections throughout Texas. The power or variance spectrum estimates for each of the road profiles of these 1,200-ft sections were then obtained. [Walker and Hudson (18) discuss the assumptions necessary for power spectrum estimates of road profile data obtained with the SDP.] The power spectrum estimates for the right and left wheelpaths and the cross power were computed for each profile section.

Figure 1 shows the relation between PSR and road profile power spectrum estimates. The power spectrum estimates for several frequencies or wavelength bands were computed and are shown for various road roughness classes, as indicated by PSR. That is, the 86 pavement sections covering the gamut of pavement roughness were grouped as shown (PSR intervals from 4.5 to 5.0, 4.0 to 4.5, and so on), and their average spectrum amplitudes were obtained. In general, the rougher the road is, the greater the spectrum amplitude is. This figure thus indicates that there should be some appropriate equation that relates SI to power spectrum estimates and thus wave amplitudes. The problem then is to determine which wavelengths or bands to include in this function or model.

A stepwise regression procedure (8) was used. The PSR values from the original rating session experiment were the dependent variables, and the logs of the wavelength amplitudes were the independent variables. Regression analysis assumes that the dependent variable is the only random variable. Because there are errors in these independent variables and these errors are not symmetrically distributed [power spectrum or variance estimates are distributed according to the chi-square distribution (2)], they would tend to bias the results unless these errors were symmetrically distributed. Thus, the log transformation on these values was used. The use of the log transformation in this case is rather intuitive but is supported by Scheffe (13) when the analysis of variance on variance estimates is used. (It should be noted that, after the log transformation is performed, only a constant separates the power spectrum amplitudes from the profile wave amplitudes. Thus, similar results can be obtained by using power spectrum estimates as the independent variables rather than wave amplitudes.) In addition, the independent variables were centered before the regression was performed.

An ideal model for riding quality is characterized by realistic and relatable terms. However, an extensive search revealed no such ideal model. Some of the problems in modeling procedures that could have prevented obtaining such a model are presented here.

First, the linear scale rating method that was used and is similar to the one used at the AASHO Road Test has been criticized as not giving an adequate subjective representation. Thus, if not all pavement classes are properly distinguished by the raters, it becomes difficult if not impossible to obtain an appropriate model.

Second, for the higher frequencies (or shorter wavelengths), adjacent power spectrum estimates are highly correlated. For the lower frequencies (or longer wavelengths), this correlation drops significantly. For example, the correlation coefficient R between the first and second bands (0.0116 and 0.0231 cpf) was 0.599. For bands above 0.231, these values increased to above 0.9. These upper frequencies, however, were not highly correlated with PSR. Also, when the values were examined, average amplitude levels for frequencies of 0.231 cpf and higher were much less than 0.01 ft for the smoother roads; that is well beyond the measuring accuracies of the vehicle. As roads get rougher, these levels increase in the same proportion. Because these frequencies probably affect roughness for some of the classes of rougher roads, a better technique should be used for including their effect in the equation. Because of their high interrelations and their unreliability for the smooth roads, these values were omitted. A satisfactory prediction model, however, was obtained by including the longer wavelengths (or lower frequencies). These values, as noted, were not very interrelated and were found suitably correlated to PSR. Thus, the model does seem to indicate that these wavelengths are important in riding quality.

Initially a 32-band model was developed (52 deg of freedom) that included 3 amplitude terms centered at 0.023, 0.046, and 0.069 cpf, 3 amplitude interaction terms, 2 cross-amplitude terms, and 1 pavement type term, or a total of 9 deg of freedom for the regression and 76 for the residual. The correlation coefficient was only 0.9 (R^2 = 0.81), and there was some lack of fit. This model is as follows:

$$\begin{aligned} SI = 3.24 &- 1.47X_1 - 0.133X_2 \\ &- 0.54X_3 + 1.08XC_1 - 0.25XC_2 \\ &+ 0.08X_2X_3 - 0.91X_3X_4 + 0.67X_6X_{10} \\ &+ 0.49T \end{aligned} \tag{3}$$

where

$X_1 = \log A_{0.023} + 2.881$;
$X_2 = \log A_{0.046} + 4.065$;
$X_3 = \log A_{0.069} + 4.544$;
$X_4 = \log A_{0.093} + 4.811$;
$X_6 = \log A_{0.139} + 5.113$;
$X_{10} = \log A_{0.231} + 5.467$;
$XC_1 = \log C_{0.023} + 3.053$;
$XC_5 = \log C_{0.116} + 5.659$;
A_i = average right and left wavelength amplitude, in in.;
C_i = cross-amplitude, in in.;

i = frequency band, in cycles/ft; and
T = 1 for rigid pavements and 0 for flexible pavements.

The regression analysis results are as follows:

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio
Regression	9	47.68	5.297	37.46
Residual	76	10.75	0.1414	

Correlation coefficient R = 0.90, and standard error for residuals = 0.38.

An attempt was made to obtain a better model by rerunning the same regression procedure on 64-band power spectrum estimates (32 deg of freedom for each estimate) of the same data. The correlation coefficient for the model in this case increased to 0.94, and the standard error of residual decreased to 0.32 (no lack of fit). Although the same frequency band centers entered the model, more interaction terms were included. Repeat runs using both models revealed little difference; thus, the 32-band model is illustrated because of fewer terms, greater regression significance, and more reliable power spectrum estimates.

A desirable regression model should make sense physically, show suitable correlation between the dependent and independent variables, exhibit an acceptable lack of fit, and produce reasonable results in actual field use.

This model appears to make sense in that the greater the amplitude terms are, the less the SI readings are. The cross-amplitude term (which comes from cross power) is a little more difficult to define physically; however, it indicates the similarities between the 2 profile heights (cross roll or roughness effects). The interaction terms are useful in fitting the model.

The best practical test for the model is how well it performs in use. The performance of this model on more than 300 miles of pavements has been quite acceptable, and it is currently being used for all SI measurements involving the SDP. Table 1 gives a typical set of repeat data runs. That is, 3 different 1,200-ft pavement sections (none of which was included in the original rating sessions) were each run 5 times with the SDP. The data were digitized, and the power spectrum estimates were computed for each run. The appropriate terms were then computed, and the SI was obtained for each run.

USES OF THE SI MODEL

As indicated, the current model is being used for all SI measurements involving the SD profilometer. In addition, because of the stability of the model, primarily due to the internal calibration facilities of the SD profilometer, these measurements are also currently being used as a standard for SI measurements by the Mays road meter (MRM) (19). The relation found between the MRM cumulative roughness readings, in in./mile, and the SD profilometer SI measurements is

$$SI = 5e^{-\left(\frac{\log_e M}{\beta}\right)^{\alpha}} \qquad (4)$$

where

M = MRM roughness readings, in./mile; and
β and α = MRM instrument coefficients (regression coefficients).

This equation was obtained by regressing the MRM readings onto the SI values and then solving for SI. A typical plot of this equation for one of the MRM devices calibrated to the SI standard is shown in Figure 2. Table 2 gives the results from different MRM calibrations during this past year.

Figure 1. Wavelength versus power spectrum estimates for rating session data.

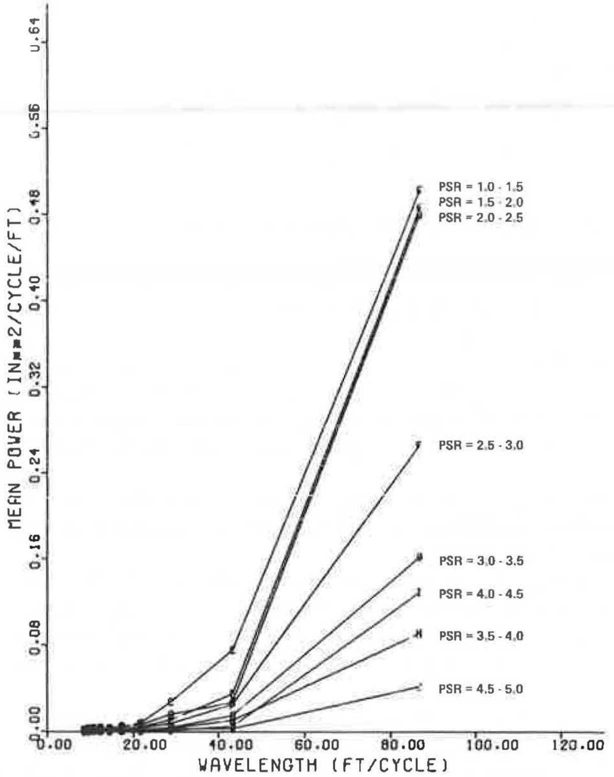

Table 1. SI replications.

Test	Run	SI
1	1	4.50
	2	4.53
	3	4.61
	4	4.57
	5	4.57
2	1	4.18
	2	3.70
	3	3.76
	4	3.98
	5	4.14
3	1	2.02
	2	1.69
	3	1.53
	4	1.92
	5	1.86

Table 2. MRM-SDP SI calibration results.

MRM	β	α	SI Model Error	R^2
1	5.679	5.1	0.327	0.998
2	5.343	4.6	0.314	0.997
3	5.192	4.0	0.292	0.994
4[a]	5.547	4.9	0.391	0.997
5	5.720	5.1	0.351	0.997
6	5.971	4.0	0.328	0.996
7	5.564	4.0	0.337	0.996
8	5.602	5.0	0.269	0.998

[a] Mechanical Mays road meter (the other results shown are for the new electronically controlled models manufactured by Rainhart Company).

Figure 2. SI values of SDP versus roughness readings of MRM.

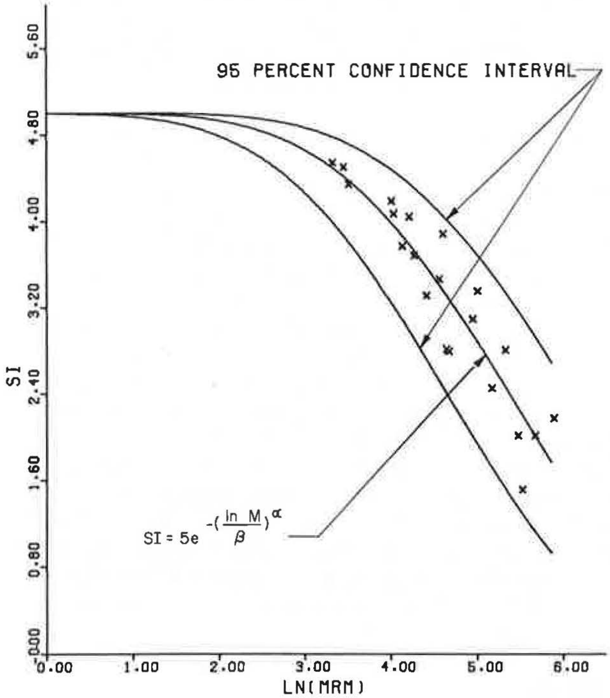

Table 3. Amplitudes for PSR intervals.

PSR Interval	Number of Sections	Frequency (cpf)	Power Mean (in.^{2}/cpf)	Amplitude of Upper 99 Percent (in.)
4.0 to 4.5	10	0.012	1.2945	1.4134
		0.023	0.0520	0.2833
		0.035	0.0159	0.1566
		0.046	0.0076	0.1085
		0.058	0.0044	0.0823
		0.069	0.0028	0.0661
		0.081	0.0025	0.0617
		0.092	0.0022	0.0580
		0.104	0.0018	0.0526
		0.116	0.0017	0.0516
2.0 to 2.5	10	0.012	2.6602	2.0262
		0.023	0.2538	0.6258
		0.035	0.0759	0.3422
		0.046	0.0307	0.2176
		0.058	0.0249	0.1960
		0.069	0.0174	0.1641
		0.081	0.0108	0.1291
		0.092	0.0087	0.1161
		0.104	0.0082	0.1127
		0.116	0.0084	0.1140

By using the SI measurements of the SDP as a standard, a general set of calibration, operation, and control procedures has been developed for all MRM devices purchased by the Texas Highway Department. These procedures provide a means of measuring roughness in standard roughness units for all MRM devices and thus enable 2 separate instruments, installed in separate vehicles, to get the same roughness readings for the same road section.

In addition to being used for SI measurements, this model can also provide useful information in regard to the importance of the various wavelength amplitudes. The original power spectrum estimates from the large-scale rating session might also be of interest. For instance, the average power spectrum estimates for various classes of roads can be obtained and used for computing the wave amplitudes (Fig. 1). Table 3 gives a summary of this information for the various road classes for the PSR intervals of 4.0 to 4.5 and 2.5 to 3.0. For each frequency band of these 2 intervals, the mean power and the corresponding upper 99 percent confidence band are given. This upper range for the individual amplitude term is also given. This upper band might be useful in construction control studies, for typically mean amplitude values should not exceed these upper ranges (control of such specifications is, of course, another matter). For example, roads in Texas are typically designed to allow deviations from a 10-ft straightedge to be no greater than ⅛-in. As noted, roads in the roughness class 2.5 to 3.0 (frequency near 0.104) are near this upper range. The values given in this table however, should be viewed as rough estimates, for their accuracy depends on the statistical assumptions necessary for accurate power spectrum estimates (18), which are not exactly met. Another useful analysis method would be to examine the profile data with digital filtering techniques. With such techniques, the amplitudes within specific frequency bands can be examined as a function of distance.

SUMMARY

A model for measuring highway roughness or riding quality based on spectrum estimates of road profile data has been presented. The road profile data are obtained with the surface dynamics road profilometer. Through actual field use on several hundred miles of varied highway pavements, the model has been found to provide acceptable riding-quality measurements. The application of some of its uses in field operations has also been briefly described. This included the use of SI measurements obtained with this model as a measurement standard for Mays road meters.

ACKNOWLEDGMENTS

This investigation was conducted at the Center for Highway Research at the University of Texas at Austin. The authors wish to thank the sponsors, the Texas Highway Department and the Federal Highway Administration. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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