cities and counties, and the other will be a structured PMS. The nonstructured system will reflect the typical policy of letting pavements fail before performing maintenance work, then overlaying or reconstructing the pavements. The system will have no formal procedures for selecting segments for maintenance treatments. The structured system will have the basic components of a PMS, including a pavement condition rating procedure, a procedure for setting priorities, and a reasonable procedure for selecting maintenance treatments based on cost-effectiveness.

The two approaches will be applied to the network over a period of 40 to 60 years. All of the costs of maintenance will be accumulated, and the condition of the pavement sections will be recorded over the analysis period. A direct comparison of the pavement network costs and overall network condition will be made for each of the systems. The results should graphically show the economic benefits of the structured system, particularly if some measure of user cost increases, caused by allowing pavements to deteriorate below acceptable standards, can be factored in.

The other major focus of the consultant effort will be to develop the three basic elements of a PMS as provided in the previous outline. The objective of this effort is to go beyond the description of the framework necessary for establishing PMSs. The three basic elements will be described at a level of detail sufficient for individual jurisdictions to pursue actual PMS development. In this way actual implementation problems can be experienced, and opportunities for standardization can be tested. The ongoing interest in improving Bay Area PMSs and maintenance practices can continue to be explored.

REFERENCES

1. Determining Bay Area Street and Road Maintenance Needs: Current and Future Costs. Metropolitan Transportation Commission, Berkeley, Calif., Aug. 1981.
2. Determining Bay Area Street and Road Maintenance Needs: Backlog Costs. Metropolitan Transportation Commission, Berkeley, Calif., April 1982.
3. W. Wells. Determining Maintenance Needs of County Roads and City Streets. Presented at TRB 62nd Annual Meeting, Washington, D.C., Jan. 17-21, 1983.

Publication of this paper sponsored by Committee on Pavement Management Systems.

A Stable, Consistent, and Transferable Roughness Scale for Worldwide Standardization

CESAR A. V. QUEIROZ, W. RONALD HUDSON, ALEX T. VISSER, and BERTELL C. BUTLER, JR.

ABSTRACT

Since the AASHO Road Test there has been great interest in the measurement of road roughness for evaluation of serviceability as defined by Carey and Irick, and, perhaps more broadly and importantly, for evaluation of road roughness as it affects vehicle operating costs and road maintenance, particularly in developing countries. In this paper work done in the United States, Brazil, Canada, Bolivia, Nigeria, Panama, and elsewhere with respect to the selection of a uniform method for calibrating road roughness devices is reviewed. Because most roughness measurements are made with response-type roughness measuring instruments, there needs to be a calibration technique for such instruments that can be easily used by any country. It is essential that the method be based on characteristics of the road surface and not on characteristics of any individual vehicle or measuring velocity of the response-type roughness meter. A specific calculation algorithm is also needed. A calibration technique is recommended that is based on a true profile of the roadway surface analyzed with wavebound analysis to determine root-mean-square vertical acceleration for several applicable waveband statistics that are combined to produce the calibration factor. The development of the methodology is presented.

Since the 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 to 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 roughness measuring systems can be calibrated.

In this paper a roughness scale is presented that can serve as a universal standard. The scale is stable and consistent and allows transferability over time and space. The roughness scale is derived from the quarter-car index (QI) scale. It was originally defined in the Brazil costs study (7). It was based on simulating a quarter-car's response to a road profile as measured by a Surface Dynamics profilometer (SD or GMR profilometer). The simulation was designed to duplicate the response of the old Bureau of Public Roads roughometer. How to obtain the QI scale from an analysis of a rod-and-level-generated road profile is discussed in this paper.

It is expected that rod and level profile summary statistics put forth in this work can be used to characterize pavement roughness over a wide range of wavelengths in a more reliable manner than other existing profilometer systems.

USE OF PROFILE SUMMARY STATISTICS TO QUANTIFY PAVEMENT ROUGHNESS

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

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

To determine the QI roughness scale from rod and level measurements of pavement profiles, four different summary statistics were tested that the published literature indicated might be useful: (a) wave amplitude, which was originally shown by Williamson et al. (4) to be highly correlated with ratings of riding quality; (b) root-mean-square vertical acceleration, which has been used as a basis for Mays meter calibration (10); (c) mean absolute vertical acceleration, which has been suggested for Mays meter calibration (11); and (d) slope variance, which was found to be highly correlated with serviceability rating at the AASHO Road Test (12).

QI ROUGHNESS SCALE

The Surface Dynamics profilometer used in Brazil and Texas studies consisted of a light delivery vehicle that houses a profile computer, analog tape recorder, quarter-car simulator, a road-following wheel in each wheelpath, 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 (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 signals and the accelerometer signals to obtain the road profile. An analog tape recorder is used to record the profile data so it can be processed after the recording. The quarter-car simulator (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 springs; the response measured is a summation of the body movement relative to the wheel axle over a fixed distance (Figure 2). The parameter values incorporated into the QCS are for a Bureau of Public Roads (BPR) type roughometer, as reported in the manufacturer's instruction manual.

The roughness output from the QCS, termed the QI, can be accepted as a standard measure of roughness. QI_p has units of deformation per unit length trav-

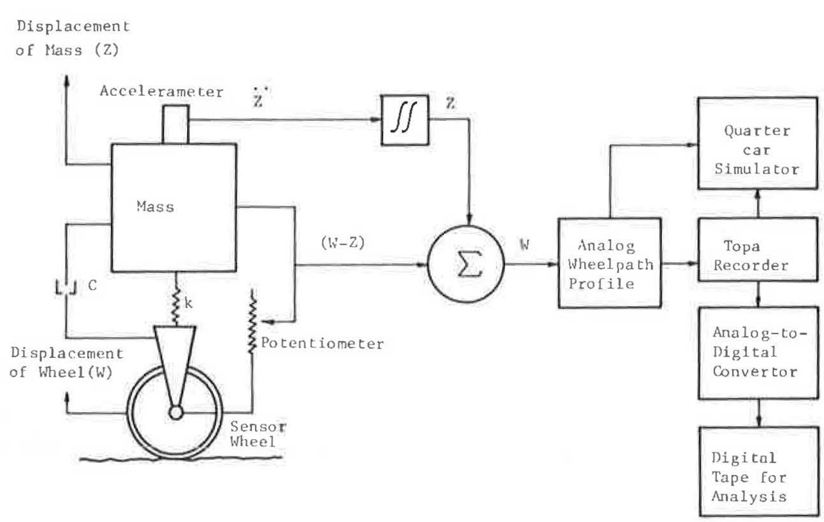

FIGURE 1 Simplified block diagram of the SD profilometer measurement system.

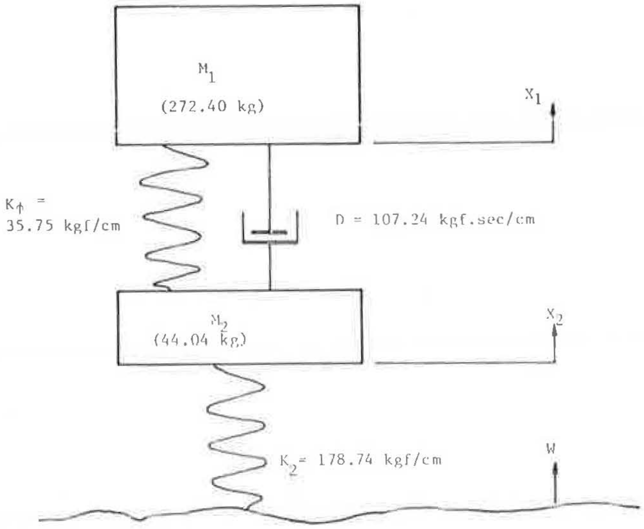

FIGURE 2 QCS schematic.

eled, but to avoid confusion with other roughness measures, the units were designated counts per kilometer. Referring to Figure 2, QI is defined by

$$QI = 1/21 \int |X_1' - X_2'| dL \quad (1)$$

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:

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

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

The solution of these equations is required for the evaluation of QI. The electronic circuits in the profilometer QCS were especially designed to give an analog solution to the equations, thus providing the QI. Note that the solution can also be obtained through digital computers, when the pavement profile is known, by using numerical integration. To indicate the range of QI, values of less than 30 counts/km have been observed on new paved roads after construction in Brazil, whereas pavements that require an overlay normally have values greater than 60 counts/km.

ROD AND LEVEL MEASUREMENTS OF PAVEMENT PROFILE

The leveling method is slow and requires considerable care and labor; therefore, this method is not feasible for regular use in measuring long road segments. Thus in this paper the rod and level measurements are examined solely for use in calibrating roughness measuring devices. Use of the leveling method is feasible where an expensive profilometer is not available. The shortest practical distance between successive profile readings or measurement points using rod and level procedures was considered to be 100 mm. The implication of longer intervals between measured points is addressed later. In spite of the continuous nature of a road profile, discrete measurements are not detrimental because the profile must in any event be expressed in discrete terms to be analyzed digitally.

A three-person team consisting of one surveyor and two assistants performed the profile measurements while traffic was continually controlled by flagmen or police. Typically, a maximum of 120 to 130 m of road were surveyed per day on points marked in each wheelpath.

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

ROUGHNESS MEASUREMENT SECTIONS

Twenty paved road sections varying from smooth to rough were selected to compare relationships between rod and level measurements of pavement profiles and the Surface Dynamics profilometer. The objective was to correlate QI with some other profile summary statistics so that a convenient standard to calibrate Mays meters (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 Mays meter must be continually calibrated and checked because their characteristics change as the tires, shock absorbers, and springs on the vehicle wear or as adjustments to the sensors are made.

The sections selected for this study included asphaltic concrete and double surface treatment surfacings. To ensure that profilometer measurements would properly reflect 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.

A total of 3,200 and 6,400 data points was 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 had 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.

As stated, wave amplitude, root-mean-square vertical acceleration (RMSVA), mean absolute vertical acceleration (MAVA), and slope variance were tested to estimate QI as a universal standard. The mathematical details are presented elsewhere (13,14). Only the details of RMSVA are reproduced here.

USE OF RMSVA TO ESTIMATE QI

RMSVA is a relatively simple profile statistic (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.

TABLE 1 Profilometer Results (QI) on Roughness Correlation Sections

Section	Length (m)	Surface	Profilometer QI		Survey Date
			Right Path	Left Path	
M05	320	AC	62	68	05/79
M06	160	AC	48	40	05/79
M07	160	AC	99	92	05/79
M08	160	AC	68	60	05/79
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	08/79
M23	320	AC	27	23	08/79
M26	320	AC	58	57	08 /79
M27	320	AC	48	41	08/79
M28	320	AC	58	53	08/79
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	08/79
M38	160	AC	105	97	11/79
A16	320	DST	62	94	06/80
A17	320	DST	72	76	06/80
M23(R)	320	AC	22	23	03/80
M28(R)	320	AC	57	55	03/80
M30(R)	320	AC	86	68	03/80

AC = asphaltic concrete
DST = double surface treatment
R = replication

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

$$VAb = \left[\sum_{i=k+1}^{N-k} (SB_i)^2/(N-2k) \right] \quad (4)$$

where

VAb = RMSVA corresponding to 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 = an estimate of the second derivative of Y at point i given by

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

or

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

A simple computer program was developed to perform RMSVA computations (14). 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:

$$QIrmsva = -8.54 + 6.17\ VA10 + 19.38\ VA25 \quad (5)$$

R squared = 0.95, standard error = 5.65, and CI = QIrmsva ± 11.68

where

QIrmsva = QI estimate from RMSVA;
VA10, VA25 = RMSVA corresponding to base lengths of 10 and 25 decimeters, respectively (mm/m^2); and
CI = approximate 95 percent confidence interval.

A visual presentation of how well Equation 5 predicts QI is shown in Figure 3, where profilometer QI is plotted against QIrmsva.

COMPARISON BETWEEN ROD AND LEVEL ANALYSIS PROCEDURES

The data in the previous sections demonstrate that it is possible to compute summary statistics from rod and level profiles that correlate well with the SD profilometer QI. This is true in varying degrees for the statistics used to summarize rod and level profile data, namely (a) wave amplitude, (b) RMSVA, (c) MAVA, and (d) slope variance. The best predictor was RMSVA.

From consideration of standard error for residuals, multiple correlation coefficient, and stability of regression coefficients, it can be concluded that wave amplitude, RMSVA, and MAVA 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 (i.e., RMSVA and MAVA) are preferable to wave amplitude, whose computation is more detailed. Because RMSVA predicts QI slightly better than MAVA, it appears reasonable to recommend the use of Equa-

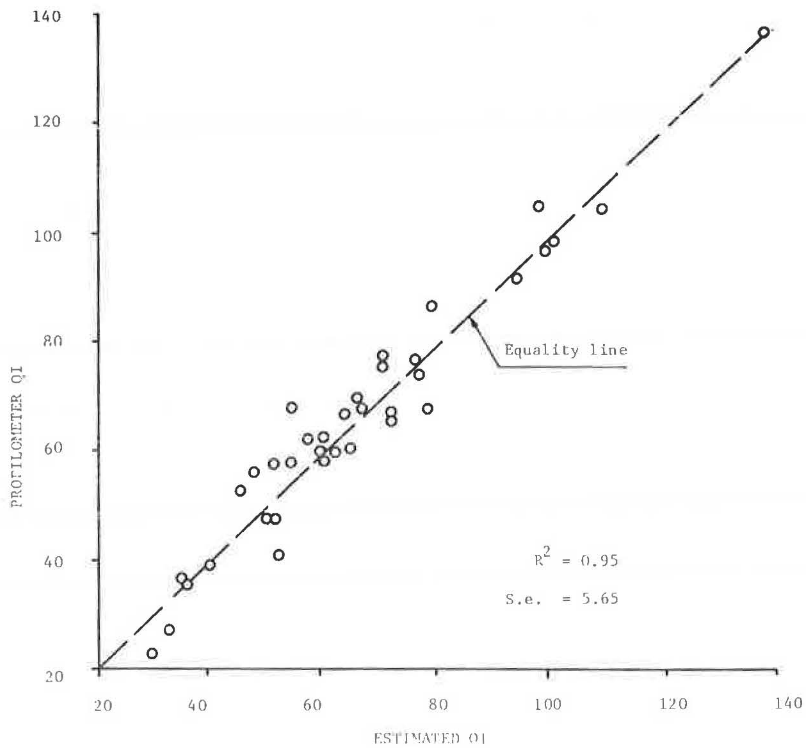

FIGURE 3 Relationship between SD profilometer QI and QI estimated from RMSVA.

tion 5 for estimating QI from rod and level measurements of pavement profile. For further applications, the QI estimate from RMSVA (i.e., QIrmsva) will be represented simply QIR.

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 (15). When the profile of a test section is measured twice, the results are not expected to be exactly the same because of variations in the exact profile line surveyed and random measurement error.

Three test sections with low, medium, and high roughness were selected for studying the repeatability of rod and level roughness measurements. The measurements on these sections were replicated about 6 months after the initial measurements.

The Walsh test was used 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 (16). The results indicated that the rod and level measurements of pavement roughness in both surveys were not significantly different at the 10 percent confidence level. Therefore, the data analyzed indicate that the rod and level procedure has good repeatability.

USE OF QI FOR CALIBRATING ROUGHNESS MEASURING SYSTEMS

Roughness measuring systems such as the Mays meter, bump integrator, and roughometer have in common the fact that their roughness output for the same road section can vary with time as changes in machine condition (e.g., tires, springs, shock absorbers, mass) occur. Roughness measuring instruments of this type are classified as a response-type road roughness measure system (RTRRMS) in contrast to systems that measure the longitudinal profile characteristic directly (17). Rod and level measurements of pavement profile fall in the second category.

In general, RTRRMSs have the advantage of relatively low cost, simple operation, and high measuring speed. However, because of their susceptibility to changes, RTRRMSs 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 (18): there are two related quantities X and Y, such that X is relatively easy to measure and Y is relatively difficult and 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 RTRRMS output and Y is some pavement profile summary statistic obtained, for example, from rod and level measurements. The problem consists of estimating unknown values of Y, corresponding to measurements of X, through a calibration equation established from simultaneous X and Y measurements on a number of sections [i.e., the calibration equation is 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 and several roughness measuring devices will be discussed later. Rod and level repeatability was noted to be good; therefore, QI obtained from rod and level measurements of pavement profile represents an acceptable means to calibrate response-type roughness measure systems.

For calibrating RTRRMSs against rod and level summary statistics (e.g., QIR), the same method developed by Walker and Hudson (19), which uses 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 and, preferably, on the order of 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 ride quality.

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

ANALYSIS OF 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 to be implemented in the field. Subsequently, it was demonstrated that rod and level summary statistics obtained with this sampling interval constitute an accurate means to estimate QI. In this section the possibility of adopting longer sampling intervals, which would expedite not only the field work but also data processing, is examined.

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 for computing VA10 and VA25, which are independent variables in Equation 5.

Differences between mean QI obtained from the 500-mm sampling interval and the basic QI (i.e., at 100-mm intervals) were analyzed by a test for correlated samples (20). The results indicate that the hypothesis of equal QI means from the two sampling intervals used cannot be rejected at the 10 percent level of significance. The good agreement obtained between QI 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.

An investigation of the influence of sampling interval on the QIwa and QImava indices was also carried out. The wave amplitudes computed from a 200-mm sampling interval are significantly different from the ones obtained when the original 100 mm is used. Therefore, it is 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.

ADEQUACY OF QI SUMMARY STATISTIC OF ROADWAY ROUGHNESS

Several statistics have been proposed to summarize measurements of roadway roughness as reviewed by Gillespie et al. (17). In this section the suitability of QI as one of these statistics is examined.

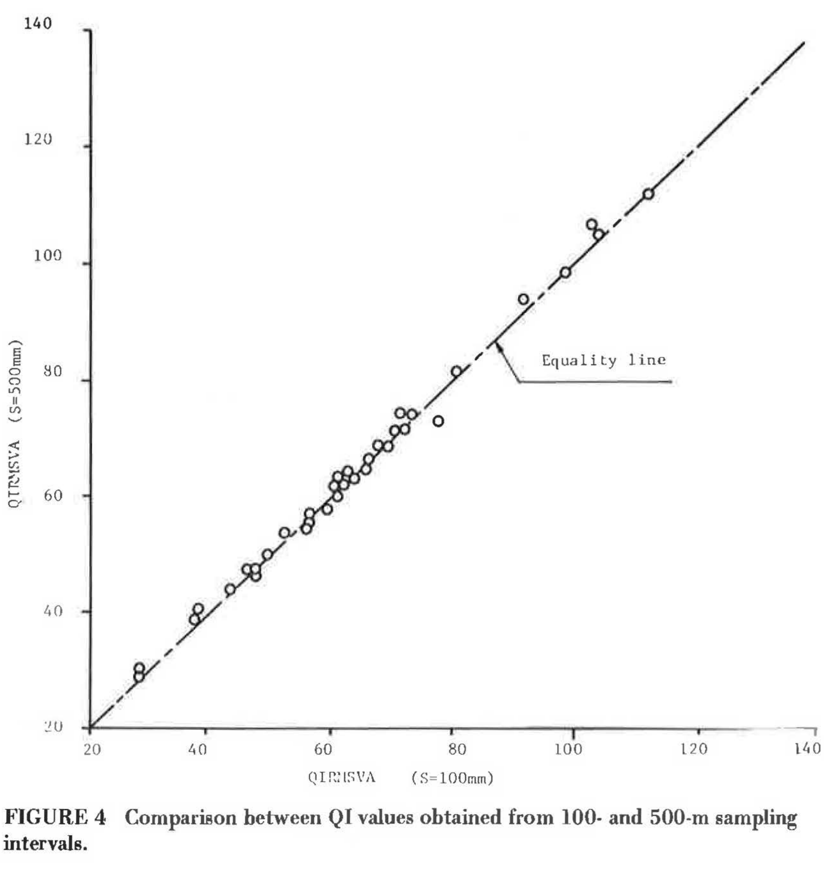

FIGURE 4 Comparison between QI values obtained from 100- and 500-m sampling intervals.

It has been demonstrated in the Brazil study (21) 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 demonstrated 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 as 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, selected on the paved and unpaved highway network in the vicinity of Brasilia by a panel of 52 raters, yielded the following correlation equation (22):

$$SI = 4.66 \exp(-0.00534QI) \tag{6}$$

R squared = 0.83

where SI is the present serviceability index (i.e., an estimate of the mean panel rating) and QI is the quarter-car index (counts/km).

This equation indicates that QI correlates well with serviceability rating. Because QI also is an important explanatory variable in road user cost prediction equations, it appears reasonable to recommend QI as a roadway roughness summary statistic for general use. Furthermore, studies of road deterioration in Brazil have provided equations to predict roughness using QI units, for both paved (14) and unpaved (23) roads, as a function of variables such as material characteristics, traffic loads, and volumes. These relationships, together with road user cost equations, provide an essential tool for the economic analysis of highway investments.

CORRELATION BETWEEN QI AND ROUGHNESS MEASURING SYSTEMS

An International Road Roughness Experiment (IRRE) conducted in Brazil in May and June 1982 examined the correlations between QI (and other roughness scales) and different road roughness measurement equipment in use throughout the world (24). A total of 49 sections, each 320 m long, were evaluated for roughness on a wide range of paved and unpaved roads. The roughness was measured at a number of speeds by seven RTRRMSs, including three Mays meter systems, a car-mounted bump-integrator unit from the Transport and Road Research Laboratory (TRRL), a National Association of Australian State Road Authorities (NAASRA) roughness meter from the Australian Road Research Board (ARRB), a TRRL bump-integrator trailer, and a BPR-type roughometer from the Federal University of Rio de Janeiro.

A summary of the correlations between QI and the RTRRMSs included in the IRRE is given in Table 2 for all road surface types studied (i.e., asphalt concrete, surface treatment, gravel, and earth). The overall correlation is good, but the highest correlation coefficients are obtained when the RTRRMSs run at 50 km/h. Therefore, it is recommended that this speed be used for calibrating an RTRRMS against the QI scale. If other speeds are selected for roughness measurements (e.g., 32 or 80 km/h), regression equations should be developed to convert RTRRMS readings at these speeds to the readings that would be obtained at 50 km/h.

CORRELATION BETWEEN QI AND RARV

A roughness scale--reference average rectified velocity (RARV)--was defined as part of an NCHRP project (17). The RARV roughness scale depends on the simulated speed and sampling interval used to measure the road profile. In the IRRE, a 500-mm sampling interval was used to measure the road profiles with rod and level; therefore, RARV based on this sampling interval was obtained for all of the 49 road sections studied. Figure 5 shows the relationship between QI and RARV for a simulated speed of 50 km/h. Similar scatters were obtained for simulated speeds of 32 and 80 km/h, where the computed R-squared values were 0.92 and 0.97, respectively. The good correlation between QI and RARV has two simple explanations. First, both QI and RARV originated from a linear simulation of a quarter of a car; their values, however, are not the same because the model parameters used in the simulation (e.g., spring constants, sprung mass, and nonsprung mass) are different. Second, RARV values obtained from different simulated speeds are intercorrelated.

TABLE 2 Summary of Correlations Between QI and RTRRMS (R-Squared Values) from the IRRE

RTRRMS	RTRRMS SPEED (KM/H)		
	32	50	80
MM01	.89	.95	.72
MM02	.94	.94	.77
MM03	.88	.91	.67
BI-CAR	.92	.92	.84
NAASRA	.93	.94	.92
BI-TRL	.92	.94	----
BPR	.85	----	----

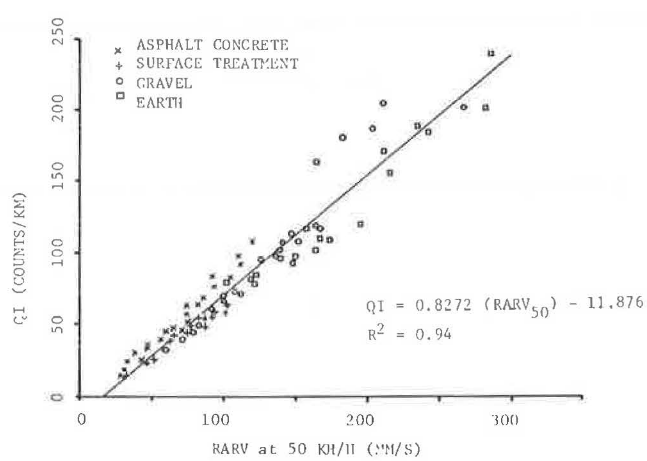

FIGURE 5 Relationship between QI and RARV at 50 km/h.

For practical purposes, QI and RARV are interchangeable when road sections of the same length are used; however, some recent work by Visser indicates that the RARV computation may present problems associated with variable section length. Because QI is easier to compute and the QI scale has been implemented in various countries (e.g., Brazil, Bolivia, South Africa, Nigeria, Panama, and at least one state in the United States), its use is recommended for worldwide standardization.

INTERNATIONAL VALIDATION OF THE QI ROUGHNESS SCALE

Two important research projects have contributed to the international validation of the QI scale: (a) the IRRE conducted in Brazil in May and June 1982, which has been discussed earlier in this paper, and (b) a correlation study of roughness measurements with QI carried out in South Africa (25). A brief summary of the South African experiment is presented here.

The aims of the study were to extend and evaluate the results from Brazil to a wider range of road sections and measuring instruments. The specific objectives were to

1. Run a correlation experiment so that the estimated QI values on paved and unpaved sections could be related to the outputs obtained with the different roughness measuring instruments used in South Africa,
2. Check the repeatability of the estimated QI values obtained from measurements at different times on a rough and smooth section, and
3. Evaluate the influence of distance between adjacent measured points of the profile on the estimated QI of gravel roads.

Several response-type roughness measuring devices are in use in South Africa and were used in the correlation experiment. These include (25) a modified Portland Cement Association (PCA) meter, a linear displacement integrator (LDI), a BPR roughometer, and a photologger roughness output.

In the original study a 100-mm spacing between adjacent rod and level elevation points was used, but it was found that on paved roads the spacing could be increased to 500 mm without affecting the roughness statistic (13). For the South African study, the 500-mm spacing was used on the paved roads, whereas a 100-mm spacing was used on unpaved roads because of uncertainties about the influence of corrugations with a 1-m period on the summary statistic.

A trained team of one surveyor, one assistant for noting the readings, and one assistant skilled in using the staff could complete a 200-m paved test section in a day. This includes traveling to the site, marking out the section, and placing traffic control devices. Normally, two assistants were employed for traffic control, except on roads carrying heavy traffic where the aid of traffic police was required. A section length of 200 m was selected because the roughness instruments measure in multiples of 100 m and because difficulty was encountered in finding a longer homogeneous length of road, especially in the rougher range.

An automatic self-leveling instrument with a vernier attachment was used for most of the measurements. The rod appropriate to this instrument is called a half-decimeter rod (i.e., a half meter is divided into 100 divisions). Therefore, in conjunction with the vernier, the precision is 0.05 mm. This precision is unnecessary for the present purpose, and results were only recorded to 0.5-mm accuracy. Specially designed code forms were used in the field to minimize transcription errors. After keypunching, the data were checked by an editing routine, and the remaining errors became obvious from plotting the profile. On the unpaved sections the same procedure as for the paved sections was used, except that elevations were measured every 100 mm instead of every 500 mm. A rough and a smooth paved section were also measured by using a standard level with a split-bubble, and a staff graduated in centimeters.

The repeatability of the rod and level procedure was checked on two paved sections, one smooth (section 25) and one rough (section 26). Note that the section numbers relate to sections on the standard calibration route. The measurements were first made in the beginning of October 1981 and repeated at the end of November 1981. This time span was long enough to ensure that no marks from the first measurement were visible, but it was also short enough to prevent any major changes in roughness on the sections. Results of the two measuring sessions are given in Table 3. The differences between the means of the two sessions are 0.7 and 1.0 for sections 25 and 26, respectively. These differences are not meaningful.

TABLE 3 Repeatability of Rod and Level Measurements in South Africa

Date	QI_R outer wheel	QI_R inner wheel	QI_R mean
Section 25			
2 Oct 1981	19.1	18.3	18.7
27 Nov 1981	21.3	17.6	19.4
24 Nov 1981 (Cm rod)	21.5	18.7	20.1
Section 26			
14 Oct 1981	67.6	75.6	71.6
30 Nov 1981	68.3	77.0	72.6
25 Nov 1981 (Cm rod)	69.7	76.1	72.9

In Brazil a standard survey level and a staff graduated in centimeters were used. To test the influence of the survey instrument, two different level instruments and staffs were used in this comparison. One instrument was an automatic self-leveling instrument with vernier attachment and a half-decimeter rod, and the other instrument was an ordinary surveyor's level with split-bubble and an ordinary staff graduated in centimeters. Sections 25 and 26 were again measured; the results are also given in Table 3. For the ordinary level the computed QI values are slightly higher than for the automatic level, but the difference is less than one unit of QI when compared with the mean of the values

TABLE 4 Computed QI Values on Unpaved Road Profiles Measured at 100- and 500-m Intervals

Section	Interval (mm)	QI outer wheel	QI inner wheel	QI mean
G1	100	67.5	152.9	110.2
	500	69.0	157.4	113.2
		68.9	156.1	112.5
		65.9	155.7	110.8
		68.5	148.0	108.2
		65.0	147.3	106.2
G2	100	131.7	135.2	133.4
	500	131.8	128.4	130.1
		135.5	131.4	133.5
		129.7	142.6	136.1
		130.3	138.0	134.1
		130.7	134.1	132.4

TABLE 5 Statistics Related to the Linear Regressions Between QI and Roughness Outputs of Different Instruments in the South African Study

Dependent Variable	Independent Variable	R-squared	Standard error of residuals	Sample size	Intercept	Slope	
						Cooefficient	t-value
QI	LDI	0.98	3.40	18	-4.60	22.46	27.1
QI	Photologger	0.96	4.45	18	6.74	0.1898	20.5
QI	ln PSI	0.97	3.78	18	92.63	-56.39	11.9
QI outer wheelpath	BPR	0.90	7.73	18	-16.98	0.6866	-24.3

obtained with the automatic level. The centimeter rod, which was less precise than the half-decimeter rod, would yield rounding errors, and this is reflected by the slightly higher QI value. However, the difference is not meaningful, and any accurate surveyor's level could be used in generating QI measurements.

Unpaved roads normally exhibit corrugations or deformations that have a greater amplitude than those found on paved roads, and concern existed about the QI generated from profile measurements taken at 500-mm intervals. For this reason measurements were taken at 100-mm intervals on the two unpaved sections, both of which exhibited corrugations. The data collected permitted an evaluation of whether the 500-mm spacing of readings has a meaningful influence on the result. The data in Table 4 give the QIs completed and the variations are not significant.

The statistics related to the correlations between QIR and the PCA roadmeter, LDI, photologger, and BPR roughometer are given in Table 5. From these statistics it can be noted that, based on the standard error of estimate and the R-squared, the decreasing order of best correlation with QI is the LDI, PCA roadmeter, photologger, and BPR roughometer. In fact, the correlation with the BPR roughometer is considerably poorer than for the other instruments. The relatively poor performance of the BPR roughometer is attributed to its advanced age and poor condition. The correlation between QI and the LDI, which is similar in characteristics to the Mays meter, is similar to the values obtained in Brazil.

OTHER VALIDATIONS

The rod-and-level-based QI scale calibration procedure has been successfully used to control roughness measurements in a number of countries. For the Ministry of Transport in Panama, Hudson et al. (26) established a roughness measuring capability to assist in determining priorities for pavement rehabilitation and maintenance for Panama's highways. The National Highway Service of Bolivia first used a TRRL pipe course and then, under Butler's direction, replaced it with the rod-and-level-based QI calibration procedures to control roughness measurement taken with two Mays meters (27). Bolivia maintains a network-wide roughness inventory on its paved roads and has studied maintenance service levels for aggregate road grading frequencies based on roughness. Hudson is also using the rod-and-level-based QI calibration procedure in Nigeria for inventorying roads and establishing a country-wide pavement evaluation and management system.

SUMMARY AND CONCLUSIONS

It has been demonstrated in this paper that rod and level measurements of pavement profile, using short sampling intervals, represent a feasible and accurate means for establishing a stable roughness scale (QI). Estimates of QI were developed from four different profile summary statistics found in the literature: wave amplitude, RMSVA, MAVA, and slope variance. From a computational point of view, the vertical acceleration procedures (RMSVA and MAVA) are superior.

When a 500-mm sampling interval is used to collect pavement profile data with rod and level, QI can be estimated more precisely from RMSVA than from MAVA; therefore, Equation 5 using RMSVA is recommended for obtaining QI.

The rod and level QI scale is particularly appealing for developing countries, where the costs of such procedures may be significantly less than the costs of other procedures, depending on sophisticated imported profilometers.

A number of alternatives for transferring a roughness standard from one region to another have been presented in the technical literature, including the rod and level survey method. Taking into account the inherent limitations of some of these alternatives and the analysis conducted in this study, and considering simplicity, reliability, and costs as important factors, it is reasonable to conclude that, with the current state of the art, the QI scale is a suitable worldwide roughness standard, and its adoption is recommended.

ACKNOWLEDGMENTS

The field data analyzed for this paper were collected in Brazil, the United States, and South Africa. Thanks are due the Brazilian National Highway Department (DNER), the Brazilian Agency for Transportation Planning (GEIPOT), the United Nations Development Program (UNDP), the World Bank (IBRD), FHWA, the Texas State Department of Highways and Public Transportation, and the South African National Institute for Transport and Road Research.

REFERENCES

1. W.N. Carey, Jr., and P.E. Irick. The Pavement Serviceability-Performance Concept. Bull. 250,

HRB, National Research Council, Washington, D.C., 1960, pp. 40-58.
2. R. Haas and W.R. Hudson. Pavement Management Systems. McGraw-Hill, New York, 1978.
3. Comparison of Different Methods of Measuring Pavement Condition. Interim Report, NCHRP Report 7, Publication 1206. HRB, National Research Council, Washington, D.C., 1964.
4. H.J. Williamson, W.R. Hudson, and C.D. Zinn. A Study of the Relationships Between Various Classes of Road-Surface Roughness and Human Ratings of Riding Quality. Research Report 156-5F. Center for Highway Research, University of Texas, Austin, Aug. 1975.
5. H. Hide, S.W. Abaynayaka, I. Sayer, and R. Wyatt. The Kenya Road Transport Cost Study: Research on Vehicle Operating Costs. TRRL Report LR 672. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1975.
6. R.J. Wyatt, R. Harrison, B.K. Moser, and L.A.P. de Quadros. The Effect of Road Design and Maintenance on Vehicle Operating Costs--Field Research in Brazil. In Transportation Research Record 702, TRB, National Research Council, Washington, D.C., 1979, pp. 313-319.
7. Inception Report, Research Concepts and Procedures. Research on the Interrelationships Between Costs of Highway Construction, Maintenance, and Utilization, UNDP Project BRA-74/012. GEIPOT, Brasilia, Brazil, April 1976.
8. W.T. Thomson. Theory of Vibration with Applications. Prentice-Hall, Englewood Cliffs, N.J., 1972.
9. A.J. Healey, C.C. Smith, R.D. Stearman, and E. Nathman. Dynamic Modeling for Automobile Acceleration Response and Ride Quality Over Rough Roadways. Research Report 14. Council for Advanced Transportation Studies, University of Texas, Austin, Dec. 1974.
10. D. McKenzie and M. Srinarawat. Root Mean Square Vertical Acceleration (RMSVA) as a Basis for Mays Meter Calibration. Brazil Project Tech. Memo BR-23. Center for Transportation Research, University of Texas, Austin, Feb. 1978.
11. W.R. Hudson, D. McKenzie, and M. Srinarawat. An Investigation of Generalized Roughness Indices for the Compatible Evaluation of Roads. Preliminary Draft. Center for Transportation Research, University of Texas, Austin, Sept. 1980.
12. The AASHO Road Test, Report 5--Pavement Research. HRB Special Report 61E, HRB, National Research Council, Washington, D.C., 1962, 532 pp.
13. C.A.V. Queiroz. A Procedure for Obtaining a Stable Roughness Scale from Rod and Level Profiles. Research on the Interrelationships Between Highways Costs, Working Document 22. GEIPOT, Brasilia, Brazil, Sept. 1981.
14. C.A.V. Queiroz. Performance Prediction Models for Pavement Management in Brazil. Ph.D. dissertation. University of Texas, Austin, May 1981.
15. Y.C. Hu, H.J. Williamson, and B.F. McCullough. A Study of the Performance of the Mays-Ride-Meter. Research Report 177-3. Center for Highway Research, University of Texas, Austin. Jan. 1977.
16. S. Siegel. Nonparametric Statistics for the Behavioral Sciences. McGraw-Hill, New York, 1956.
17. T.D. Gillespie, M.W. Sayers, and L. Segel. Calibration of Response-Type Road Roughness Measuring Systems. NCHRP Report 228. TRB, National Research Council, Washington, D.C., Dec. 1980, 81 pp.
18. H. Scheffe. A Statistical Theory of Calibration. The Annals of Statistics, Vol. 1, No. 1, 1973, pp. 1-37.
19. R.S. Walker and W.R. Hudson. A Correlation Study of the Mays-Road-Meter with the Surface Dynamics Profilometer. Research Report 156-1. Center for Transportation Research, University of Texas, Austin, Feb. 1973.
20. B.J. Winer. Statistical Principles in Experimental Design, 2nd ed. McGraw-Hill, New York, 1971.
21. Road User Costs Surveys. Research on the Interrelationships Between Costs of Highway Construction, Maintenance, and Utilization, Final Report III. GEIPOT, IBRD, and TRDF, Brasilia, Brazil, 1980.
22. A.T. Visser and C.A.V. Queiroz. Roughness Measurement Systems. Research on the Interrelationships Between Costs of Highway Construction, Maintenance, and Utilization, Working Document 10. GEIPOT, Brasilia, Brazil, July 1979.
23. A.T. Visser. An Evaluation of Unpaved Road Performance and Maintenance. Ph.D. dissertation. University of Texas, Austin, May 1981.
24. M. Sayers, T.D. Gillespie, and C.A.V. Queiroz. International Experiment to Establish Correlation and Standard Calibration Methods for Road Roughness Measurements. Report UMTRI-82-45-1. Transportation Research Institute, University of Michigan, Ann Arbor, Dec. 1982.
25. A.T. Visser. A Correlation Study of Roughness Measurements with an Index Obtained from a Road Profile Measured with Rod and Level. CSIR Technical Report RC/2/82. National Institute for Transport and Road Research, Pretoria, South Africa, March 1982.
26. W.R. Hudson, S.B. Seeds, and L.O. Moses. Procedures for Pavement Roughness Measurement and Equipment Calibration. Report PM-1/1. Ministerio de obras Publicas, Republic de Panama, Sept. 1982.
27. Manual de Rugosidad. Bolivian Servicio Nacional de Caminos, La Paz, Bolivia, June 1983.

Publication of this paper sponsored by Committee on Monitoring, Evaluation and Data Storage.