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Calibrating Response-Type Roughness Measurement Systems Through Rod-and-Level Profiles

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Road roughness is highly correlated with serviceability and various components of user costs. Response-type systems (e.g., the Mays meter, the roughometer, and the bump integrator) are frequently used to measure roughness mainly because of their relatively low cost and high measuring speed, whereas a sophisticated device such as the Surface Dynamics Profilometer is necessary for calibrating those systems. An analysis of rod-and-level measurements of pavement profile is presented. Rod-and-level measurements represent a feasible alternative to the Profilometer in that they provide an accurate means for calibrating response-type roughness-measuring systems. Four different profile summary statistics from the literature are used to establish a stable roughness scale: wave amplitude, root mean square vertical acceleration (RMSVA), mean absolute vertical acceleration (MAVA), and slope variance. RMSVA computed for different base lengths is recommended for characterizing road roughness. Accurate RMSVA estimates can be obtained when a 500-mm sampling interval is used to collect pavement profile data with rod and level. It is found that rod-and-level measurements of pavement profile currently constitute the most feasible means for the general transfer of roughness standards. Moreover, the rod-and-level method is particularly appealing for developing countries, where the social costs of labor-intensive procedures may be significantly less than the costs of procedures that depend on sophisticated imported instruments. Rod-and-level measurements are very slow when a short sampling interval of 500 mm is used. Therefore, use of the method is recommended for keeping updated records of pavement roughness on about 20 control sections. These sections, in turn, can be used for calibrating response-type roughness-measuring instruments.

Since the American Association of State Highway Officials (AASHO) Road Test, where the concept of pavement serviceability was developed by Carey and Irick (1), increasing importance has been given to user-related pavement evaluation. This type of evaluation is concerned primarily with the overall function of the pavement--that is, how well it serves traffic or the riding public.

The serviceability of a pavement is largely a function of its roughness (2), and several models can be found in the literature that estimate serviceability as a function of roughness alone (3,4). Moreover, it has been demonstrated that roughness is the principal measurement of pavement condition directly related to vehicle operating costs (5,6).

Roughness is normally measured with response-type measuring systems, which are relatively fast and inexpensive. However, the output of these systems is not stable over relatively long periods of time. Consequently, it is necessary to establish a stable roughness scale against which response-type measuring systems can be calibrated.

A convenient roughness scale was provided by the surface dynamics (SD) profilometer for a United Nations Development Program (UNDP) project in Brazil (7). This paper is devoted to developing a procedure, based on rod-and-level measurements of roadway profiles, through which the roughness standard provided by the profilometer can be transferred among different regions or countries. Furthermore, it is expected that the rod-and-level profile summary statistics presented here can be used to characterize pavement roughness over a wide range of wavelengths in a more reliable manner than can be done by using the SD profilometer.

USE OF PROFILE SUMMARY STATISTICS TO QUANTIFY PAVEMENT ROUGHNESS

The motion of a vehicle on a pavement results from the excitation of a dynamic system, the vehicle, by the vertical displacements of the pavement profile. If the parameters defining the dynamic system are known as well as the roadway profile, vibration theory can be used to determine the vertical movement of the vehicle at a given speed (8,9).

Most vehicle parameters (tires, suspension, body mounts, seats, etc.) are relatively similar. Moreover, on any particular road, most cars will be driven at similar speeds. Therefore, the excitations of the car, and thus the riding characteristics, become primarily a function of the road profile (2).

Figure 1. Simplified block diagram of SD profilometer measurement system.

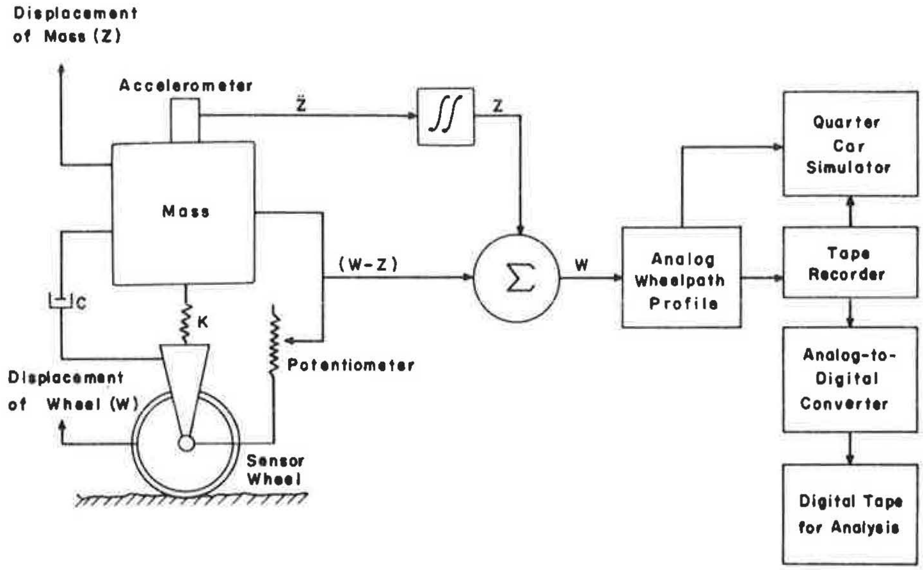
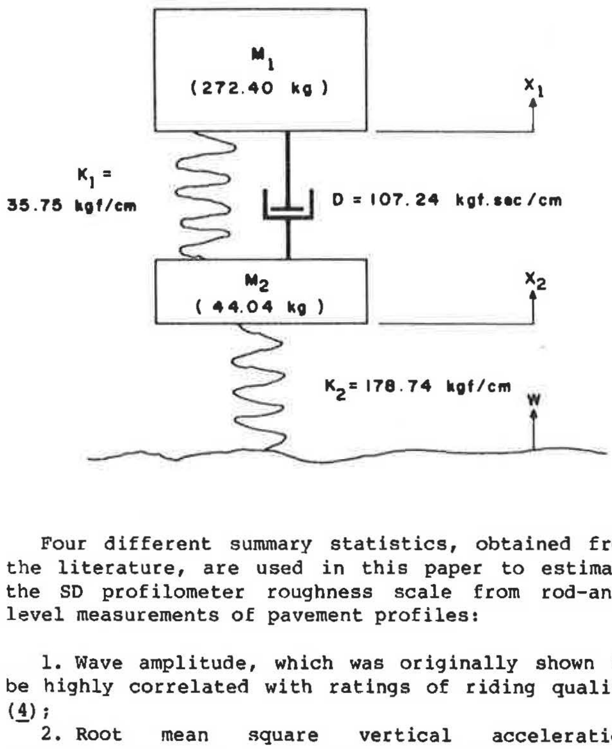


Figure 2. QCS system.



Four different summary statistics, obtained from the literature, are used in this paper to estimate the SD profilometer roughness scale from rod-and-level measurements of pavement profiles:

1. Wave amplitude, which was originally shown to be highly correlated with ratings of riding quality (4);
2. Root mean square vertical acceleration (RMSVA), which was first used as a basis for Maysmeter calibration (10);
3. Mean absolute vertical acceleration (MAVA), which has been suggested for Maysmeter calibration (11); and
4. Slope variance, which was found to be highly correlated with serviceability at the AASHO Road Test (12).

SD PROFILOMETER ROUGHNESS SCALE

The SD profilometer consists of a light delivery vehicle that houses a profile computer, an analog tape recorder, a quarter-car simulator (QCS), a road-following wheel in each wheel path, and potentiometers and accelerometers. A potentiometer is connected between each road-following wheel and the vehicle body to measure the relative movement between the test wheel and the body (see Figure 1). Two accelerometers are secured on the vehicle body directly over the road-following wheels to sense the movement of the body. The potentiometer and accelerometer signals are then electronically combined to remove car body movement and obtain a stable roughness measurement (13).

The profile computer is a special-purpose electronic system that processes the potentiometer and accelerometer signals to obtain the road profile. An analog tape recorder is used to record the profile data so they can be processed after the recording. The QCS is a special-purpose analog computer that simulates the motion of a single-tire mass system over the road profile as it is generated or from the analog tape. The system consists of a body mass, one tire, shock absorber, and spring, and the response measured is a summation of the body movement relative to the wheel axle over a fixed distance (see Figure 2). The parameter values incorporated into the QCS are for the Bureau of Public Roads (BPR) roughometer, as reported in the manufacturer's instruction manual.

The roughness output from the QCS, termed the quarter-car index (QI), can be accepted as a standard measure of roughness. The QI has units of length per length, but, to avoid confusion with other roughness measures, the units were designated counts per kilometer. Referring to Figure 2, QI is defined as follows:

$$QI = (1/2L) \int_0^L |X_1' - X_2'| dL \tag{1}$$

where

X_1 = ordinate of sprung mass ($X_1' = dX_1/dL$),
X_2 = ordinate of unsprung mass ($X_2' = dX_2/dL$), and
L = distance along the road.

Application of Newton's second law to M_1 and M_2 in Figure 2 gives the following set of second-order differential equations:

$$-K_1(X_1 - X_2) - D(\dot{X}_1 - \dot{X}_2) = M_1\ddot{X}_1 \tag{2}$$

$$K_1(X_1 - X_2) + D(\dot{X}_1 - \dot{X}_2) - K_2(X_2 - W) = M_2\ddot{X}_2 \tag{3}$$

The solution of these equations is required for the

Table 1. Profilometer QI results on roughness correlation sections.

Section	Length (m)	Type of Surface	Profilometer QI Right Path	Profilometer QI Left Path	Survey Date
M05	320	AC	62	68	5/79
M06	160	AC	48	40	5/79
M07	160	AC	99	92	5/79
M08	160	AC	68	60	5/79
M09	160	AC	137	105	10/79
M13	320	DST	77	61	10/79
M14	320	DST	62	60	11/79
M15	320	DST	59	74	10/79
M22	320	AC	77	68	8/79
M23	320	AC	27	23	8/79
M26	320	AC	58	57	8/79
M27	320	AC	48	41	8/79
M28	320	AC	58	53	8/79
M29	320	AC	76	67	10/79
M30	320	AC	87	67	10/79
M31	320	AC	66	70	10/79
M32	320	AC	37	36	8/79
M38	160	AC	105	97	11/79
A16	320	DST	62	94	6/80
A17	320	DST	72	76	6/80
M23[a]	320	AC	22	23	3/80
M28[a]	320	AC	57	55	3/80
M30[a]	320	AC	86	68	3/80

Note: AC = asphaltic concrete and DST = double surface treatment.
[a]Replication.

evaluation of QI. The electronic circuits in the profilometer QCS were especially designed to give an analog solution to the equations, which provides the QI. It should be noted that the solution can also be obtained through digital computers, when the pavement profile is known, by using numerical integration. As a general indication, a QI value of about 30 counts/km has been observed on paved roads after construction in Brazil; pavements that require overlay normally show values greater than 60 counts/km.

ROD-AND-LEVEL MEASUREMENTS OF PAVEMENT PROFILE

Because the rod-and-level method is slow and requires considerable care and labor, it is not feasible for measuring long road segments. Thus, this paper examines the use of rod and level solely for calibration of other roughness-measuring devices.

In collecting rod-and-level data, 10 cm was considered to be approximately the shortest feasible distance between successive points that could be used in the field. Therefore, rod-and-level measurements of road profile were made every 10 cm. The implication of longer intervals between measured points is addressed later in this paper. In spite of the continuous nature of a road profile, discrete measurements are not detrimental because the profile must be expressed in discrete terms to be analyzed digitally.

A three-man team--one surveyor and two assistants--performed the profile measurements while traffic was continually controlled by the highway patrol. Typically, a maximum of about 120-130 m of road was surveyed per day on points marked with chalk in each wheelpath.

A standard survey level and a rod graduated in millimeters were used; all elevations were recorded in millimeters. Specially designed code forms were used in the field to minimize transcription errors, and the data were double-checked on the computer by using an edit program and plotting each data point of each profile. Several errors were detected and corrected through this procedure. The use of profile plots is particularly appealing because it provides for visual identification of errors. Efforts were made to correct all errors so that only reliable data were analyzed.

Roughness Measurement Sections

Twenty paved road sections near Brasilia, varying from smooth to rough, were selected to compare relations between rod-and-level measurements of pavement profiles and the SD profilometer. The objective was to correlate QI with some other profile summary statistics so that a convenient standard to calibrate Maysmeters (or other response-type roughness-measuring devices) could be available in the absence of an SD profilometer. Response-type roughness-measuring systems such as the Maysmeter must be continually calibrated and checked because their characteristics change with time as the tires, shock absorbers, and springs on the vehicle wear or adjustments to the sensors are made.

The sections selected for this study included asphaltic concrete and double-surface-treatment surfacings. To ensure that the profilometer measurements would indicate properly the section roughness at the time of the survey, each section was measured with the profilometer a week before, during, and after the measurements with rod and level. From these runs, a QI value was established for each wheelpath of each section. The results are given in Table 1.

Totals of 3200 and 6400 data points were obtained to describe the profile of a short and long section, respectively. Short sections (160 m) were used only when a uniform 320-m section was not found at the required roughness level. In addition, three long sections that showed low, medium, and high roughness levels were surveyed twice to provide replicate data for a repeatability study. Thus, a total of 131 200 data points was obtained with rod and level for this analysis.

Use of Summary Statistics to Estimate QI

Wave Amplitude

Stepwise regression (14) and ridge analysis (15) were used in the selection of the subset of independent variables that has the greatest combined value for predicting the profilometer QI. Select variables that describe wave amplitude distribution, including mean amplitudes and 90th percentiles, were used as independent variables. The following equation, which is significant and has stable coefficients, was found to best fit the data:

$$QI_{wa} = 29.26A_2 + 21.02A_3 \quad R^2 = 0.95,\ SE = 5.52,\ CI = QI_{wa} \pm 11.42 \qquad (4)$$

where

- QI_{wa} = QI estimate based on wave amplitudes computed from rod-and-level profile,
- A_2 = mean amplitude in millimeters in the wavelength range from 1.2 to 3.0 m,
- A_3 = mean amplitude in millimeters in the wavelength range from 3.0 to 7.6 m, and
- CI = approximate 95 percent confidence interval.

A sample of 36 observations was used to derive Equation 4. This sample size was obtained by considering separately the profiles of both wheelpaths in each section and deleting sections A16 and A17 from the data set. These two surface treatment sections were outliers in all parts of the analysis. Probably because of their high texture, the profilometer sensor wheels bounced during the measurements and the results are not accurate.

Only amplitudes in the wavelength range of 1.2-7.6 m are present in Equation 4. The apparent interpretation is that QI is a measure of pavement roughness that corresponds to irregularities in that wavelength range. Assuming a vehicle speed of 80 km/h, or 22.2 m/s, the wavelength range from 1.2 to 7.6 m corresponds to a frequency range of 2.9-18.5 Hz. These figures are in reasonable agreement with the frequency range of higher-amplitude ratios for a typical vehicle (16).

Therefore, it seems reasonable to conclude that QI is an acceptable measure of pavement roughness in that it represents a quantification of those irregularities to which a typical highway vehicle is more sensitive. Moreover, it has been shown that roadway roughness, in terms of QI, can be predicted as a function of pavement age, structural variables, and traffic (17).

It should be noted that an equation similar to Equation 4 has been developed in which the wave amplitudes were calculated from profiles measured with the SD profilometer (18). The equation obtained was as follows:

$$QI_{wap} = 43.34\,WA_2 + 13.76\,WA_3 \qquad R^2 = 0.92,\ SE = 9.01,\ CI = QI_{wap} \pm 17.77 \tag{5}$$

where QI_{wap} is the QI estimate based on wave amplitudes computed from profiles measured with the profilometer and WA_2 and WA_3 are wave amplitudes corresponding to wavelengths of 1.2-3.0 m and 3.0-7.6 m, respectively (mm).

From a comparison of Equations 4 and 5, it seems that profilometer and rod-and-level measurements can pick up similar information on pavement roughness. However, some difference in the magnitude of the information collected by the two methods is shown by the different coefficient values in the equations.

RMSVA

RMSVA is a relatively simple profile statistic that was initially proposed to summarize profilometer data (10). RMSVA can be defined as the root-mean-square difference between adjacent profile slopes, where each slope is the ratio of elevation change to the corresponding horizontal distance interval selected. This horizontal distance is the base length, and RMSVA can be computed for several base lengths.

RMSVA is obtained from elevations Y_1, Y_2, ..., Y_N of equally spaced points along one wheelpath by

$$VA^b = \left[\sum_{i=k+1}^{N-k} (SB_i)^2/(N-2k)\right]^{1/2} \tag{6}$$

where

VA_b = RMSVA corresponding to the base length b,
b = ks (i.e., the base length),
k = arbitrary integer used to define b as a multiple of s,
s = sampling interval (i.e., the horizontal distance between adjacent points), and
SB_i = estimate of the second derivative of Y at point i, given by

$$SB_i = [(Y_{i+k} - Y_i)/ks - (Y_i - Y_{i-k})/ks]/ks$$

or

$$SB_i = (Y_{i+k} - 2Y_i + Y_{i-k})/(ks)^2$$

A simple program was developed to perform RMSVA computations (17). The least-squares method and ridge analysis were used to develop a model to predict profilometer QI from rod-and-level profile RMSVA. The following equation was found to best fit the data:

$$QI_{rmsva} = -8.54 + 6.17\,VA10 + 19.38\,VA25 \qquad R^2 = 0.95,\ SE = 5.65,\ CI = QI_{rmsva} \pm 11.68 \tag{7}$$

where QI_{rmsva} is the QI estimate from RMSVA and VA10 and VA25 are RMSVAs corresponding to base lengths of 10 and 25 dm, respectively (10^{-6}/mm).

A demonstration of how well Equation 7 predicts QI is shown in Figure 3, where profilometer QI is plotted versus QI_{rmsva}.

MAVA

MAVA is a profile summary statistic that has been suggested to characterize roadway roughness (11). Like RMSVA, MAVA is computed from SB_i--i.e., an estimate of the second derivative of the profile at point i. MAVA can be defined as

$$MA^b = \sum_{i=k+1}^{N-k} |SB_i|/(N-2k) \tag{8}$$

where

MA_b = MAVA corresponding to base length b,
$|SB_i|$ = absolute value of SB_i, and
N = number of profile elevations.

The following regression equation is significant, has stable coefficients, and was found to best fit the data:

$$QI_{mava} = -7.55 + 8.91\,MA10 + 23.5\,MA25 \qquad R^2 = 0.94,\ SE = 5.95,\ CI = QI_{mava} \pm 12.30 \tag{9}$$

where QI_{mava} is the QI estimate from MAVA and MA10 and MA25 are MAVAs corresponding to base lengths of 10 and 25 dm, respectively (10^{-6}/mm).

It is important to note that RMSVA and MAVA, as defined by Equations 6 and 8, have the units of a reciprocal of distance (the first profile derivative, slope, has no dimension, and the second derivative has the dimension of inverse of distance). In this paper, elevations are measured in millimeters and horizontal distances are normally measured in meters. Therefore, RMSVA and MAVA are given in millimeters per square meter of 10^{-6}/mm.

Slope Variance

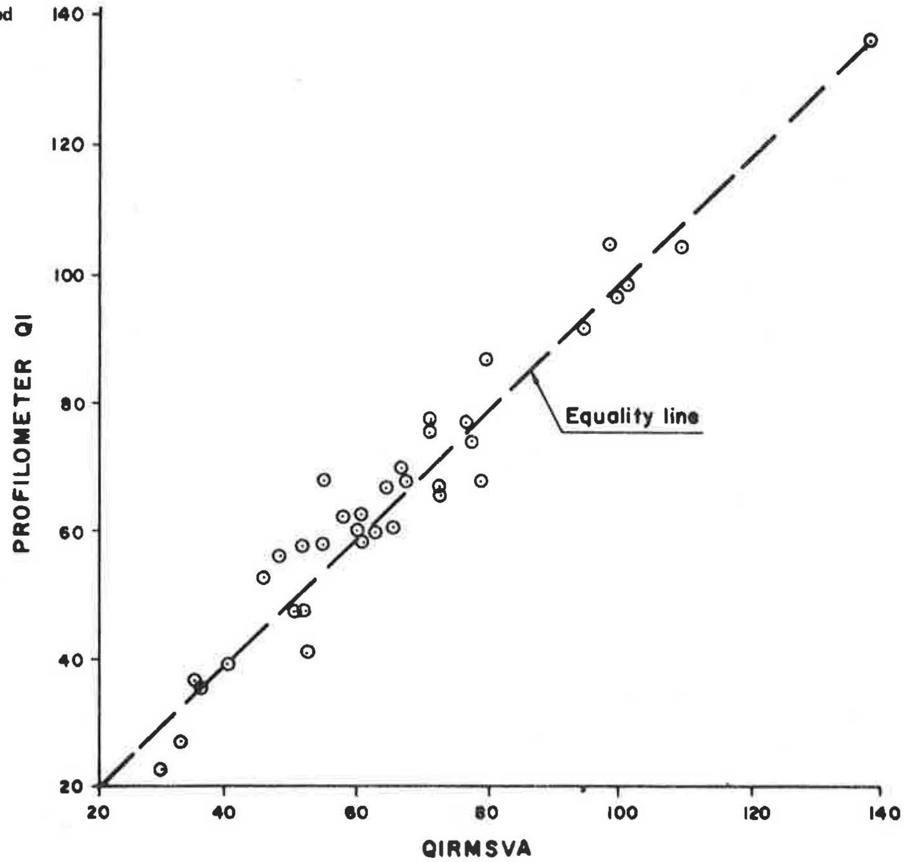
It was considered that slope variance should be evaluated in this study at least for historical reasons. In fact, it was found at the AASHO Road Test (12) that of several alternative statistics longitudinal profile variation of a section of pavement, when represented by the logarithm of the slope variance, correlated most highly with the present serviceability rating of that section. Slope variance--i.e., the variance of the slope measurements--is computed from

$$SV = \left[\sum_{i=1}^{n} X_i^2 - (1/n)\left(\sum_{i=1}^{n} X_i\right)^2\right]/(n-1) \tag{10}$$

where

SV = slope variance,
X_i = ith slope measurement, and
n = total number of measurements.

Figure 3. SD profilometer QI versus QI estimated from RMSVA.



Rod-and-level elevations of both wheelpaths were obtained for the roughness control sections given in Table 1, as previously described. Therefore, profile slopes could be calculated by dividing the difference between two elevations by the horizontal distance between the two elevation points.

The profiles were measured at a sampling interval of 10 cm. Consequently, it was possible to estimate slopes on a base length of 10 cm or any multiple of 10 cm. A computer program was developed to compute the slopes of a pavement profile to correspond to each base length selected by the user and, from the slopes, their variance (17).

The following significant regression equation was found to best fit the data:

$$QI_{sv} = 23.6 + 41.9\ SV2 - 51.7\ SV240 \qquad R^2 = 0.74 \qquad (11)$$

$$SE = 12.40$$

$$CI = QI_{sv} \pm 25.64$$

where QI_{SV} is the QI estimate from slope variance and SV2 and SV240 are slope variances corresponding to base lengths of 2 and 240 dm, respectively (10^{-4}).

COMPARISON BETWEEN ROD-AND-LEVEL ANALYSIS PROCEDURES

The previous sections showed that it is possible to compute summary statistics from rod-and-level profiles, which correlate very well with the SD profilometer QI. Namely, the statistics used to summarize rod-and-level profile data were (a) wave amplitude, (b) RMSVA, (c) MAVA, and (d) slope variance. From consideration of standard error for residuals, multiple correlation coefficient, and stability of regression coefficients, it can be concluded that the first three approaches predict QI to about the same degree of accuracy and represent a better estimate than slope variance. From a computational point of view, the vertical acceleration procedures (RMSVA and MAVA) are preferable to wave amplitude, computation of which requires sophisticated software. Because RMSVA predicts QI slightly better than MAVA, it seems reasonable to recommend the use of Equation 7 for estimating QI from rod-and-level measurements of pavement profile. For further applications in this paper, the QI estimate from RMSVA--i.e., QI_{rmsva}--is represented simply by QI_r.

Correlation Between Rod and Level and Other Roughness-Measuring Devices

The roughness control sections used in this study were also measured by three other types of roughness-measuring instruments: (a) seven Maysmeter systems belonging to the Brazil study, (b) a BPR-type roughometer from the Federal University of Rio de Janeiro, and (c) a bump integrator from the U.K. Transport and Road Research Laboratory. It was shown that the correlation between a selected profile statistic, QI_r, and these three types of instruments is very good (17).

Repeatability of Rod-and-Level Roughness Measurements

The repeatability of an instrument refers to the degree to which the repeated measurements made with the instrument agree with each other (19). When the profile of a test section is measured twice with rod and level, the results are not expected to be exactly the same due to the different wheelpaths surveyed, measurement random error, and changes in the pavement condition if there is a relatively long time interval between the measurements.

Three test sections with low, medium, and high QI values were selected for studying the repeatability of rod-and-level roughness measurements. For logistic reasons, the measurements on these sections could only be replicated about six months after the initial measurements. However, because of previous experience on these and other roughness control sections, it was judged that significant changes in the pavement conditions would not occur in a six-month period. Therefore, the data obtained are used for assessing rod-and-level repeatability.

Because QI is the standard roughness measurement used in this study, three QI estimates discussed previously--QI_{wa}, QI_r, and QI_{mava}--were calculated for each wheelpath.

The Walsh test was used here to compare the means of the QI statistics obtained from the replicate pavement profile surveys. This nonparametric test was selected because of its power and usefulness for small samples (20). The results showed that the rod-and-level measurements of pavement roughness in both surveys (1979 and 1980) are not significantly different at the 10 percent confidence level. Therefore, the data analyzed show that the rod-and-level procedure has good repeatability.

Use of QIr for Calibrating Roughness-Measuring Systems

Roughness-measuring systems such as the Maysmeter, the bump integrator, and the roughometer have in common the fact that their roughness output for the same road section can vary with time as changes in their conditions occur (e.g., tires, springs, shock absorbers, and mass). Roughness-measuring instruments of this type can be classified as response-type road roughness measure (RTRRM) systems in contrast to systems that measure the longitudinal profile characteristic directly (21). Rod-and-level measurements of pavement profile fall in the second category.

In general, RTRRM systems have the advantage of relatively low cost, simple operation, and high measuring speed. However, because of their susceptibility to changes, they require periodic calibration against a stable measuring system to provide consistent and useful measures of pavement roughness.

The kind of calibration problem of concern here can be described as follows (22). There are two related quantities, X and Y; X is relatively easy to measure and Y relatively difficult in that it requires more effort or expense; furthermore, the error in a measurement of Y is negligible compared with that for X. In this context, X can be interpreted as an RTRRM system output and Y as some pavement profile summary statistic obtained, for example, from rod-and-level measurements. The problem consists of estimating unknown values of Y that correspond to measurements of X through a calibration equation established from simultaneous X and Y measurements on a number of sections--a calibration equation of the form $Y = f(X)$.

From the foregoing discussion, it can be concluded that a roughness measure Y, to be useful as a roughness standard, has to be repeatable and highly correlated with the roughness outputs from the devices whose calibration is desired. The good correlation between the rod-and-level summary statistic QI_r and the output of several roughness-measuring devices has been reported. Rod-and-level repeatability was shown to be very good. Therefore, QI_r obtained from rod-and-level measurements of pavement profile represents an acceptable means of calibrating response-type roughness-measuring systems.

For calibrating RTRRM systems against the rod-and-level summary statistic QI_r, the same method developed by Walker and Hudson (23) using the SD profilometer as standard is recommended. The method requires that about 20 paved sections covering the roughness range of interest be selected. Test section length should be a multiple of the roughness device output intervals, preferably about 300 m or longer. Depending on the pavement structure and traffic loads on these calibration sections, rod-and-level measurements of both wheelpaths should be conducted about twice a year, or even at shorter time intervals, if seasonal effects are suspected to be a significant factor in riding quality.

In summary, the calibration procedure recommended for use with rod and level is similar to the procedure used when the SD profilometer is the standard. The roughness device to be calibrated is exposed to a number of test sections whose wheelpath profiles have been measured with rod and level; the roughness device output is then correlated against a profile summary statistic such as QI_r. Thus, a calibration equation is obtained that permits the pavement roughness, in terms of QI, to be estimated from measurements with the other roughness device.

Evaluation of QI Summary Statistic

Sampling Rate Effect on Accuracy of QI Estimates

As stated previously, a 100-mm sampling interval was chosen for the rod-and-level measurements of pavement profile in this study because it represents the minimum interval feasible for use in the field. Subsequently, it was shown that rod-and-level summary statistics obtained with this sampling interval constitute an accurate means of estimating QI. This section examines the possibility of adopting longer sampling intervals, which would expedite not only the field work but also data processing.

By eliminating intermediate data points, different sampling intervals were simulated for this analysis. A maximum sampling interval of 500 mm was selected because it is necessary in computing VA10 and VA25, which are independent variables in Equation 7.

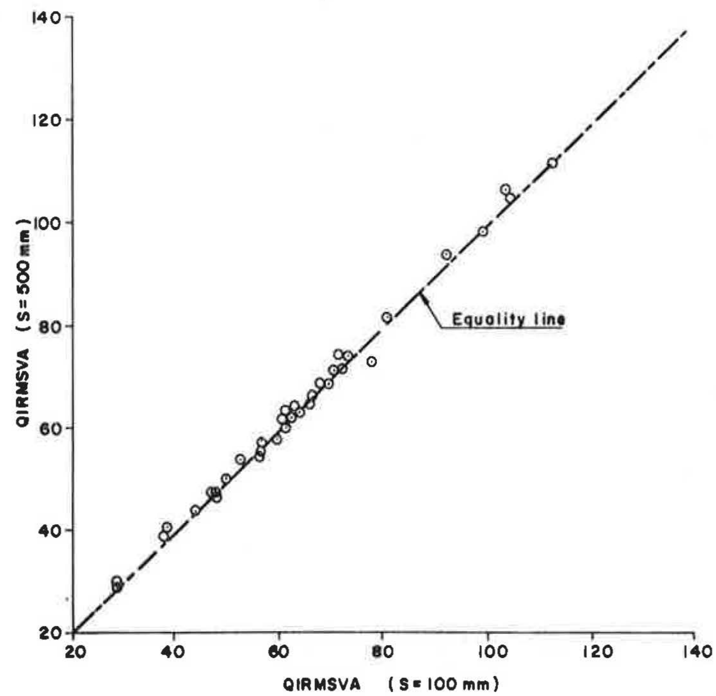
Differences between mean QI_r obtained from a 500-mm sampling interval and the basic QI_r (i.e., at 100-mm intervals) were analyzed by a t-test for correlated samples (24). The results show that the hypothesis of equal QI_r means from the two sampling intervals used cannot be rejected at the 10 percent level of significance. The good agreement obtained between QI_r values calculated from 100- and 500-mm sampling intervals is shown in Figure 4. Therefore, a sampling interval of 500 mm is recommended for use in future applications.

The influence of sampling intervals on the QI_{wa} and QI_{mava} indices was also investigated. The wave amplitudes computed from a 200-mm sampling interval are significantly different from the ones obtained when the original 100 mm is used. It is therefore considered that only 100-mm sampling intervals or less can yield accurate wave amplitude values--and, consequently, accurate QI estimates--when this approach is used. The influence of sampling intervals on MAVA was found to be similar to the influence on RMSVA.

Influence of Surface Texture on Profilometer QI

As pointed out earlier, sections A16 and A17 were outliers in all parts of the analysis discussed in this paper. The probable reason is that the high texture of these surface-treated sections caused the profilometer sensor wheels to bounce during the measurements. Consequently, the profilometer results are not accurate for these sections.

Figure 4. Comparison between QI_r values obtained from 100- and 500-mm sampling intervals.



Because of the relatively large sampling intervals used for rod-and-level measurements (i.e., 100 mm or more), one would expect that the QI_r summary statistic is not influenced by surface texture. In fact, a correlation study between QI_r and two Maysmeter systems showed no outliers even when sections A16 and A17 were included in the analysis. Therefore, it can be concluded that QI_r (i.e., the roughness summary statistic obtained from rod-and-level RMSVA) represents a roughness scale more robust than the SD profilometer QI for the calibration of response-type roughness-measuring systems.

Since its acquisition in 1976, the SD profilometer available in Brazil has shown several maintenance problems. Because of the increasing need for imported parts and Brazil's current policy to reduce imports, it was deemed necessary to minimize use of the profilometer. Consequently, the QI_r roughness statistic has been successfully used as a basis for Maysmeter calibration since early 1981.

Adequacy of QI as Summary Statistic of Roadway Roughness

Several statistics have been proposed to summarize measurements of roadway roughness, as reviewed by Gillespie and others (21). It has been shown in the Brazil study (25) that QI is an extremely useful measure of roadway roughness because it is one of the most significant independent variables in the equations developed to predict road user costs. Bump integrator measurements of pavement roughness, which are highly correlated with QI, were also shown to be an important predictor of vehicle operating costs in the Kenya study (5). Therefore, insofar as road user costs are concerned, QI can be considered a good summary statistic of roadway roughness.

It has been stated that a good roughness index should correlate well with human panel ratings of riding quality (4). The evaluation of 40 test sections on the paved and unpaved highway network in the vicinity of Brasilia, selected by a panel of 52 raters, yielded the following correlation equation (26):

$$SI = 4.66e^{-0.00534QI} \qquad R^2 = 0.83 \qquad (12)$$

where SI is present serviceability index (i.e., an estimate of the mean panel rating).

The above equation shows that QI correlates well with serviceability. Because QI is also an important explanatory variable in road user cost prediction equations, it seems reasonable to recommend QI--and consequently its estimate from rod and level, QI_r--as a roadway roughness summary statistic for general use. QI_r is preferable to the profilometer QI because it can be easily transferred among different regions or countries. Furthermore, studies of road deterioration in Brazil have provided equations to predict roughness, in terms of QI, for both paved (17) and unpaved (27) roads as a function of variables such as material characteristics and traffic loads and volumes. These relations, together with road user cost equations, provide an essential tool for the economic analysis of highway investments.

SUMMARY AND CONCLUSIONS

It has been shown in this paper that rod-and-level measurements of pavement profile, made by using short sampling intervals, represent a feasible alternative for an SD profilometer because they can provide an accurate means of establishing a stable roughness scale. Estimates of QI were developed from four different profile summary statistics found in the literature: wave amplitude, RMSVA, MAVA, and slope variance. The first three approaches are comparable and superior to the slope variance approach in prediction accuracy. From a computational point of view, the vertical acceleration procedures (RMSVA and MAVA) are superior to spectral analysis, which requires sophisticated software for computing wave amplitudes.

When a 500-mm sampling interval is used to collect pavement profile data with rod and level, two approaches analyzed in this paper can be used for obtaining accurate QI estimates--namely, RMSVA and MAVA. Because QI can be estimated more precisely from RMSVA than from MAVA, Equation 7 (which computes QI_r) is recommended for obtaining QI where and when the SD profilometer is not available.

Rod-and-level measurements are very slow when a short sampling interval of 500 mm is used. Therefore, their use is recommended for keeping updated records of pavement roughness on about 20 control sections. These sections, in turn, can be used for calibrating response-type roughness-measuring instruments. It takes a survey crew half a day to measure a 320-m-long section in both wheelpaths.

It should be noted that the rod-and-level method of estimating QI is particularly appealing for developing countries, where the social costs of labor-intensive procedures may be significantly less than the costs of procedures that depend on sophisticated imported instruments.

A number of alternatives for transferring a roughness standard from one region to another, including rod and level, have been presented in the technical literature. Based on the inherent limitations of some of these alternatives, the analysis conducted in this study, and the importance of simplicity, reliability, and cost, it seems reasonable to conclude that rod-and-level measurements of pavement profile currently constitute a unique means for the general transfer of roughness standards.

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