

The International Road Roughness Experiment: A Basis for Establishing a Standard Scale for Road Roughness Measurements

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ABSTRACT

With the general lack of equivalence between the many methods and measures by which road roughness is characterized, standardized indices offer the means to achieve a time-stable data base that can be utilized by all. The International Road Roughness Experiment (IRRE) was organized in Brasilia, Brazil, to find a suitable index and to quantify the relationships between different equipment and roughness indices in use. Roughness measurements were made on 49 test sites by diverse types of equipment in common use. The data were analyzed to determine the equivalence between the roughness measures that could be obtained with each type of equipment and whether one common measure was applicable to all. The results from the IRRE showed that a standard roughness index is practical and measurable by most of the equipment in use today, whether of the profilometer or road meter type. As a result of the IRRE, a standard index was selected that is based on the quarter-car analysis method with standard parameter values and a reference speed of 80 km/h. Provided in this paper is the background on the fundamental of roughness characterization that guided the selection of the standard road roughness index.

Roughness is an indicator of road condition and is useful for making objective decisions related to the management of road networks. Today roughness is measured by many methods (ranging from rod and level surveys to instrumented vehicles) and may be quantified by any of a number of measures or indices. With the growth of the base of roughness data in recent years, it has become painfully clear that the many different methods and indices used for characterizing road roughness are generally not equivalent. Many early methods came into existence as a consequence of what could be measured, although progress is being made today in identifying what should be measured (1). In many cases, the measures are determined by the performance of hardware that cannot be adequately controlled to achieve time-stable data. Thus, utilization of roughness data can be difficult, particularly when considering roughness data obtained by more than one method. Establishing standard roughness indices is a way to eliminate most of these problems. Yet, it should be recognized that more than one index may ultimately be needed to satisfy the differing needs to quantify roughness influence on ride comfort, vehicle vibrations, surface distress, and other factors.

The International Road Roughness Experiment (IRRE) was proposed by the World Bank and the government of Brazil to find a standard roughness index appropriate for the many types of roughness measuring equipment now in use, and to provide a basis for comparing roughness measures obtained by different procedures

and instruments. The IRRE was held in Brasilia, Brazil, in 1982, and was conducted by research teams from Brazil, the United Kingdom, France, the United States, and Belgium. Forty-nine road test sites were measured using a variety of test equipment and measurement conditions. The sites included a full roughness range of asphaltic concrete, surface treatment, gravel, and earth roads. The data acquired were analyzed to determine the extent to which the different types of equipment could be used to obtain a common measure of roughness and how the different measures of roughness in common use could be related quantitatively.

The results from the IRRE showed that a standard roughness index is, in fact, practical, and an index was proposed that is measurable by most of the equipment now in use, including road meters and profilometers (2). This selected measure has been denoted as the International Roughness Index (IRI). The IRI is based on the quarter-car analysis method, with standardized parameter values and a reference simulation speed of 80 km/h. Guidelines have recently been published for measuring the IRI with the various instruments currently available throughout the world (3).

This paper is intended to provide some of the background relevant to the selection of the IRI, concentrating mainly on the concept of roughness as a property of the longitudinal profile of the traveled wheeltracks of the road. It is also intended to cover the fundamental similarities and differences between the different approaches that have been taken toward calculating a single roughness index from the measured profile of the road.

TYPES OF ROUGHNESS-MEASURING EQUIPMENT

The equipment in common use for measuring roughness falls into two generic categories. In the first--

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profilometric methods--the longitudinal elevation profile of the road is measured and then analyzed to obtain one or more roughness indices. Both manual quasistatic methods and high-speed profilometers are in use, with the high-speed profilometer systems being more popular in developed countries and the manual methods being a practical alternative in developing countries. In the second category--response-type road roughness measuring systems (RTRRMSs)--a vehicle is instrumented with a road meter device. The road meter produces a roughness reading as the result of the vehicle motions that occur while traversing the road. RTRRMSs offer a means to rapidly acquire roughness data with relatively inexpensive equipment. However, the roughness measure is intimately tied to vehicle response, which varies among vehicles and also varies with time, vehicle condition, and weather. Thus, the RTRRMS measures are less accurate in general, and require a fairly complicated calibration to convert the measures to a standard scale.

Today, the majority of roughness data are obtained with RTRRMSs, and therefore the IRI must be compatible with the RTRRMS-type of measure if it is to be widely used. For this reason the IRRE included three Mays meter cars (4), a car with Bump Integrator (5) and National Association of Australian State Road Authorities (NAASRA) road meter (6), a Bump Integrator trailer (5), and a Bureau of Public Roads (BPR) roughmeter (7). The use of profilometric methods is rapidly growing, however, offering greater measuring capabilities and accuracy. Thus, it is also essential that the IRI be compatible with instruments that can measure the profile directly in order to avoid premature obsolescence. Four profilometer methods were included in the IRRE: rod and level surveys, the French Bridge and Pavement Laboratory (LCPC) longitudinal profile analyzer (APL) (8), the Transport and Road Research Laboratory (TRRL) Beam, and a General Motors Research (GMR)-type inertial profilometer (9).

ROUGHNESS MEASURES

There was complete agreement among the participants in the IRRE that the IRI should be defined as a property of the true road profile so that it can be measured directly with profilometers. At the same time, the index should be strongly correlated with the measures obtained with RTRRMSs so that their measures can be converted to the IRI scale with maximum accuracy.

Analyses of the IRRE data showed that all of the RTRRMSs give highly correlated measures when they are operated at the same test speed and that all could be calibrated to a single roughness scale without compromising their accuracy. Thus, the selection of an IRI was largely a matter of choosing a standard RTRRMS speed, and then choosing an analysis by which the profile can be reduced to a single index that is highly correlated with the RTRRMS measures obtained at that speed. Although it would appear that there are many existing and possible roughness indices that may be considered, in actuality, many are equivalent in the fundamental properties that are being quantified. The equivalence can be best understood by considering the ways in which a profile may be reduced to a summary index.

Techniques for Calculating Roughness from Profile

What exactly is road roughness? A qualitative definition is that roughness is "the variation in surface elevation that induces vibrations in traversing

vehicles." Thus, texture properties that contribute to tire noise vibrations are a form of road roughness. At the other extreme are long undulations that cause low-frequency bounding vibrations in a vehicle at high speeds. In order to quantify the roughness of the longitudinal profile of a wheeltrack, an analysis is needed to reduce the continuous profile to a single summary index. For use as an IRI, a profile analysis must include those roughness components that affect the RTRRMS measures, while excluding the components that are unrelated. Some profile analyses are essentially incompatible with the RTRRMS measure, so that good correlations (r^2 values of 0.9 and higher) cannot usually be obtained in the field. In this paper, only those analyses are considered that are closely linked with RTRRMSs.

Summary Statistics: Root-Mean-Square and Average Rectified Values

Because vertical deviations in a profile occur both in the positive and negative direction, they tend to average out over distance. Two methods of profile analysis are widely used to avoid this cancellation and meaningfully summarize the deviations. One of the methods is to square the amplitude of the variable so that it will always be positive. The result is a mean-square average of the variable of interest. The statistical properties of squared variables are well known, and therefore this method is a convenient first choice of statisticians. Often, the square root of the average--the root-mean-square (RMS) average--is used to keep the original units of the variable. The second method is to take the absolute value of the variable (rectify it) so that it will always be positive and use the average rectified (AR) value. Indices obtained using this technique are sometimes called absolute mean values or mean absolute values. This method is easier to apply directly during measurement and has been implemented by using either one-way mechanical clutches or electronic counters in nearly all road meters used in RTRRMSs.

In published studies, there has been little difference in the results obtained using RMS summary measures versus AR measures (10). The main difference will occur when roughness varies along the length of the road, in which case the RMS method will tend to weight the rougher section more when averaging than will the AR method. For example, consider two adjacent sections of road, each 1 mi long, with the second mile twice as rough as the first. The mean-square roughness for the second mile will be four times that of the first, and the RMS roughness for the combined 2-mi section will be 1.58 times the roughness of the first mile. Using the AR method, the combined roughness would be the simple average, being 1.50 times the roughness of the first section.

Variation in Profile Elevation

A logical first choice for characterizing the roughness of a profile might be to use the RMS or AR value of the profile elevation itself. Unfortunately, such a simple measure proves to be strongly dependent on the measurement method used. The reason for this is that all roads have a characteristic distribution of the profile variation over wavelengths. Although it is true that different surface types will have unique signatures in their roughness distribution, all surface types are alike in that elevation amplitudes increase by many orders of magnitude over the wavelength range of interest, while the slope amplitudes are approximately constant over all wavelengths. (In this context, the word constant means that the amplitudes are within several orders of magnitude.) This

leads to some useful generalities, which apply now only to analyses based on profile elevation, but also to those based on profile slope and profile vertical acceleration. Some of these generalities will now be illustrated by example, based on profiles obtained by rod and level survey (vertical precision = 0.001 ft; longitudinal interval = 1.0 ft).

Before examining the profiles, it is worth noting that the true variation in profile elevation is not suitable as a measure of roughness. The inclusion of hills would yield roughness measures that are dominated by the height of the hills. If the road happens to be going up a hill, even if the road is perfectly smooth, the elevation will change considerably, and a high variation would be obtained because of the hill, not the road surface. Therefore, in the example, the underlying hill (as determined by the mean slope value) was removed before the plots were prepared.

Figure 1a shows the measured elevation profile of one wheeltrack of a relatively smooth pavement (plotted with different scale factors in the longitudinal and vertical directions in order to show the profile details). The variation may be summarized in a roughness index using the AR method by the average height of the cross-hatched area (area divided by length).

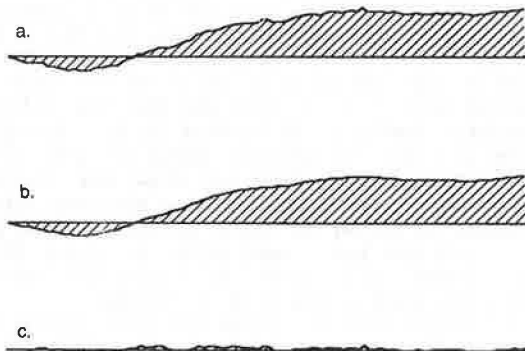


FIGURE 1 Effect of long and short wavelengths on roughness derived from profile elevation. (a) Full profile: roughness is indicated by cross-hatched area. (b) Reduction of short wavelengths has almost no effect on roughness. (c) Reduction of long wavelengths has a very strong effect on roughness.

The profile can be processed mathematically to filter out certain wavelengths, as is commonly done with some roughness measurement methods. Figure 1b shows that when the short wavelength variations caused by texture and localized defects are removed from the profile, the area (the roughness measure) is essentially unaffected. On the other hand, Figure 1c shows that when the longer wavelengths are removed, most of the area is eliminated and that the roughness would be much lower. The variation in elevation is strongly influenced by the longest wavelength included in the measurement. High-speed profilometers, such as the APL trailer and the General Motors (GM)-type inertial design, generally have a limit as to the longest wavelength that can be measured, determined by the design of the particular instrument and (usually) the travel speed during profile measurement. Because each has different limits on wavelength, they would not measure the same roughness (the largest values being obtained by the instrument that sees the longest wavelengths). When profile is measured with rod and level, there is no limitation of the type observed with profilometers

because even the static slope of the road is included in the measure. Practically speaking, however, the longest significant wavelength is largely determined by the length over which the survey is made, so the roughness becomes a function of length.

Thus, pure elevation variation is unacceptable as a roughness index because it is influenced by the longest wavelength observed by the profilometric measurement method. Even in the case of perfect measurement (rod and level or equivalent), the index is influenced by the length of the profile. In order for a roughness index based on elevation to be valid for more than one particular profilometer or test length, the longest wavelength of interest must be clearly identified and then all longer wavelengths must be attenuated through an appropriate analysis. Several analyses that do this were used in the IRRE and three of those are described later.

Variation in Profile Slope

Traditionally, most roughness measures do not use units of elevation, but instead use units of slope. The early AASHO and rolling straightedge profilometer (CHLOE) instruments produced a measure called slope variance, and most RTRRMSs provide a measure with units of slope, such as mm/km or inches/mi. As with elevation, however, the true slope variance of the road is also an unmeasurable property. Figure 2a shows the slope profile of the same road as used in the previous figure. (The slope was computed by tak-

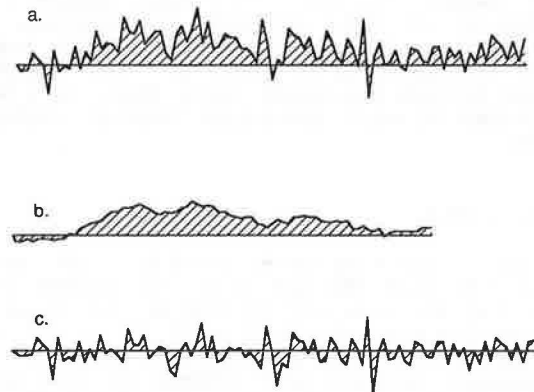


FIGURE 2 Effect of long and short wavelengths on roughness derived from profile slope. (a) Full profile: roughness is indicated by cross-hatched area. (b) Reduction of short wavelengths decreases roughness. (c) Reduction of long wavelengths decreases roughness.

ing the difference in adjacent elevation values and dividing by the separating distance.) In the slope profile, the shorter wavelengths are seen to be more significant than for the case of the elevation profile. Once again, the roughness, defined by average rectified slope (ARS), is proportional to the average height of the cross-hatched area. Figures 2b and 2c show that the average height is reduced by removing short wavelengths and also by removing long wavelengths. The quarter-car analysis, described later, is able to produce a standard roughness index by limiting both the long and short wavelengths outside of the range of interest.

Although the variation in profile slope is only moderately influenced by the longest wavelength included in the measure, nonetheless, the true slope

variance is an unmeasurable property. Figure 3 shows why. When inspected closely enough, any road profile will change elevation abruptly at some point, showing a change in height that occurs over zero distance. The profile is vertical, and at that point, the true slope is infinite. Consequently, the RMS slope and ARS measures are also infinite. Figure 3 also shows that when the profile elevation is sampled at discrete locations that are a fixed distance (ΔX) apart, the slope values will be finite. The maximum slope measured will be decreased as longer sample intervals are used.

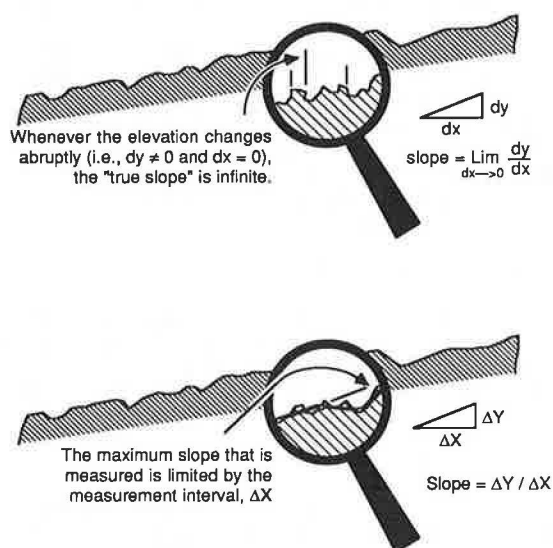


FIGURE 3 Illustration of the infinite slopes that occur in an elevation profile.

Variation in Spatial Vertical Acceleration

Figures 4a, 4b, and 4c show the corresponding profiles for the second derivative of profile--spatial vertical acceleration. In this case, the average height of the cross-hatched area is determined most strongly by the shortest wavelength that is included

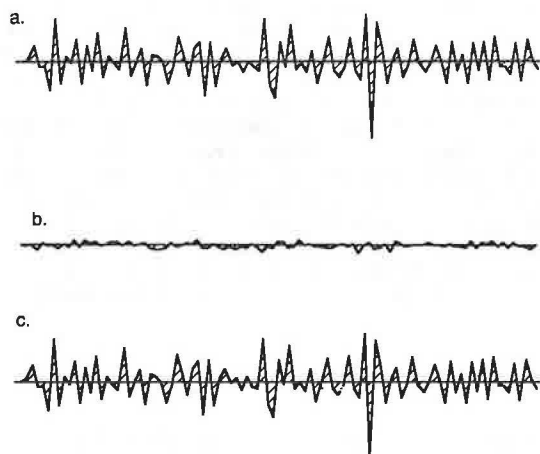


FIGURE 4 Effect of long and short wavelengths on roughness derived from profile spatial acceleration. (a) Full profile: roughness is indicated by cross-hatched area. (b) Reduction of short wavelengths has a very strong effect on roughness. (c) Reduction of long wavelengths has almost no effect on roughness.

in the measure. Figure 3 shows that the true slope of a road profile will be infinite at many points. Similarly, the true vertical acceleration will also be infinite at many points. (It will be infinite if there are discontinuities in slope, even if the slope is itself finite.) In a sense, the vertical acceleration is similar to the elevation; the roles of the long and short wavelengths are reversed. In this case, a valid roughness index must be based on an analysis that clearly identifies the shortest wavelength of interest and attenuates all shorter wavelengths. The RMSVA analysis, which does this, is described later.

Table 1 gives a summary of the sensitivity that each of the three simple roughness indices have to the wavelengths included in the measurement.

Moving Average--The Belgian Coefficient of Evenness Measure

The profiles shown in Figures 1-3 were filtered using an analysis called a moving average. The profile is smoothed by averaging adjacent elevation values together, as shown in Figure 5. With an additional step, the same analysis can be used to eliminate the long wavelengths while leaving the shorter ones. To do this, the smoothed profile is subtracted from the original, such that the long wavelength portion is cancelled out, leaving only the shorter wavelengths. This was done in Figure 1c by using a moving average of 5 m (16 points).

This type of analysis is used by several agencies, including the Belgian Road Research Center (CRR), as a means for quantifying roughness based on an elevation profile (11). In Belgium, the roughness index is calculated by using the AR method, and the measure is called the coefficient of evenness (CP). It is reported in CP units, where one CP unit is 0.020 mm. The moving average analysis is dependent on the baselength used in the averaging, and therefore it is customary to subscript the baselength used, for example, $CP_{5.0}$.

When there are many samples included in the baselength (10 or more), the effect of sample interval is negligible if the same baselength is kept. By processing the same profile using different baselengths, information about different wavelengths can be extracted. The CP value is most sensitive to wavelengths that are close to the baselength used to define the moving average. For example, the $CP_{2.5}$ numeric primarily indicates roughness over the wavelength range of 1.2 to 5 m, with maximum sensitivity at the wavelength corresponding to the baselength of 2.5 m.

The CP analysis is conceptually that of the AR elevation shown in Figure 1. The problem with the true AR elevation being sensitive to profile length (and unmeasurable with a high-speed profilometer) has been eliminated by intentionally filtering out wavelengths longer than the band of interest.

APL 72 Short-Wave Energy Index

The French Bridge and Pavement Laboratory (LCPC) uses the mean-square method for summarizing the energy of variations in profile elevation and eliminates the effect of wavelengths outside of the desired range using electronic band-pass filters (8). Typically, the profile is measured electronically and stored as a voltage on an FM tape recorder. The tape is played back in the laboratory into three independent filters that summarize the short, medium, and long wavelength components of the measured signal. Each one of these filters acts similarly to two moving averages: one

TABLE 1 Effect of Wavelengths on Profile Variations

Effect of Including	On Elevation	On Slope	On Vertical Acceleration
Longest wavelengths	Increases variation greatly	Increases variation	Negligible effect
Shortest wavelengths	Negligible effect	Increases variation	Increases variation greatly

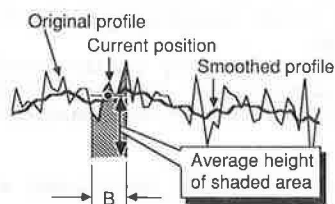


FIGURE 5 Illustration of the process of filtering with a moving average.

eliminating the long wavelengths and one eliminating short wavelengths. The short-wave index, covering wavelengths from 1.0 to 3.3 m/cycle correlates well with the RTRRMS measures.

Although the details of this electronic technique share little in common with the numerical moving average method, the results are nearly identical because the theoretical responses of the two forms of analysis are similar for the longest wavelengths included in the analyses. The analyses treat short wavelengths very differently (the APL 72 system completely eliminates short wavelengths, whereas the CP analysis leaves them intact), but because the short wavelengths have, at most, only a slight effect on the summary index, this has a negligible influence when the analyses are applied to real road profiles.

RMSD--The TRRL Beam Analysis

The British Transport and Road Research Laboratory (TRRL) overseas unit has developed an instrument for statically measuring profile in developing countries that has been called the TRRL Beam. The beam measures elevation profile along individual 3-m sections and includes a microcomputer that is programmed to compute a roughness statistic based on an analysis that is, in concept, similar to the moving average (2).

In the RMSD analysis, the profile is processed in discrete sections equal in length to a standard baselength, such as 1.8 m. A linear regression line is computed for the profile length yielding an equation of the form

$$\hat{y} = a + b \cdot x \quad (1)$$

where x is the longitudinal distance, \hat{y} is the estimate of the profile elevation at position x , and a and b are determined by a least-squares fit. At each position, there will be a deviation between the measured elevation value and the estimate from the linear regression line. The RMS deviation (RMSD) is used as the roughness index. The profile is processed one segment at a time, but the RMSD is accumulated over the entire profile. The TRRL overseas unit recommends that both the baselength and the measurement interval be standardized, with values of 1.8 m and 300 mm, respectively.

The RMSD analysis is approximately similar to the RMS value of elevation. The problem with true RMS

elevation being dependent on measurement length has been controlled by using the linear regressions over a 1.8-m baselength to eliminate wavelengths outside of the range of interest.

Because most roughness data have units of slope instead of displacement, a conversion equation is used by TRRL to rescale the RMSD measure to an estimate of an idealized RTRRMS [the TRRL Bump Integrator (BI) trailer, as it performed in the 1982 IRRE]. The conversion is based on a quadratic equation derived by correlating RMSD values with the ARS measures from the RTRRMS. The equation is

$$RBI_{32r} = 472 + 1437 \cdot RMSD + 225 \cdot RMSD^2 \quad (2)$$

where RBI is the reference bump integrator (RBI) index, based on a travel speed of 32 km/h and estimated from RMSD. RBI is assigned arbitrary units of mm/km to match the BI trailer, and RMSD has units of mm.

Quarter-Car Analysis

For the last 10 years, roughness measures similar to those obtained from RTRRMSs have been computed from profile measurements using a quarter-car simulation (QCS). A QCS is a mathematical model found in many dynamics textbooks. The response of this model is influenced by several parameters that describe the vehicle being simulated, including two masses, two spring rates, a damping rate, and a simulation speed. The first quarter-car simulation was intended to replicate the measures from RTRRMS developed by the Bureau of Public Roads, called the BPR roughometer. In 1979, a standard set of vehicle parameters selected to maximize correlation with RTRRMSs was proposed in an NCHRP research project (12). Details about the QCS analysis have been described many times (2,3,12-14) and will not be repeated here.

Unlike the preceding three analyses, the QCS is close in concept to an average slope measure, rather than elevation. Basically, the analysis acts as a filter that removes both long and short wavelengths outside of the range of interest so that the AR slope that is reported can be independent of the method used to obtain the profile measurement. Using the standard model parameters from the NCHRP project (12), this measure is called reference average rectified slope (RARS). The measure included an effect due to simulation speed, and therefore the speed is usually subscripted. For example, measures made by using a simulation speed of 80 km/h are reported as RARS₈₀.

RMSVA

Root-mean-square vertical acceleration (RMSVA) is an analysis illustrated in Figure 6. Figure 3 shows that an approximation of the first profile derivative--the slope--is calculated as $\Delta Y/\Delta X$, where ΔY is the change in profile elevation and ΔX is the distance between those elevation measures. In Figure 6, the slope is calculated by using an arbitrary baselength B , which is an integer multiple of ΔX . Re-

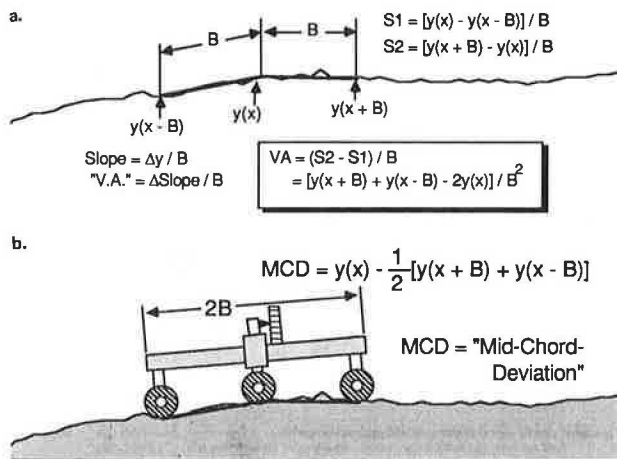


FIGURE 6 Analysis of the RMSVA and its equivalence to mid-chord-deviation. (a) The RMSVA analysis is obtained by applying a finite-difference slope equation to the profile to compute slope and then applying the same equation again to obtain a form of vertical acceleration. (b) The RMSVA analysis is a rescaled version of the mid-chord-deviation, as measured with a rolling straightedge.

peating the difference equation again gives an approximation of the second derivative--the vertical spatial acceleration. This variable will approach the vertical acceleration of the profile as the baselength B approaches zero. When B has larger values, the analysis attenuates the short wavelengths contributing to vertical acceleration. Because the baselength affects the index, the baselength should be subscripted, for example, $\text{RMSVA}_{2.5}$.

The RMSVA statistic can be considered as the RMS value of vertical acceleration with wavelengths outside of the range of interest attenuated by the use of a long baselength. This is somewhat confusing, however, because the attenuation is not as simple as with all of the other analyses mentioned earlier. As a result, most of the roughness included in the RMSVA numeric comes from wavelengths outside of the region where the analysis approximates vertical acceleration. As will be shown later, the analysis is identical to a rolling straightedge, and the RMSVA statistic is perhaps better understood by thinking of it as the mid-chord-deviation obtained from a rolling straightedge.

RMSVA is not actually used directly as a roughness index, but as a building block for defining an index. Two such indices are in use: the quarter-car (QI_r) index developed in Brazil, and the reference Mays meter (MO) index developed in Texas.

QI_r

The QI_r analysis was developed by Brazilian researchers as a means for using profiles measured with rod and level to calibrate RTRRMSs (10). The analysis was needed to replace a quarter-car index measured with a specific profilometer system, which experienced hardware problems that made its reliability suspect. Using a data base consisting of QI measures from the profilometer and RMSVA measures from rod and level, the following equation was derived:

$$\text{QI}_r = -8.54 + 6.17 \cdot \text{RMSVA}_{1.0} + 19.38 \cdot \text{RMSVA}_{2.5} \quad (3)$$

where RMSVA is to have units of $\text{mm/m}^2 = 1/\text{m} \cdot 10^{-3}$, and QI_r has the arbitrary units of counts/km. (The r subscript indicates the index derives from RMSVA.)

MO

The MO analysis was developed in Texas, also as a means for calibrating RTRRMSs (14). Following the same method used in Brazil, a correlation was developed between RMSVA measures (from a profilometer) and ARS measures from several RTRRMSs with installed Mays meters. The reference Mays meter index was defined as

$$\text{MO} = -20 + 23 \cdot C \cdot \text{RMSVA}_{1.2} + 58 \cdot C \cdot \text{RMSVA}_{4.9} \quad (4)$$

where C is a constant needed for unit conversion from a spatial acceleration to a temporal acceleration.

The MO index was not considered during the IRRE; it is included here because it has been the subject of several recent publications and because it is so similar to the QI_r index that generalizations about QI_r also apply to the MO.

Rolling Straightedge

One of the earliest approaches to measuring a profile property directly to obtain roughness was the rolling straightedge, sometimes called a profilograph. With this type of instrument, a rolling straightedge is used to establish a reference datum, and deviations from that reference are measured and summarized by using the RMS or AR method to obtain a roughness measure. Figure 6b shows a simple view of such an instrument. The AASHO profilometer, the CHLOE profilometer, and the University of Michigan profilometer were all variations of the rolling straightedge concept. The first validation of the high-speed GM-type of inertial profilometer involved demonstrating that when a profile is processed using a rolling straightedge analysis, agreement is obtained with the measures from a rolling straightedge instrument (9).

Figure 6 shows that the equation describing the mid-chord-deviation from the rolling straightedge is nearly the same as the RMSVA equation. The only difference is in the scale factor of $2/B^2$ used in the RMSVA equation to present the measure with the units of spatial acceleration, rather than simple deviation. Thus, the RMSVA analysis is completely identical to a rolling straightedge with an arbitrary scale factor.

Comparison Between the Roughness Indices

Wavelengths

Each analysis described previously isolates wavelengths of interest from the measured longitudinal profile. Table 2 gives a summary of the parameters used in each analysis to control the wavelengths that contribute to the roughness indices. Given that the amplitudes of profile slope are fairly uniform over wavelength, it is convenient to calculate and plot the response of the roughness analyses to wave number (wave number = $1/\text{wavelength}$) based on a slope input. By using the same type of input for each, the responses can be compared directly. Also, by choosing slope rather than elevation as the input, the relative significance of the different wave numbers can be easily observed. Figure 7 shows the responses of four of the profile analyses. Although the analyses differ in concept and development, because they have been optimized for correlation with RTRRMSs, they all end up responding to approximately the same wave numbers: 0.05 to 0.7 cycle/m (wavelengths from 1.5 to 2.0 m/cycle). In the IRRE and other experiments, good correlations have been found between RTRRMSs and all

TABLE 2 Summary of Wavelengths Observed by Profile Analyses

	Type of Statistic	Limit of long Wavelengths	Limit of short Wavelengths	Proposed Parameter Values
Moving average (Belgian CP)	Elevation (AR)	Baselength, B (wavelengths > 2B are attenuated)	Interval, ΔX^a	B = 2.5 m
APL 72 waveband	Elevation (RMS)	Filter cut-off Frequency 1	Filter cut-off Frequency 2 ^b	Short-waves (1.0-3.3 m/cycle)
TRRL beam RMSD	Elevation (RMS)	Baselength, B (wavelengths > 2B are attenuated)	Interval, ΔX (exact effect is not known)	B = 1.8 m $\Delta X = 0.30$ m
Quarter-car analysis (NCHRP Report 228)	Slope (AR)	Vehicle parameters, simulation speed	Vehicle parameters, simulation speed	NCHRP parameters, V = 80 km/h
RMSVA	Rolling straightedge (RMS)	Baselength, B	—	(See QI, MO)
QI _r (Brazil)	RMSVA (RMS)	Baselength, B	—	B1 = 2.5 m B2 = 1.0 m
MO (Texas)	RMSVA (RMS)	Baselength, B	—	B1 = 1.22 m B2 = 4.88

^aThe sample interval only has an influence when the baselength is less than 10 ΔX .

^bThe short-wavelength cut-off has only a secondary effect because road profiles naturally attenuate short wavelengths of elevation variables.

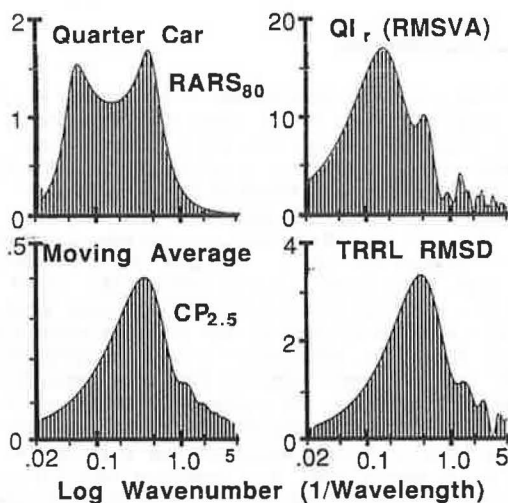


FIGURE 7 Sensitivity of four profile analyses to wave number.

of the analyses mentioned previously when the parameter values given in Table 2 are used.

Sample Interval-- ΔX

All of the analyses except the APL 72 wave band can be performed numerically by computer. Thus, they can be applied to profiles measured statically by rod and level or to profiles measured with any high-speed profilometer whose profile signal can be digitally sampled. An important parameter in this process is the distance between samples, ΔX .

The choice of sample interval is usually selected for a profilometer based on hardware considerations, and a standard interval for all profilometers is nonexistent. To require a standard interval would seriously compromise the flexibility associated with profilometers, and in some cases, would also compromise their accuracy. Thus, it is important that the analysis chosen for the IRI be flexible regarding the required sample interval.

In the case of manual methods, such as rod and level, the choice of sample interval has a direct bearing on the work needed to perform a measurement. A small ΔX value means that more elevation measures are needed for a given road length. Because profiling by rod and level is slow and labor-intensive, it is always desirable to select the largest ΔX values that can be used while still obtaining a valid measure.

Table 3 gives a summary of the ranges of ΔX allowed for each of the analyses to provide the associated roughness index with negligible bias. (Although bias is eliminated when ΔX is within the ranges shown, better repeatability and reproducibility are usually obtained as ΔX approaches zero.) The broadest continuous range is allowed by the quarter-car analysis, including intervals up to 700 mm (slightly more than 2 ft). The largest interval is the 1.22 m (4 ft) that would be allowed for the MO analysis, but the range of values is not continuous. The RMSVA analysis essentially uses the baselength parameter as the sample interval, and therefore the analyses based on RMSVA will work for any interval that divides evenly into both of the baselengths. Therefore, while an interval of 1.22 m is valid for the MO analysis, an interval of 1.0 m is not. The TRRL analysis is standardized for 300 mm, and therefore only that interval is valid. Because the APL 72 energy analysis is not numerical, digitizing considerations are not applicable.

TABLE 3 Practical Considerations of Profile Analyses

	Allowable Sample Interval Range (mm)	Averaging Method for Subsections	Loss of Profile Length (m)	Value of Perfectly Smooth Road
2.5 m moving average, CP _{2.5}	0-250	Simple	2.50	0
APL 72 short-wave energy	—	RMS	—	0
Reference BI, TRRL beam RMSD _{1.8,300}	300	Complicated, (conversion + RMS)	—	472 mm/km
Quarter-car analysis (RARS ₈₀)	0-700	Simple	0.25	0
RMSVA (rolling straightedge)	B/k, k=1,2,...	RMS	B	0
QI _r (Brazil)	500, 250, 167, 125,...	No exact method	2.50	-8.54 counts/km
MO (Texas)	1219, 610, 406, 305,...	No exact method	4.88	-20 in/mi

Effect of Site Length

It is often convenient to compute roughness for relatively short sections, for example, 200 m long. Later, those measures are combined to apply the same measures to longer sections, for example, 1 km long. The method used to combine the measures from the subsections should give the same result as would be obtained by making a single measure over the entire length.

For an RTRRMS, which is based on the AR method of averaging, roughness measures from sections of equal length are simply averaged. Table 3 shows that the moving average and quarter-car indices are combined in this fashion. As noted earlier, RMS measures are averaged by adding the squares of the measures and then taking the square root of the sum. As indicated in Table 3, the RMSD analysis requires an even more complex method. Because a quadratic equation is used to present the RMSD measures in units of mm/km, there is no simple way to combine the converted indices. They must be first converted back to RMSD, using the inverse of the quadratic equation. Then, the RMSD values can be combined using an RMS average. Finally, that RMSD value must be converted back to mm/km using the quadratic equation.

For the QI and MO analyses, no method exists to combine measures for short sections to obtain the measure that would be calculated for the entire length. To visualize this, consider an unrealistic (but mathematically simple) case in which a section that is 1.0 km long is measured in two sections. In the first half, the RMSVA_{1.0} value is 9.5 whereas the RMSD_{2.5} value is zero. The resulting QI_r is then 50 counts/km. In the second section, the RMSVA_{1.0} value is zero and the RMSVA_{2.5} value is 3.02, also giving a QI_r of 50. For the entire section, the RMSVA_{1.0} value would be 6.7 (the RMS average of 9.5 and 0), whereas the RMSVA_{2.5} measure would be 2.14. Thus, the true QI_r value for the entire length is 74.3, even though both subsections have QI_r values of 50. Thus, the QI and MO indices can be length dependent.

Note that values of zero RMSVA would never be measured in practice; therefore the effect will be smaller and in most cases nonexistent. This example is included to help explain the more plausible scenario in which a 1-mi road with an MO rating of 100 in./mi can be composed of two subsections with MO ratings of 90 and 95.

Loss of Profile Length

The moving average and rolling straightedge (RMSVA) analyses use geometric smoothing, which requires measurement of the profile on either side of the point being considered. In each of these cases, a length equal to 1/2 of the baselength will not be processed at the beginning of the profile. The same is also true at the end of the profile.

Intuitive Understanding of the Scales

The moving average and the rolling straightedge (RMSVA) have been shown to be easily visualized geometric analyses of profile (see Figures 5 and 6). The quarter-car analysis owes much of its popularity to the fact that most practitioners are familiar with the RTRRMS measure that it replicates. The popularity of the RTRRMS-type of measure (ARS) is evident because the RMSD and RMSVA analyses are not used in their direct forms, but are instead converted to an approximation of the RTRRMS statistic and given units of ARS. As indicated in Table 3, these conversions include offsets, such that the roughness indices have arbitrary scales that do not coincide with a simple intuitive concept of roughness. A profile with zero variation will not give a zero roughness reading under the RMSD, QI_r, or MO analysis methods. Further, there is no simple relation between the roughness reading and any single property of the original profile. For example, if one road has twice the roughness of another on the RMSD scale (with units of mm/km), there is no physical property of the road that can be identified as being twice as large in one road as the other. In contrast, with

the quarter-car index if one road is twice as rough as another, it means that the slope amplitudes are twice as high over the wavelengths included.

Compatibility with Profilometric Methods

Perhaps the most critical consideration is the practical one that the IRI must be measurable with most of the profilometric equipment now in use, in addition to the equipment that can be envisioned over the coming years. Clearly, an index that is tailored to a specific piece of equipment is inappropriate as an IRI. In the case of the rod and level method, which is gaining popularity in developing countries as the only viable profilometric method, a sample interval on the order of 0.5 m is a practical limit. If shorter intervals are absolutely required to eliminate bias in the measures, the manpower needed to perform the measurements becomes too great.

The IRRE included paved and unpaved roads, which were profiled using rod and level ($\Delta X = 500$ mm), the TRRL Beam, and an APL trailer operated in two configurations. Of all the analyses described in this paper, only the quarter-car RARS₈₀ index could be measured on all types of roads using all of the profilometric methods. Briefly, the problems with the other analyses were as follows:

CP_{2.5}

The moving average analysis becomes sensitive to the sample interval when shorter baselengths are used. A baselength of 2.5 m was found to provide much better correlation with the RTRRMSs than the longer baselengths. CP₁₀ was measurable by most of the equipment, but did not have the same degree of correlation with the RTRRMSs.

APL 72 Short-Wave Index

This analysis was developed specifically with the APL profilometer in mind, and cannot be applied directly to rod and level methods.

RMSD

This analysis is tailored to the TRRL beam instrument, and would require further development for use with other methods of measuring profile. It was not tested with the APL system and has not been used with any profile measuring method other than the TRRL beam.

QI_r

The APL profilometer was not able to measure QI_r directly for all of the surface conditions covered in the IRRE.

Correlation With the RTRRMSs

When profilometric methods are not possible for whatever reason, it is expected that the roughness measures will be made with an RTRRMS calibrated to the IRI scale. The accuracy of the RTRRMS measure is limited by the correlation between the IRI and the RTRRMS, and therefore a high correlation with RTRRMSs is required. Also, the correlation should be insensitive to surface type, so that practitioners can apply a single calibration equation to all RTRRMS measures.

It was demonstrated that the measures from any two RTRRMSs are highly correlated if they are operated at the same speed and that the correlations drop when the speeds used for the systems differ. Therefore, an essential part of the IRI is the standardization of RTRRMS measuring speed. When all of the factors were considered, it became clear that a relatively high speed suitable for highway use was necessary. A standard speed of 80 km/h (50 mi/h) was selected, as it is already standard for many organizations.

The best correlations were obtained using the quarter-car analysis, RARS₈₀. The next closest profile analysis was QI_r , which generally showed the same correlations except in the cases of a few outlier test sites. The measures from the RTRRMSs did not correlate as well with any of the profile references, but the errors observed using the quarter-car were about one-half of those observed using QI_r .

Using a lower standard speed, TRRL obtained high correlations by using the RMSD analysis. However, this analysis was tested (by TRRL) only on the sites that were measured with the TRRL beam-18 sites, of which 10 were measured in both wheeltracks. Thus, the correlations with most of the RTRRMSs were based on only 10 data points (For the BI trailer, 28 wheeltracks were covered.) Even though the RMSD parameters were optimized to obtain high correlation of those sites, the performance of the quarter-car (using the appropriate simulation speed) was just as good.

The quarter-car, the QI_r , the RMSD, and most recently, the MO, have all been developed to provide a reference for calibrating RTRRMSs. Of these, only the quarter-car directly computes the ARS-type of roughness index observed by an RTRRMS. It is also the only analysis based on the mechanics of the measuring

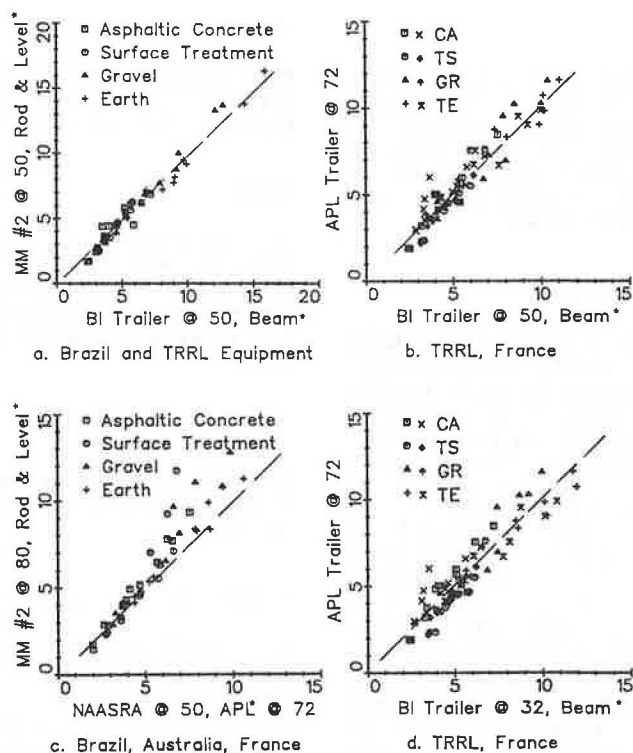
process, rather than an empirical correlation. Correlation experiments have been used only to validate its performance. Each of the other analyses used some other instrument as a reference, and those reference instruments no longer exist. But as Figure 7 shows, the correlation methods used with the other analyses result in choices of parameter values that cause those analyses to resemble the quarter-car analysis to the extent possible. For all practical purposes, the quarter-car can be considered as the culmination of the reference RTRRMS concept underlying QI , MO, and the BI trailer.

The success that can be achieved by using the IRI as a standard measure of roughness can be seen when measurements from diverse types of equipment calibrated to that standard are compared. Figure 8 shows the agreement possible between a Mays meter car, a National Association State Road Authorities (NAASRA) car, the TRRL Bump Integrator trailer, and the APL trailer. Included in this plot are results from roughness measurements at speeds other than the standard of 80 km/h (speeds are indicated in the axis labels), and each of the RTRRMSs was calibrated from profile measured by a difference source.

The IRRE included no test sites with portland cement concrete (PCC) surfaces, and therefore it is mentioned here that the IRI had already been tested and validated on PCC sites before the IRRE, as a part of the correlation program reported in NCHRP Report 228 (12). Thus, the IRI has been tested for all conventional road surfaces used in the United States.

CONCLUSIONS

The IRRE added further proof that most problems with compatibility between RTRRMSs can be solved simply by adopting a standard measuring speed and calibrating RTRRMS to the same profile-based roughness index.



*Source of data used for calibration

FIGURE 8 Examples of agreement among equipment using the IRI roughness scale.

In choosing a profile-based index to define the IRI, a number of analytic methods were considered. When the parameters are optimized for correlation with RTRRMSs, the analyses become very similar regarding the wavelengths that are emphasized in the roughness indices. Essentially, they begin to resemble a quarter-car analysis. The quarter-car analysis was therefore used to define the IRI roughness scale.

Because the quarter-car analysis most directly measures the profile components contributing to the RTRRMS measures, it avoids some practical problems that arise with the other indices. The QI_r , RMSD, and MO analyses all result in roughness scales that are obtained by conversions that introduce peculiarities into the scales, such as nonzero reading for a perfect road and dependence on the profile length.

Because they respond to approximately the same wavelengths, results obtained using the different analyses are almost perfectly correlated for most types of roads. In special cases (on roads with peculiar properties) differences are observed, with the quarter-car providing the best match with the RTRRMSs.

ABBREVIATIONS AND ACRONYMS

APL	Longitudinal profile analyzer (instrument developed by LCPC)
APL 72	Waveband analysis (roughness index associated with the APL)
AR	Average-rectified (averaging method)
ARS	Average rectified slope (roughness measure)
BI	Bump integrator (instrument developed by TRRL)
BPR	Bureau of Public Roads
CHLOE	Rolling straightedge profilometer (instrument developed by AASHO)
CP	Coefficient of smoothness (roughness index used in Belgium)
CRR	Center for Road Research (Belgium)
ΔX	Sample interval (distance between measures)
GMR	General Motors Research
IRRE	International road roughness experiment (Brasilia, Brazil, 1982)
IRI	International roughness index
LCPC	Central Bridge and Pavement Laboratory (France)
MO	Reference Mays meter index (roughness index from Texas)
NAASRA	National Association of Australian State Road Authorities
QCS	Quarter-car simulation
QI	Quarter-car index (roughness index developed in Brazil)
QI_r	Estimate of QI from RMSVA (roughness index developed in Brazil)
RARS	Reference averaging rectified slope (roughness index from a QCS)
RBI	Reference bump integrator (roughness index developed by TRRL)
RMS	Root-mean-square (averaging method)
RMSD	RMS deviation (roughness index developed by TRRL)
RMSVA	RMS vertical acceleration (roughness index developed in Texas)
RTRRMS	Response-type road roughness measuring system (category of instruments)
TRRL	Transport and Road Research Laboratory (United Kingdom)

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