International Roughness Index: Relationship to Other Measures of Roughness and Riding Quality

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ABSTRACT

Different measures of road roughness with varying degrees of reproducibility and repeatability have been applied by various agencies in the world, but the exchange of roughness information has been hampered by a lack of an acceptable reference and a quantitative basis for relating the different measures. Presented in this paper is such a basis developed from an analysis of data from the International Road Roughness Experiment (IRRE) and other sources. The International Roughness Index (IRI), developed from the IRRE as a suitable calibration standard for all response-type and profilometric instruments, is the transferable reference scale. It is the metric equivalent of a reference inches/mile index. Two-way conversion relationships and confidence intervals are presented for the Quarter-car Index (QI), British Bump Integrator trailer index (BI), and various profile numerics of the French Analyseur de Profil en Long (APL) (longitudial profile analyzer) profilometer from the IRRE, and for the Serviceability Index from other sources. The characteristics of each scale, and the sources of variation and range of application of the conversions are discussed.

Road roughness is a major determinant of riding quality and the economic benefits from maintenance (1), and is thus an extremely important measure in the road condition inventory of a highway network. The quantification of the benefits and the prediction of roughness trends in the future under any given maintenance policy, however, are dependent on the ability to relate the measure of roughness to the measures used in major empirical studies that have been conducted in various countries.

Three primary scales have been used in the major studies of road deterioration and road user costs, which form the basis of economic models at present (1,2). In the studies in Kenya, the Caribbean, and India, roughness was referenced to the Bump Integrator trailer (BI) of the Transport and Road Research Laboratory (TRRL) (United Kingdom) in units of mm/km. In the Brazil study, roughness was referenced to the Quarter-car Index (QI), a profile-based scale in units of counts/km, often abbreviated simply to units of QI (2-4). In addition, in North America, riding comfort and vehicle cost data have been related to the Serviceability Index of pavement condition originating at the AASHO Road Test (5).

In road condition surveys worldwide, many more different roughness measures are being used. Most come from response-type measuring systems mounted in a passenger car or on a trailer and measuring the relative axle-body displacement of the rear axle in units such as mm/km, inches/mile, counts/unit length, and so forth, including, for example, the Bump Integrator, Mays ride integrator, Mays ride meter, Cox meter, National Association of Australian State Road Authorities (NAASRA) meter, BPR Roughometer, and other variations. In many francophone countries, dynamic profilometry systems such as the Analyseur de Profil en Long (APL) trailer of the Laboratoire Central des Ponts et Chaussées (LCPC), France, and the Viagraphe have been used. The extent to which all these systems have been calibrated and controlled to be reproducible and repeatable over time has varied considerably. Although some local standards have been developed, there has been difficulty in relating the roughness measures to one of the three primary scales mentioned previously, and the profile numerics developed for the French profilometry systems are unique to those systems.

To provide a common quantitative basis with which to reference these different measures of roughness, both for the purposes of instrument calibration and for comparison of results, the World Bank initiated the International Road Roughness Experiment (IRRE) (6) held in Brazil in 1982. The IRRE included 10 different methods and the involvement of and sponsorship by organizations from Brazil, the United States, the United Kingdom, France, Belgium, and Australia. This experiment resulted in the establishment of the international Roughness Index (IRI), an independent profile-related index appropriate as a reference scale for all profilometric and response-type systems (6), and the issuance of guidelines on the calibration and measurement of roughness (7).

The IRI mathematically summarizes the longitudinal surface profile of the road in a wheeltrack, representing the vibrations induced in a typical passenger car by road roughness. It is defined by the reference average rectified slope ($RARS_{80}$, the ratio of the accumulated suspension motion to the distance traveled) of a standard quarter-car simulation for a traveling speed of 80 km/h. It is computed from surface elevation data collected by either topographical survey or mechanical profilometer. The computational method and mathematical equations are described by Sayers et al. (7) with further background provided by Sayers, Gillespie, and Queiroz (6). The index is expressed in units of m/km IRI and is the metric equivalent of the reference inches/mile statistic from an earlier NCHRP study (8).

In this paper, the data from the IRRE and other sources are used to develop a basis for relating the major roughness scales to one another in order to

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facilitate the use of previous and current research findings and road inventory data. The ultimate result is a chart and series of equations that can be used for converting between any two scales, with the IRI scale serving as the reference.

ROUGHNESS MEASURES

Roughness is the variation in elevation of a road surface that typically has a complex profile comprising a spectrum of different wavelengths and amplitudes. The spectrum tends to vary with the type of surface. For example, asphalt-paved surfaces have little short wavelength roughness, whereas surface treatment, gravel, and earth surfaces have a mixture of short, medium, and long wavelengths (earth surfaces in particular can have high concentrations of short wavelengths and large amplitudes).

The measures of roughness fall into three categories as follows [elaborated on with respect to accuracy by Sayers et al. (7)]:

1. A profile numeric defined directly by mathematical function from the absolute profile of road surface elevations in one or two wheelpaths (when the profile is measured dynamically, some loss of accuracy usually occurs);
2. Summary numerics measured through response-type systems calibrated to a profile or other numeric by correlation (usually the cumulative axle-body relative displacement averaged over a given distance and expressed as a slope); and
3. Subjective ratings of riding quality or pavement serviceability, usually made by a panel of raters within a scale defined by subjective descriptors.

Differences arise between roughness measures due partly to the way the measuring instrument responds to the road profile and partly to the way the data are processed. In the case of profile numerics, the numeric represents either some measure of the displacement amplitude relative to a moving average amplitude (in which case the result varies with the baselength chosen), or else it represents the response of a standard vehicle through a mathematical model of the way a vehicle responds to roughness (in which case the result varies with the mathematical definition and the simulated speed of travel).

In the case of response-type systems, the differences arise primarily through the frequency response

TABLE 1 Summary Descriptions of Some Major Road Roughness Measures

Measures	Symbol	Units	Description
International roughness index	IRI	m/km IRI	Reference index summarizing the road profile by a mathematical model representing the response of a traversing vehicle *(6)*. Computed from elevation data in a wheelpath *(7)* for use as a profile numeric for profilometric methods and a calibration standard for response-type instruments. Defined by reference average rectified slope ($RARS_{80}$) of axle-body displacement of quarter-car simulation with fixed-vehicle constants and a simulated speed of 80 km/h *(6,7)*. Scales from 0 (perfect) upward to about 20 (poor unpaved road).
Referenced Response Measures			
Quarter-car index	QI QI_m QI_r	Counts/km QI	A profile-related measure developed for Brazil Road Costs Study and since applied elsewhere *(3,4)*. Originally defined by a quarter-car simulation of vehicle response at 55 mph on wheelpath profile elevations measured by (GMR) surface dynamics profilometer and used as a calibration standard for response-type systems. No longer exactly reproducible except as redefined. Subscripted by m (QI_m) represents the calibrated Mays meter estimate of QI used as a basis for all Brazil road costs study data *(2)*, or by r (QI_r) represents profile index redefined in terms of root mean squared vertical acceleration (RMSVA) of 1 and 2.5 m baselengths of elevation data by correlation *(4)*.
Bump integrator trailer (TRRL)	BI BI_r	mm/km	Single wheel trailer (based on BPR roughometer) standardized by TRRL, towed at 32 km/h and measuring axle-body displacement by unidirectional frictional clutch sensor. Used in road costs studies of Kenya, Caribbean, and India and in several developing countries. Usual application is vehicle-mounted sensor calibrated to one of several standard trailer units. Responses of trailer units have possibly varied over time; a profile index (BI_r) based on root mean squared deviation of elevations on a 1.8-m baselength and 300 mm sample interval ($RMSD_{300,\,1.8}$) was recently defined by correlation to one trailer unit *(6)*. Scales from low positive value upward to about 16,000 (poor unpaved road).
Inches per mile (reference quarter-car simulation)	IM_r (RQCS)	in./mile	A calibration reference used for response-type systems by some North American agencies, identical in definition to the IRI scale but expressed in units of inches/mile (note: 63.36 inches/mile = 1 m/km). Roughness expressed in these units usually represents response-type system measures, which may not have been calibrated to this reference. Scale from 0 (perfect for reference) upward.
Profile Numerics for Dynamic Profilometers			
Waveband energy (APL72)	W_{sw} W_{mw} W_{lw}	(L^2) (L^2) (L^2)	Numerics developed by LCPC for the APL profilometer traveling at a speed of 72 km/h, defining the mean-square energy values of short (1 to 3.3 m), medium (3.3 to 13 m), and long (13 to 40 m) wavelength bands, computed by squaring and integrating the filtered signal value over a section length of 200 m for a speed of 72 km/h *(6)*. Scales from 0 (perfect) upward. Sometimes presented in combination as a rating index, I, from 1 (worst) to 10 (best) by unit increments.
Coefficient of planarity (APL72)	$CP_{2.5}$	0.01 mm	Profile numeric developed by Center for Road Research (CRR) Belgium for the APL profilometer towed at 72 km/h, defined by an analysis of the deviation of the profile from a moving average reference line *(6)*. Computed for standard baselengths of 2.5, 10, and 40 m for every 100 m (expressed in the subscript); the IRRE indicated that $CP_{2.5}$ correlated most highly with IRI and most response measures. Scales from 0 (perfect) upwards.
Coefficient APL_{25}	$CAPL_{25}$	(L)	Profile numeric developed by LCPC for the APL profilometer towed at 21.6 km/h, computed as the average absolute value of the profile signal over section lengths of 25 m *(6)*. Scales from 0 (perfect) upward.
Relating to Subjective Rating			
Serviceability index	SI	PSI	Mathematical function representing subjective panel rating of pavement serviceability; that is, ride quality and the need for maintenance, defined at the AASHO Road Test in terms of slope variance of the surface profile, mean rut depth, and areas of cracking and patching by statistical correlation. Difficult to reproduce, usually redefined by a local panel rating. Scales from 5.0 (excellent condition) to 0 (worst).

characteristics of each system. A vehicle typically has two resonant frequencies: one at 1 to 2 Hz for resonance of the body on the suspension, and the other at 8 to 12 Hz for the resonance of the wheel-axle system between the stiff springs of the tires and the suspension. The amplitude of road roughness in these ranges is exaggerated by the vehicle. Thus for certain combinations of roughness wavelength and vehicle speed, the amplitude is exaggerated and at others it is attenuated. Hence, two response-type systems operating at different speeds, or two systems with differing resonance characteristics, will tend to exaggerate or "see" different aspects of roughness on a given road and give different results.

The eight measures of road roughness considered in this paper cover the three categories previously defined and are described in detail in Table 1. For further discussion of these measures, see Sayers et al. (6). The measures include

1. IRI, the International Roughness Index, in m/km IRI;
2. IM_r, the inches/mile equivalent of IRI used in North America and sometimes called reference quarter-car simulation (RQCS), or Golden car;
3. QI_m, the Quarter-car Index of the Brazil road costs study as measured by calibrated Mays meters, in counts/km;
4. BI_r, the response of the TRRL Bump Integrator trailer used during the IRRE, in mm/km;
5. W_{sw}, the short-wavelength energy numeric defined by LCPC for the APL profilometers;
6. $CP_{2.5}$, the coefficient of planarity on a 2.5-m-baselength defined by the Belgian Centre des Recherches Routières (CRR), in 0.01 mm;
7. $CAPL_{25}$, the coefficient of the APL25 profilometer analysis defined by LCPC; and
8. SI, the present serviceability index usually defined by regional panel ratings to be similar to the SI defined at the AASHO Road Test, in PSI (present serviceability index).

Comparable data for individual response-type systems not calibrated to one of the foregoing measures were not available. Although the Australian NAASRA meter was tested at the IRRE, the mounting vehicle differed from the Australian standard vehicle so the data cannot be used to develop a valid conversion.

RELATIONSHIPS AMONG PHYSICAL ROUGHNESS MEASURES

International Experiment Data

The IRRE was conducted in Brazil on a series of 49 road sections each 320 m long (6). The sections consisted of asphalt concrete, surface treatment, gravel, and earth surfaces in nearly equal amounts. The roughness on each section was measured by rod and level surveying, TRRL 3-m-beam profilometer, APL profilometer trailer (at both 72 and 21.6 km/h), and various response-type systems, including a TRRL Bump Integrator trailer, three Chevrolet sedans mounted with Mays meter sensors (an adaptation of the Mays ride meter), and a sedan mounted with a Bump Integrator and NAASRA meter sensors in parallel. Each instrument was used according to the standard procedure specified for it under the control of the relevant agency.

The range of values and bivariate linear correlations between different measures observed at the IRRE are given in Table 2 for the scales just described, with the exception of the Serviceability Index, which was not measured in the experiment. The observed data for the same scales are given in Table

TABLE 2 Bivariate Linear Correlation Coefficients and Ranges for Major Roughness Scales, as Observed at the International Road Roughness Experiment

Roughness Index[a]	IRI	QI_m	BI_r	$CP_{2.5}$	W_{sw}	W_{mw}	$CAPL_{25}$
IRI	1.000						
QI_m	0.962	1.000					
BI_r	0.973	0.933	1.000				
$CP_{2.5}$	0.958	0.923	0.927	1.000			
W_{sw}	0.937	0.921	0.893	0.942	1.000		
W_{mw}	0.768	0.629	0.702	0.692	0.686	1.000	
$CAPL_{25}$	0.719	0.705	0.644	0.744	0.732	0.851	1.000
No. observations	49	49	49	45	45	45	49
Mean	6.03	77.8	4,724	84.2	21.5	67.0	12.5
Standard deviation	3.30	43.7	3,141	36.6	11.4	51.4	5.0
Minimum	1.90	19.2	1,310	28.0	3.0	7.8	4.6
Maximum	16.6	211.5	16,485	169.0	37.2	181.9	21.7

Note: Further details of the definition of each index given by Sayers et al. *(6)*.
Source: Derived from data of the IRRE from Sayers, Gillespie, and Queiroz (1986).
[a] IRI = International Roughness Index, m/km IRI.
QI_m = Quarter-car Index of Brazil Road Costs Study, counts/km.
BI_r = Bump Integrator trailer of Transport and Road Research Laboratory, mm/km.
$CP_{2.5}$ = Coefficient of planarity on 2.5 m baselength for French APL72 profilometer, 0.01 mm.
W_{sw} = Energy index of short wavelengths (1 to 3.3 m) for French APL72 profilometer.
W_{mw} = Energy index of medium wavelengths (3.3 to 13 m) for French APL72 profilometer.
$CAPL_{25}$ = Rectified displacement coefficient from French APL25 profilometer.

3, including the reference inches per mile statistic (IM_r), which was computed simply by the dimensional conversion from m/km as 63.36 IRI.

The IRI data were computed as the $RARS_{80}$ statistic from rod and level survey data following the method outlined by Sayers et al. (7).

The QI_m data represent the Mays meter values calibrated to the Quarter-car Index scale by a methodology similar to that used in the original Brazil road costs study (3), so that they would closely represent the empirical foundation of all the vehicle operating cost and road deterioration relationships derived from that study. Separate calibration equations were established for each vehicle from the QI_r profile index computed from rod and level data using only data from asphalt concrete surfaces (4,9) as follows:

$$\hat{QI}_r = 12.155\ MM_1 \equiv QI_{m1}$$

$$\hat{QI}_r = 10.565\ MM_2 \equiv QI_{m2}$$

$$\hat{QI}_r = 11.034\ MM_3 \equiv QI_{m3}$$

where

$\hat{QI}_r$ = least-squares regression estimate of QI_r profile index from calibration of MM_i against QI_r, in counts/km QI;
QI_{m1} to QI_{m3} = calibrated roughness measure for Mays meter vehicle numbers 1 to 3, in counts/km QI; and
MM_1 to MM_3 = three-run average Mays meter count per unit distance for vehicle numbers 1 to 3, in m/km.

Then

$$QI_m = \text{mean}\ (QI_{m1}, QI_{m2}, QI_{m3}).$$

Although the original study used QI instead of QI_r as the calibration standard, it has been shown (2) that the calibration equations were not significantly

TABLE 3 Roughness Data by Various Measures in the International Road Roughness Experiment

Surface	SEC	IRI	IM_r	BI	QI_m	QI_r	$CP_{2.5}$	$CAPL_{25}$	W_{sw}	W_{mw}
Asphalt concrete	CA01	4.1	260	1,970	54	47	56	17.7	9.4	122.2
	CA02	4.6	291	2,340	55	61	65	15.0	12.0	80.4
	CA03	6.3	399	3,690	75	84	91	17.2	29.1	119.3
	CA04	5.3	336	3,280	66	75	80	16.7	21.2	141.5
	CA05	6.2	393	4,220	78	87	90	18.0	30.6	159.6
	CA06	7.3	463	5,025	96	95	108	19.0	29.7	78.9
	CA07	2.5	158	1,785	33	29	49	7.0	6.3	28.5
	CA08	2.6	165	1,775	34	27	42	7.0	6.8	17.4
	CA09	3.5	222	2,420	51	37	60	11.0	10.7	33.1
	CA10	3.3	209	2,235	45	36	62	11.0	16.5	45.5
	CA11	5.4	342	3,545	72	71	69	16.0	17.8	136.3
	CA12	1.9	120	1,310	19	17	28	5.0	3.3	11.2
	CA13	1.9	120	1,325	22	17	28	5.5	3.0	10.5
Surface treatment	TS01	4.3	272	3,335	77	46	70	7.5	19.2	18.4
	TS02	5.1	323	4,060	59	57	73	9.5	18.4	39.8
	TS03	4.7	298	4,245	75	54	80	10.4	22.8	27.4
	TS04	5.5	348	4,010	101	59	89	19.4	25.8	25.0
	TS05	5.7	361	4,685	124	60	94	9.0	29.4	20.8
	TS06	3.3	209	2,485	37	35	50	8.2	8.8	27.3
	TS07	3.3	209	2,555	38	38	51	8.4	9.2	39.0
	TS08	4.0	253	3,045	46	46	50	10.9	11.6	61.5
	TS09	3.9	247	3,150	43	42	60	7.8	14.9	18.0
	TS10	3.8	241	3,335	44	42	61	7.2	16.0	20.7
	TS11	2.5	158	2,210	28	26	36	4.6	6.3	13.6
	TS12	2.5	158	2,315	27	25	40	5.2	4.6	7.8
Gravel	GR01	3.7	234	2,315	36	42	58	5.8	13.3	17.4
	GR02	3.8	241	2,485	38	42	58	7.0	12.9	14.2
	GR03	7.2	456	5,320	90	93	103	17.0	33.4	94.6
	GR04	6.4	406	4,565	77	83	113	14.6	36.0	109.9
	GR05	9.2	583	6,985	133	115	169	20.0	37.2	104.1
	GR06	8.3	526	7,010	117	103	153	20.2	37.2	117.8
	GR07	5.5	348	3,970	80	67	89	7.7	30.6	42.4
	GR08	4.4	279	2,910	54	51	75	7.1	15.3	16.9
	GR09	9.2	583	6,060	105	110	139	16.9	37.2	98.6
	GR10	7.1	450	4,655	94	84	134	13.2	37.2	94.6
	GR11	14.1	893	10,890	187	194	–	13.4	–	–
	GR12	12.7	805	10,385	180	193	–	18.0	–	–
Earth	TE01	4.3	272	3,400	53	50	71	11.4	17.5	51.7
	TE02	4.1	260	3,270	51	48	72	10.7	17.7	35.4
	TE03	7.2	456	6,350	90	90	125	14.5	34.8	93.7
	TE04	7.3	463	7,065	94	89	128	18.6	33.7	181.9
	TE05	13.9	881	13,350	164	187	–	16.8	–	–
	TE06	16.6	1,052	16,485	211	221	–	21.7	–	–
	TE07	4.4	279	3,745	65	54	83	9.5	22.9	43.8
	TE08	5.0	317	3,905	67	58	86	9.0	22.9	30.4
	TE09	8.6	545	6,390	94	109	129	14.7	35.0	107.2
	TE10	10.2	646	9,300	121	138	156	17.3	37.2	155.1
	TE11	9.6	608	8,455	111	134	158	16.8	37.2	155.0
	TE12	9.0	570	7,860	99	140	108	18.1	37.1	148.0

Note: Refer to Table 1 for definition and units of roughness measurement.
Source: Derived from data given by Sayers et al. *(6)*.

affected. A significnt difference does exist, however, between QI_r and QI_m because of the non-zero intercept in the definition of the QI_r profit statistic (as will be seen in Table 4). Hence it was important to use QI_m instead of QI_r in this correlation exercise.

The BI_r data represent the roughness measured by the Bump Integrator trailer at 32 km/h, which were three-run averages of both wheelpaths. These data represent the output of the trailer as it was at the IRRE, under controlled operating conditions, and were considered by TRRL to be representative of its performance in previous studies.

The $CP_{2.5}$, W_{sw}, W_{mw}, and $CAPL_{25}$ numerics for the APL profilometer were the section-mean values (across both wheelpaths) of the values reported at the IRRE [(6), Appendix G].

It can be seen that the data cover a wide range, from very smooth (1.9 m/km IRI) to very rough (16.6 m/km IRI) roads. Further comment on the correlations will be made later.

Analysis

The objective of the analysis was to develop practical conversion relationships among the various measures. Typically, when two variables are imperfectly correlated, either both are measured with error or the two represent different measures. In this situation, linear regressions of the one variable on the other, and the other on the one are normally not interchangeable because the least-squared deviations differ in the two senses. For this analysis, a conversion relationship was obtained by making linear least-squares estimates of coefficients in both senses between each pair of variables and averaging as follows:

$$y_i = a + bx_i + u_i \quad (1)$$

$$x_i = c + dy_i + v_i \quad (2)$$

The conversion equation should be such that

$$Y = p + qX \text{ and } X = (Y - p)/q \quad (3)$$

take

$$\hat{p} = (a - c/d)/2 \quad (4)$$

$$\hat{q} = (b + 1/d)/2 \quad (5)$$

where

x_i, y_i = the ith pair of values of roughness measures x and y, respectively;
u_i, v_i = residual errors of y and x, respectively;
a, b, c, d = coefficients estimated by linear regression;
p, q = coefficients adopted for conversion equation; and
X, Y = conversion equation estimates of x y, respectively, given the other.

The goodness of fit of Equation 3 as a conversion relationship was quantified by regressing the observed values of y_i on the predicted values Y_i without intercept.

The resulting conversion relationships are given in Table 4. The root mean squared error (RMSE) of the conversion prediction and the estimated bias are given for each. The bias in each case is very small, typically less than 2 percent, and negligible.

A selection of the conversion relationships is plotted with the observed data in Figures 1 and 2. One observation is given per test section, and the surfacing types are distinguished by symbols. Figure 1 shows the relationships between the Brazil QI_m scale, the TRRL BI scale, and the IRI scale, which were pertinent to the major road costs studies. Figure 2 shows the relationships of three numerics of the APL profilometer to the IRI.

Discussion of Relationships

Very high correlations exist between the IRI scale and both the QI_m and BI measures used in the major empirical studies, so that interchange between either of the historical measures and IRI can be made with reasonable confidence. This is shown in Figures 1a and 1c. The standard error for estimating IRI roughness was 0.92 and 0.76 m/km IRI from QI_m and BI measures, respectively. From the plots it can be seen that this error is reasonably uniform over the range of roughness and across all four surface types.

A feature to note in the QI_m data is that two of the measurements on surface treatment pavements are high values that appear as outliers in both Figures 1a and 1b. The high values result not from a shortcoming of the QI scale but from resonance of the wheel-axle system in the specific vehicles used for the Mays meters; this occurred on two sections that had minor surface corrugations at about 2 m spacing. Neither profile statistic, IRI, or $CP_{2.5}$, was unduly affected by the corrugations, which reflects the good damping characteristics incorporated in each one. The Bump Integrator trailer, traveling at the slower speed of 32 km/h compared with the 80 km/h speed of the Mays meter vehicle, was not affected either, as shown in Figure 1c.

The BI trailer tends to be more sensitive to earth roads than passenger cars (or IRI or QI_m) because of the particular characteristics of its suspension system. The system has a resonant frequency that corresponds to a wavelength of about

TABLE 4 Summary of Relationships and Statistics for Conversions Between Roughness Scales

Conversion Relationship		Standard Error	Coefficient of Variation	Bias Slope	Units
$E[\hat{IRI}]$	$= QI_m/13$	0.919	15.4	0.989	m/km
	$= (QI_r + 10)/14$	0.442	7.34	0.975	m/km
	$= 0.0032\ BI^{0.89}$	0.764	12.7	1.008	m/km
	$= CP_{2.5}/16$	0.654	12.4	0.993	m/km
	$\cong 5.5 \log_e (5.0/PSI)$	–	–	–	m/km
	$= 0.80\ RARS_{50}$	0.478	–	1.002	m/km
	$= 0.78\ W_{sw}^{0.63}$	0.693		0.994	m/km
	$= CAPL_{25}/3.0$ if asphalt				
	$= CAPL_{25}/2.2$ if not asphalt	1.050		1.030	m/km
$E[\hat{QI}_m]$	$= 13\ IRI$	12.0	15.3	0.993	Counts/km
	$= 9.5 + 0.90\ QI_r$	14.5	18.7	0.985	Counts/km
	= {BI/55 if not earth; BI/73 if earth}	11.7	15.0	1.002	Counts/km
	$= 0.81\ CP_{2.5}$	11.7	17.2	0.986	Counts/km
	$\cong 72 \log_e (5.0/PSI)$	–	–	–	Counts/km
	$= 7.9\ W_{sw}^{0.70}$	8.78		0.996	Counts/km
	$= 6.2\ CAPL_{25}$	18.29		1.13	Counts/km
$E[\hat{QI}_r]$	$= -10 + 14\ IRI$	6.32	8.35	1.024	Counts/km
	$\cong BI/62$	14.0	18.3	1.006	Counts/km
	$= -10 + 0.89\ CP_{2.5}$	13.1	20.3	0.980	Counts/km
$E[\hat{BI}]$	$= 630\ IRI^{1.12}$	694	14.7	0.998	mm/km
	$= 36\ QI_m^{1.12}$	1100	22.8	0.985	mm/km
	= {55 QI_m if not earth; 73 QI_m if earth}	673	14.2	0.976	mm/km
	$= 62\ QI_r$	850	18.1	0.971	mm/km
$E[\hat{CP}_{2.5}]$	$= 16\ IRI$	10.5	12.4	0.994	0.01 mm
	$= 11 + 1.12\ QI_r$	14.8	17.6	0.995	0.01 mm
	$= 1.23\ QI_m$	14.4	17.2	0.986	0.01 mm
	$= 11.7\ W_{sw}^{0.65}$ (if $CP_{2.5} < 150$)	8.87		1.018	0.01 mm

Note: Roughness scale codes:
BI = TRRL Bump Integrator trailer at 32 km/h (mm/km).
$CAPL_{25}$ = APL profilometer coefficient for 21.6 km/h operation.
$CP_{2.5}$ = APL profilometer coefficient of planarity (.01 mm).
IRI = International Roughness Index (m/km) [denotes $RARS_{80}$ *(7)*].
QI_m = RTRRMS-estimate of QI roughness in Brazil study (counts/km).
QI_r = Profile RMSVA-function of QI roughness (counts/km).
$RARS_{50}$ = ARS response of reference roughness simulation at 50 km/h *(7)*.
W_{sw} = Short wavelength (1 to 3.3 m) energy index W of APL72 profilometer as defined by French LCPC [*(6)*, Appendix G].

Source: Computer analysis of data from the International Road Roughness Experiment *(6)*.

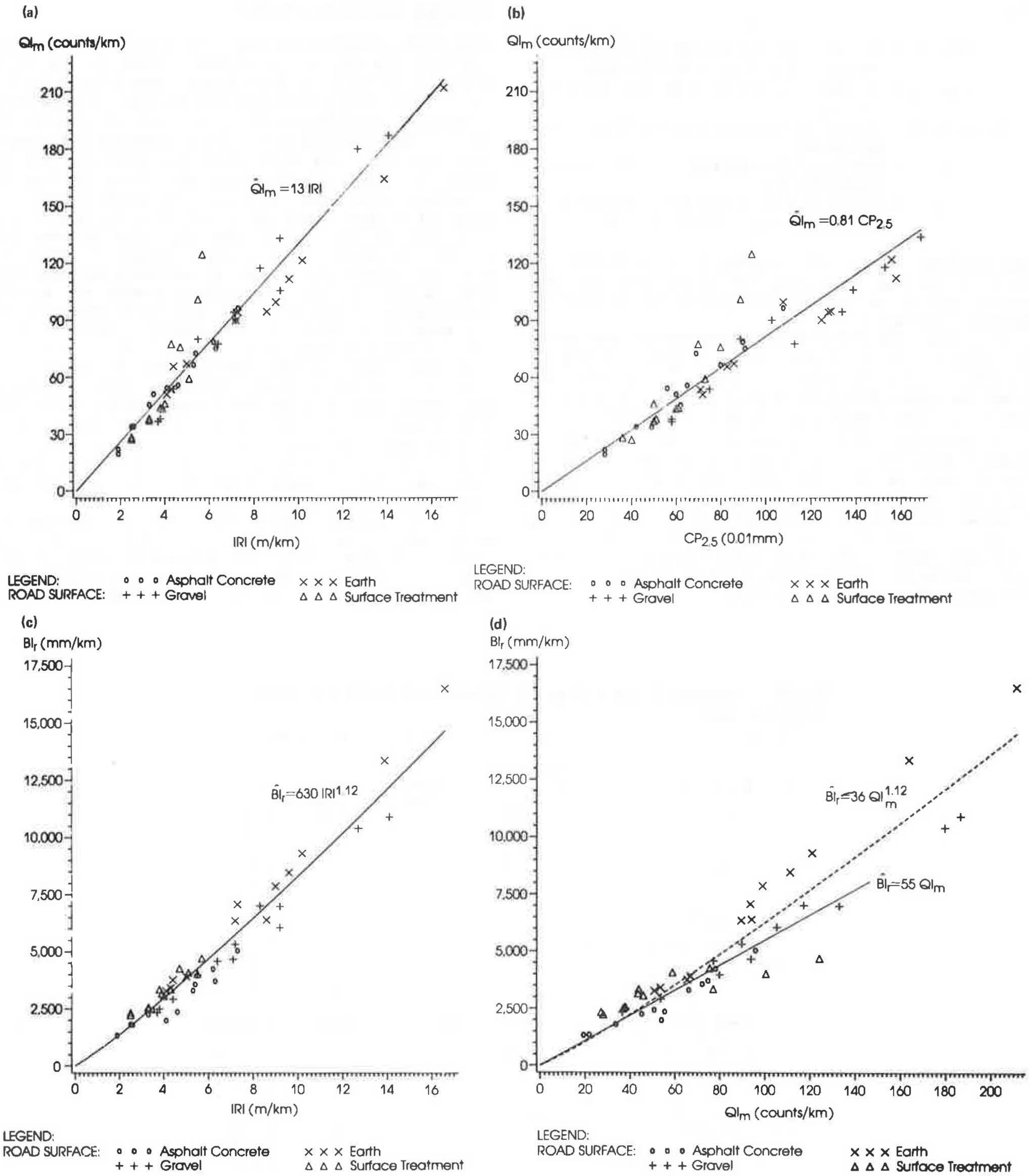


FIGURE 1 Relationships for conversion between QI_m (Brazil road costs study), BI (TRRL Bump Integrator trailer), and $CP_{2.5}$ (French/Belgian APL profilometer) scales of road roughness: (a) Brazil calibrated Mays meter, QI_m, and profile roughness, IRI; (b) Brazil calibrated Mays meter, QI_m, and APL72 profilometer coefficient, $CP_{2.5}$; (c) TRRL Bump Integrator trailer at 32 km/h and profile roughness, IRI; and (d) TRRL Bump Integrator trailer at 32 km/h and Brazil calibrated Mays meter, QI_m.

0.76 m, and the shock absorbers are loosely damped with gain levels 50 to 100 percent greater than typical passenger cars at the resonance frequencies. Thus, the BI trailer responds to the strong short wavelength content in earth surfaces with an exaggerated response, which results in the nonlinearity evident in Figures 1c and 1d for earth surfaces. This also implies that high roughness measurements coming from the BI trailer probably overstate the response of a typical passenger car (even when traveling at a comparably slow speed), so that the nonlinearity is important when interpreting vehicle operating cost relationships that are related to BI trailer roughness.

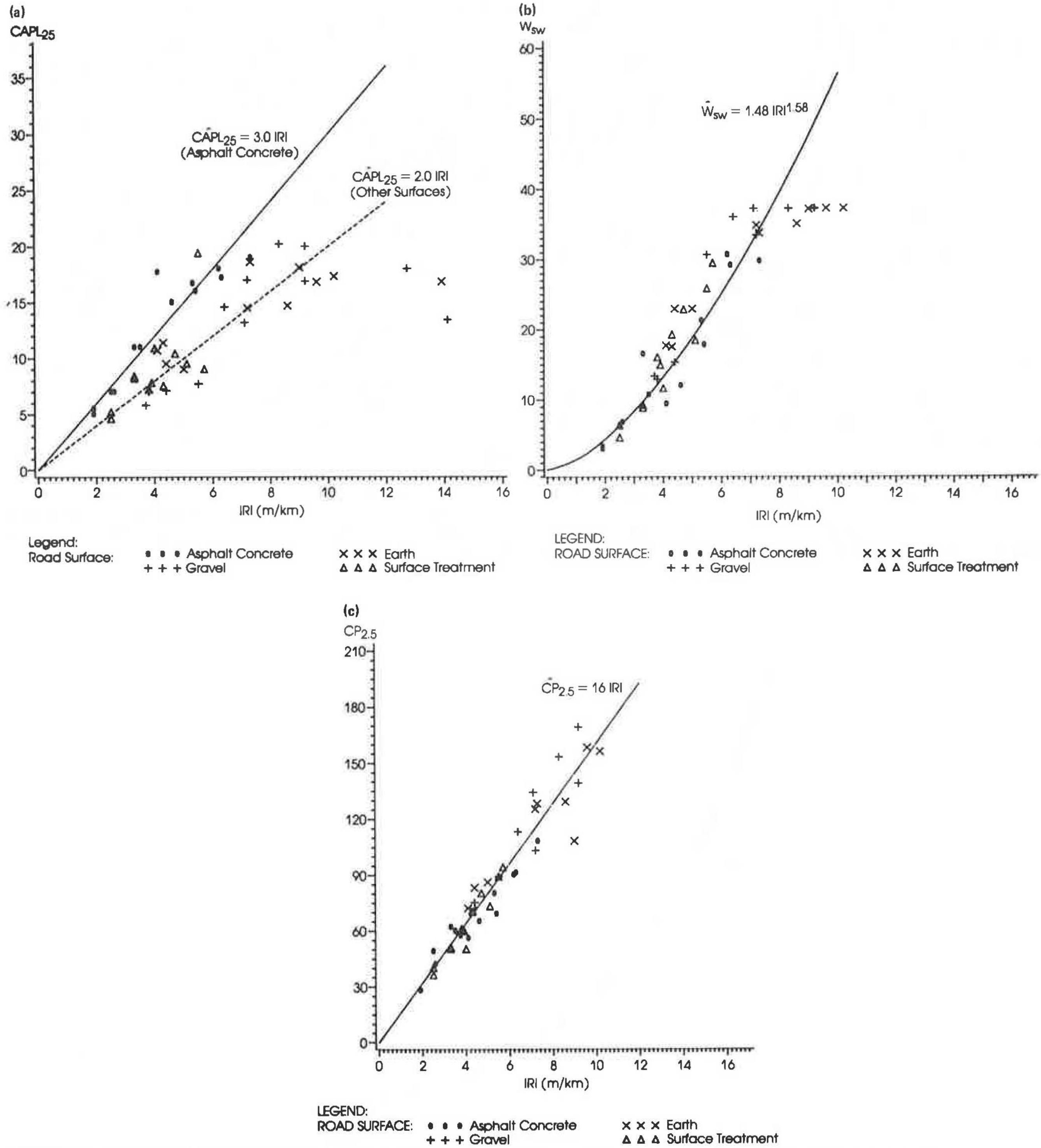


FIGURE 2 Relationships of various roughness coefficients of the French APL profilometer systems APL72 and APL25 to the International Roughness Index: (a) APL25 profilometer coefficient, $CAPL_{25}$, and profile roughness, IRI; (b) APL72 profilometer short wavelength energy, W_{sw}, and profile roughness, IRI; and (c) APL72 profilometer coefficient, $CP_{2.5}$, and profile roughness, IRI.

On surfaces other than earth, the relationship between the BI and QI_m scales is virtually linear as shown by the solid line in Figure 1d. The relationship given as

$$BI\ (mm/km) = 55\ QI_m\ (counts/km) \qquad (6)$$

was derived in a separate analysis (9). Other studies have indicated that the value of the ratio (55) can rise to 75 or higher when the BI trailer suspension system is not adequately maintained. Note that when the measurement error is proportional to the square root of the mean value [which is valid here, see Paterson (2)], and no intercept is expected because the measures are essentially similar (i.e., $p = 0$ in Equation 3), it can be shown that q in Equation 3 is estimated by

$$\hat{q} = \sum y_i / \sum x_i = \bar{y}/\bar{x} \qquad (7)$$

where $\bar{x}$, $\bar{y}$ are the mean values of x, y, respectively. This result is particularly useful because it means that a linear conversion under the foregoing conditions can be derived simply from the ratio of the mean values of each scale.

Of the various profile numerics developed for the APL profilometer, the two that correlate the most highly with vehicle response, and in particular the IRI roughness scale, are the $CP_{2.5}$ and short wavelength energy (W_{sw}) indices shown in Figure 2 and Table 2. The APL25 coefficient ($CAPL_{25}$) has a generally poor correlation with IRI and other response-type measures because it is sensitive mostly to long (7 to 15 m) rather than short wavelengths, and the correlation is thus best on asphalt concrete surfaces (see Figure 2a and Table 4). All the APL statistics, except $CP_{2.5}$, tend to reach signal saturation as can be seen from Figures 2a and 2b. For example, the W_{sw} index for the APL25 is not applicable to roughness levels above 8 m/km IRI. In order to avoid mechanical damage, the APL profilometer was not operated on roads with roughness greater than 11 m/km IRI during the IRRE; that is, unpaved roads with moderately high roughness.

RELATIONSHIP OF SERVICEABILITY INDEX TO ROUGHNESS

Roughness defined by a slope variance statistic was included as one component of the Serviceability Index function estimated from panel ratings of pavement serviceability at the AASHO Road Test. Some attempts have since been made to relate roughness to serviceability by calibration of the vehicles to slope variance and application of the original SI function given in the AASHO Road Test (5). However, it has been more common for agencies to relate roughness directly to new local panel ratings of serviceability (PSR). Ratings, however, tend to vary considerably with the expectation of the users and their previous exposure to very high roughness levels, so that the ratings typically vary from country to country. SI was not defined for unpaved roads.

Relationships between PSR and the QI_m and IRI roughness scales are given in Figure 3. These were derived from four panel rating sources: Brazil and Texas [(3), Working Document 10], South Africa (10), and Pennsylvania (11). For the first three, PSR was related directly to the QI profile numeric; in Texas, the panel rating was an estimate derived from a waveband correlation with profile data derived in Texas that was applied to Brazilian road profile data. For the Pennsylvania relationship, an approximate conversion of 1 count/km QI_m = 6.6 in./mi was applied to the roughness data.

Considerable variations exist in the Serviceability Index scales derived from the different sources: the Texas, Pennsylvania, and South Africa ratings represent users who are used to high-standard paved

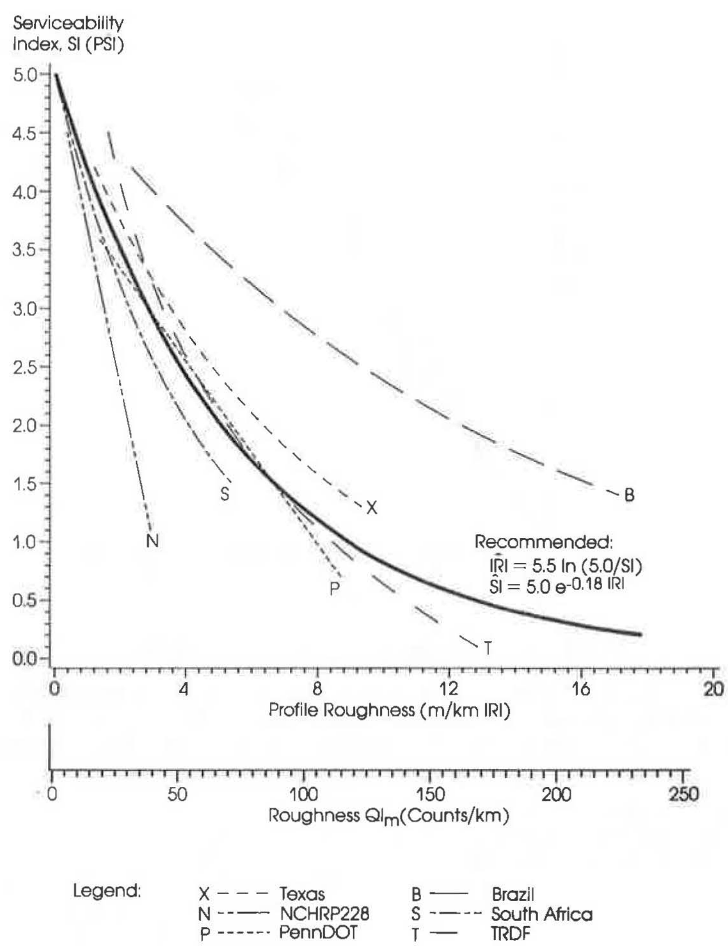


FIGURE 3 Approximate relationships between AASHO serviceability index, PSI, and the QIm and IRI roughness scales, based on panel ratings from four sources.

roads, but the means nevertheless vary by up to one rating interval when rating a given roughness, whereas the Brazilian raters attach much higher ratings to rough roads than do the other groups. A linear relationship between rating and roughness may be adequate over the range of two to four rating units on paved roads as claimed by Janoff et al. (12) but does not apply more generally. By extrapolation, the scales indicate that a roughness of 130 to 175 QI is equivalent to 0 PSI, except for the Brazilian panel, which included unpaved roads and rated a roughness of 175 as better than 1 PSI. The best continuous function meeting the perfect score of 5 on the SI scale at a roughness of zero is as follows:

$$QI_m = 72 \log_e (5.0/SI)$$

$$IRI = 5.5 \log_e (5.0/SI)$$

However, the linear function may be just as appropriate over normal ranges of paved road roughness, that is

$$QI_m = \max [136 - 33\ SI;\ 0]$$

$$IRI = \max [10.5 - 2.5\ SI;\ 0]$$

The slope of the QI_m/PSI relationship varies from -20 for serviceability above 3.5 PSI to -33 for serviceability below 3.0 PSI. The common initial and terminal levels of serviceability are therefore approximately

4.2 PSI ≈ 13 counts/km QI_m ≈ 1.0 k/km IRI

2.5 PSI ≈ 50 counts/km QI_m ≈ 3.8 m/km IRI

2.0 PSI ≈ 65 counts/km QI_m ≈ 5.0 m/km IRI

1.5 PSI ≈ 86 counts/km QI_m ≈ 6.6 m/km IRI

CONVERSION CHART

For convenience of application, the results of the foregoing analyses are presented in the form of a conversion chart in Figure 4. The IRI scale is used as a reference on each side of the chart, and for North American users, the equivalent reference scale in inches/mile units (IM_r) is presented alongside.

For all other roughness measures shown on the chart, the bars have three sets of graduations, the estimated value on the centerline, a low value on the left, and a high value on the right. The low and high values are defined by the 15th and 85th percentiles of the preceding data and indicate the range over which the actual value for a specific road section can be expected. For example, to estimate the roughness of 6 m/km IRI in terms of the QI_m scale, an estimated value of 78 counts/km QI_m is obtained, and the authors are about 70 percent confident that the actual value will be between 66 and 90. For converting between two of the nonreference scales, the centerline of the given scale is used, and the estimated low and high values of the desired scale are read. For calculator applications, the conversion functions and confidence intervals are listed at the bottom of the chart.

The ranges of validity of the conversion functions are shown by the length of the bars on the chart. Individual observations may exceed the ranges shown on the IRI, QI_m, BI, and IM_r scales, but typically such high levels of roughness are confined to short sections. In the case of the APL numerics, the ranges are limited by the mechanical capability of the equipment and by the signal processing method to cases of paved roads and unpaved roads of low to moderate roughness.

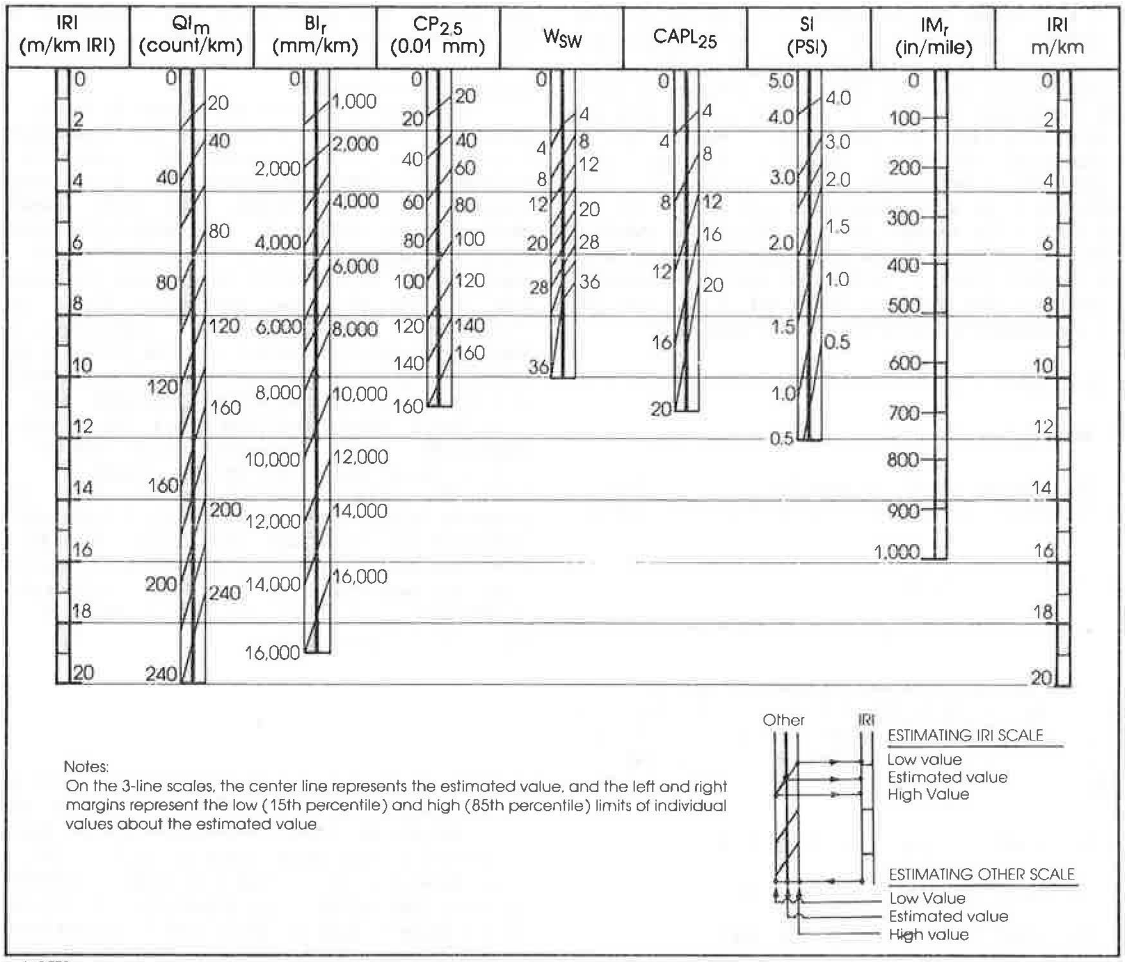
A chart such as the one shown in Figure 4 meets a practical need, but there are two important caveats. First there is the potential inference that the various roughness measures are interchangeable and measure the same thing. The IRRE showed clearly that, while different response-type systems were highly correlated when operated under identical conditions, significant variations do exist between the scales on some surfaces. These arise from differences in the operating conditions, equipment, wear, and interpretation of the diverse spectrum of wavelengths in a road profile. These variations are accommodated in the chart through the confidence intervals, which indicate that the conversions are approximate and give the range within which the actual value may vary. Second, there is no guarantee that the data collected at the IRRE are exactly representative of the historical data collected in previous studies. Not all these studies will have been conducted with the recommended degree of control as was done at the IRRE, although there is reasonable confidence in this respect for the QI_m, BI_r, and APL measures.

CONCLUSION

An acceptable basis for comparing the roughness measures used in past and present major studies has been established for use where one of the following calibration references exist: $BI_r QI_m$, $CP_{2.5}$, IM_r or IRI. However, the various roughness measures sense, filter, and amplify the road profile characteristics in different ways so that exact equivalences do not exist between them. The conversion chart and relationships, shown in Figure 4, present the means for comparing a number of scales that have been in use and for relating them to the International Roughness Index. These conversions and their inexactness were based primarily on data from the international experiment conducted in Brazil, and they are generally valid only over the range of asphalt, surface treatment, gravel, and earth surface types included in the experiment. That validity, however, covers a wide range, and significant deviations are only likely on extremely different surface types, including surfaces with periodic defects, such as corrugations, or strong short wavelength content such as potholed roads, earth roads, surfaces placed by manual labor (macadams, cobbles, set-stones, etc.), and coarse-gravel roads.

The degree to which the conversions presented here are applicable to either historical or present measurements made with a system similar to one of those described, depends largely on how the operating conditions compare with those existing at the IRRE. In the case of the profile-related systems (QI_m, W_{sw}, and $CP_{2.5}$), which are time-stable, the degree of confidence is high. In the case of the Bump Integrator trailer, and other systems using hardware as a reference, the applicability depends on the degree of similarity of the hardware to the system used at the IRRE, which can differ in extreme cases by up to 40 percent when out of calibration.

The widespread adoption of IRI as a reference and calibration standard is being encouraged worldwide to improve the reliability of exchanging information related to road roughness. The IRI would then be a common denominator, in some cases existing in parallel with a local index or series of profile statistics.



NOTES:
Conversions estimated on data from the International Road Roughness Experiment, (Sayers, Gillespie and Queiroz, 1986) as follows

1. IRI — International Roughness Index (Sayers, Gillespie and Paterson, World Bank Technical Paper 46, 1986)
2. QI_m — Quarter-car Index of calibrated Maysmeter, Brazil-UNDP Road Costs Study
   $\hat{IRI} = QI_m/13 \pm 0.37\sqrt{IRI}$ $IRI<17$
3. BI_r — Bump Integrator trailer at 32 km/h, Transport and Road Research Laboratory, UK
   $\hat{IRI} = 0.0032\ BI_r^{0.89} \pm 0.31\sqrt{IRI}$; $IRI<17$
4. $CP_{2.5}$ — Coefficient of planarity over 2.5m baselength for APL72 Profilometer, Centre de Recherches Routiers, Belgium:
   $\hat{IRI} = CP_{2.5}/16 \pm 0.27\sqrt{IRI}$, $IRI<11$
5. W_{sw} — Short Wavelength Energy for APL72 Profilometer, Laboratoire Central des Ponts et Chaussées, France
   $\hat{IRI} = 0.78\ W_{sw}^{0.63} \pm 0.69\ IRI$, $IRI<9$
6. $CAPL_{25}$ — Coefficient of APL25 Profilometer, Laboratoire Central des Ponts et Chaussées, France:
   $\hat{IRI} = 0.45\ k\ CAPL_{25} \pm 16\%$; $IRI<11$
   where k = 1 for general use, k = 0.74 for asphalt concrete surfaces, k = 1.11 for surface treatment, earth or gravel.
7. SI — Serviceability Index, American Association of State Highway and Transportation Officials:
   $\hat{IRI} = 5.5 \ln(5.0/SI) \pm 25\%$; $IRI<12$
8. IM_r — Inches/mile equivalent of IRI from Reference Quarter-Car Simulation at 50 mile/hr (see 'HSRI-reference' in Gillespie, Sayers and Segel NCHRP report 228, 1980; and '$RARS_{80}$' in Sayers, Gillespie and Queiroz, World Bank Technical Paper 45, 1986):
   $IRI = IM_r/63.36$

FIGURE 4 Chart for approximate conversions between the International Roughness Index and major roughness scales.

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