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) (longitudinal 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 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 (RARSg), 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...
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 baseline length 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

<table>
<thead>
<tr>
<th>Measures</th>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>International roughness index</td>
<td>IRI</td>
<td>m/km IRI</td>
<td>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_{ref}) 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).</td>
</tr>
<tr>
<td>Referenced Response Measures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quarter-car index</td>
<td>QI</td>
<td>Counts/km QI</td>
<td>A profile-related measure developed for Brazil Road Costs Study and singly 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 (QIm) represents the calibrated Maysa meter estimate of QI used as a basis for all Brazil road costs study data (2), or by r (QIr) represents profile index redefined in terms of root mean square vertical acceleration (RMSVA) of 1 and 2.5 m baselines of elevation data by correlation (6). Single axle trailer (based on NPR 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. Usually application is vehicle-mounted sensor calibrations. Responses of trailer standard trailer units have possibly varied over time; a profile index (Blr) based on root mean square deviation of elevations on a 1.8-m baseline and 300 mm sample interval (RMSDA_{0-300}, 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). A calibration reference level 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.</td>
</tr>
<tr>
<td>Bump integrator trailer (TRRL)</td>
<td>BI</td>
<td>mm/km</td>
<td></td>
</tr>
<tr>
<td>Inches per mile (reference quarter-car simulation)</td>
<td>IM_{q} (IRCS)</td>
<td>in./mile</td>
<td></td>
</tr>
<tr>
<td>Profile Numerics for Dynamic Profilometers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waveband energy (APL72)</td>
<td>W_{sw}</td>
<td>(L^2)</td>
<td>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.</td>
</tr>
<tr>
<td>Coefficient of planarity (APL72)</td>
<td>CP_{25}</td>
<td>0.01 mm</td>
<td>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 baselines of 2.5, 10, and 40 m for every 100 m (expressed in the subscript); the IREX indicated that CP_{25} correlated most highly with IRI and most response measures. Scales from 0 (perfect) upwards.</td>
</tr>
<tr>
<td>Coefficient APL_{25}</td>
<td>CAPL_{25}</td>
<td>(L)</td>
<td>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.</td>
</tr>
</tbody>
</table>

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 this paper 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 sys-
tems 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. (4). The measures include

1. IRI, the International Roughness Index, in
m/km IRI;
2. IMr, the inches/mile equivalent of IRI used
in North America and sometimes called reference
quarter-car simulation (QCSR), or Golden car;
3. Qim, the Quarter-car Index of the Brazil
road costs study as measured by calibrated Mays
meters, in counts/km;
4. Blr, the response of the TRRL Bump Integrator
trailer used during the IRRRE, in mm/km;
5. Ww, the short-wavelength energy numeric
defined by LCPC for the APL profilometers;
6. CP2.5, the coefficient of planarity on a
2.5-m-base length defined by the Belgian Centre des
Recherches Routières (CRR), in 0.01 mm;
7. QAP25, the coefficient of the APL25 profi-
lometer 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 NASHO Road Test, in PSI (pre-
sent 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 TRRL, 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 IRRRE was conducted in Brazil on a series of 49
road sections each 320 m long (6). The sections con-
stisted 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 Inte-
grator and NAASRA meter sensors in parallel. Each
instrument was used according to the standard proce-
sure specified for it under the control of the rel-

evant agency.

The range of values and bivariate linear correla-
tions between different measures observed at the
IRRRE are given in Table 2 for the scales just de-
scribed, 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>
<thead>
<tr>
<th>Roughness Index</th>
<th>IRI</th>
<th>Qln</th>
<th>Blr</th>
<th>CP2.5</th>
<th>Ww</th>
<th>Wmw</th>
<th>CAPL25</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRI</td>
<td>1.00</td>
<td>0.962</td>
<td>1.000</td>
<td>0.973</td>
<td>0.933</td>
<td>1.000</td>
<td>0.935</td>
</tr>
<tr>
<td>Qln</td>
<td>0.962</td>
<td>1.000</td>
<td>0.973</td>
<td>0.933</td>
<td>1.000</td>
<td>0.935</td>
<td>0.935</td>
</tr>
<tr>
<td>Blr</td>
<td>0.973</td>
<td>0.933</td>
<td>1.000</td>
<td>0.958</td>
<td>0.923</td>
<td>0.977</td>
<td>1.000</td>
</tr>
<tr>
<td>CP2.5</td>
<td>0.935</td>
<td>0.935</td>
<td>0.935</td>
<td>0.958</td>
<td>0.923</td>
<td>0.977</td>
<td>1.000</td>
</tr>
<tr>
<td>Ww</td>
<td>0.937</td>
<td>0.921</td>
<td>0.893</td>
<td>0.937</td>
<td>1.000</td>
<td>0.942</td>
<td>1.000</td>
</tr>
<tr>
<td>Wmw</td>
<td>0.937</td>
<td>0.921</td>
<td>0.893</td>
<td>0.937</td>
<td>1.000</td>
<td>0.942</td>
<td>1.000</td>
</tr>
<tr>
<td>CAPL25</td>
<td>0.719</td>
<td>0.705</td>
<td>0.644</td>
<td>0.719</td>
<td>0.705</td>
<td>0.644</td>
<td>0.719</td>
</tr>
</tbody>
</table>

Note: Further details of the definition of each index given by Sayers et al. (6).
Source: Derived from data of the IRRRE from Sayers, Gillespie, and Queiros (1986).

1 IRI = International Roughness Index, m/km IRI.
2 Qlm = Quarter-car Index of Brazil Road Costs Study, counts/km.
3 IMr = Bump Integrator trailer of Transport and Road Research Laboratory, mm/km.
4 CP2.5 = Coefficient of planarity on 2.5 m base length for French APL27 profilometer, 0.01 mm.
5 Ww = Energy index of short wavelengths (1 to 3.3 m) for French APL27 profilometer.
6 Wmw = Energy index of medium wavelengths (3.3 to 13 m) for French APL27 profilometer.
7 QAP25 = Rectified displacement coefficient from French APL25 profilometer.

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

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

\[
\begin{align*}
\hat{Q}_I &= 12.155 \cdot M_{m1} = Q_{m1} \\
\hat{Q}_I &= 10.565 \cdot M_{m2} = Q_{m2} \\
\hat{Q}_I &= 11.034 \cdot M_{m3} = Q_{m3}
\end{align*}
\]

where

\[
\begin{align*}
\hat{Q}_I &= \text{least-squares regression estimate of Q}_I \text{ profile index from calibration of } M_{m1} \text{ against } Q_I, \text{ in counts/km } Q_I \\
Q_{m1} \text{ to } Q_{m3} &= \text{calibrated roughness measure for Mays meter vehicle numbers 1 to 3, in counts/km } Q_I; \text{ and}
M_{m1} \text{ to } M_{m3} &= \text{three-run average Mays meter count per unit distance for vehicle numbers 1 to 3, in m/km.}
\end{align*}
\]
The BTR 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 $C_{5,5}$, $W_{5,5}$, $W_{5,5}$, and $C_{5,5}^{APL}$ numerics for the APL profiler were the section-mean values (across both wheelpaths) of the values reported at the IRRE [[G], 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:

$$Y_1 = a + bx_1$$

$$x_1 = c + dy_1 + v_1$$

The conversion equation should be such that

$$Y = p + qX$$

$$X = (Y - p)/q$$

**Note:** Refer to Table 1 for definition and units of roughness measurement. Source: Derived from data given by Sayers et al. (6).
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 square 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 $Q_{10}$ 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 $Q_{10}$ 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 $Q_{10}$ 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 $Q_{10}$ 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 Q1 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 $Q_{10}$, 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 $Q_{10}$) because of the particular characteristics of its suspension system. The system has a resonant frequency that corresponds to a wavelength of about

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

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 square 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 $Q_{10}$ 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.

### Table 4: Summary of Relationships and Statistics for Conversions Between Roughness Scales

<table>
<thead>
<tr>
<th>Conversion Relationship</th>
<th>Standard Error</th>
<th>Coefficient of Variation</th>
<th>Bias Slope</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>E[RI] = $Q_{10}$/13</td>
<td>0.19</td>
<td>15.4</td>
<td>0.989</td>
<td>m/km</td>
</tr>
<tr>
<td>E[RI] = (Q1 + 0.3)/14</td>
<td>0.44</td>
<td>7.34</td>
<td>0.975</td>
<td>m/km</td>
</tr>
<tr>
<td>E[RI] = 0.0032 BI</td>
<td>0.76</td>
<td>12.7</td>
<td>1.008</td>
<td>m/km</td>
</tr>
<tr>
<td>E[RI] = CP2.s/16</td>
<td>0.65</td>
<td>12.4</td>
<td>0.993</td>
<td>m/km</td>
</tr>
<tr>
<td>E[RI] = 5.5 log_10 (50/PSI)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>m/km</td>
</tr>
<tr>
<td>E[RI] = 0.80 RARS 50</td>
<td>0.47</td>
<td>-</td>
<td>1.002</td>
<td>m/km</td>
</tr>
<tr>
<td>E[RI] = 0.78 W 5.67</td>
<td>0.63</td>
<td>-</td>
<td>0.994</td>
<td>m/km</td>
</tr>
<tr>
<td>E[RI] = CAPL/3.0 if asphalt</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>m/km</td>
</tr>
<tr>
<td>E[RI] = CAPL/2.12 if not asphalt</td>
<td>1.050</td>
<td>-</td>
<td>-</td>
<td>m/km</td>
</tr>
<tr>
<td>E[Q10] = 13 IRI</td>
<td>12.0</td>
<td>15.3</td>
<td>0.993</td>
<td>Counts/km</td>
</tr>
<tr>
<td>E[Q10] = 9.5 + 0.90 QL</td>
<td>14.0</td>
<td>18.7</td>
<td>0.985</td>
<td>Counts/km</td>
</tr>
<tr>
<td>E[Q10] = BI/73 if earth</td>
<td>11.7</td>
<td>15.0</td>
<td>1.002</td>
<td>Counts/km</td>
</tr>
<tr>
<td>E[Q10] = 0.81 CP2.s</td>
<td>7.88</td>
<td>17.2</td>
<td>0.986</td>
<td>Counts/km</td>
</tr>
<tr>
<td>E[Q10] = 110 + 14 IRI</td>
<td>6.32</td>
<td>8.35</td>
<td>1.024</td>
<td>Counts/km</td>
</tr>
<tr>
<td>E[BI] = BI/62</td>
<td>14.0</td>
<td>18.3</td>
<td>1.006</td>
<td>Counts/km</td>
</tr>
<tr>
<td>E[BI] = -10 + 0.89 CP2.s</td>
<td>12.1</td>
<td>-</td>
<td>0.980</td>
<td>Counts/km</td>
</tr>
<tr>
<td>E[BI] = 630 IRI 13.2</td>
<td>694</td>
<td>14.7</td>
<td>0.998</td>
<td>mm/km</td>
</tr>
<tr>
<td>E[BI] = 36 QL 1.12</td>
<td>1100</td>
<td>22.8</td>
<td>0.985</td>
<td>mm/km</td>
</tr>
<tr>
<td>E[BI] = 65 QL if not earth</td>
<td>673</td>
<td>14.2</td>
<td>0.976</td>
<td>mm/km</td>
</tr>
<tr>
<td>E[BI] = 73 QL if earth</td>
<td>14.8</td>
<td>17.6</td>
<td>0.995</td>
<td>mm/km</td>
</tr>
<tr>
<td>E[BI] = 62 QL</td>
<td>14.4</td>
<td>17.2</td>
<td>0.986</td>
<td>0.01 mm</td>
</tr>
<tr>
<td>E[BI] = 11.5 QL</td>
<td>14.4</td>
<td>17.2</td>
<td>0.986</td>
<td>0.01 mm</td>
</tr>
<tr>
<td>E[BI] = 1.23 QL</td>
<td>8.87</td>
<td>-</td>
<td>1.018</td>
<td>0.01 mm</td>
</tr>
</tbody>
</table>

Note: Roughness scale codes:
- BI = TRRL Bump Integrator trailer at 32 km/h (mm/km).
- CAPL1.5 = APL profilometer coefficient for 21.6 km/h operation.
- CP2.s = APL profilometer coefficient of planarity (0.1 mm).
- Q10 = International Roughness Index (mm/km) (denotes RARS 50).
- Q2s = RTRMS-estimate of Q1 roughness in Brazil study (counts/km).
- Q3s = Profile RMSV-function of Q1 roughness (counts/km).
- RARS 50 = ARI response of reference roughness simulation at 50 km/h.
- W = Short wavelength (1 to 3.3 m) energy index W of APL-72 profilometer as defined by French LCPC [6], Appendix G.

Source: Computer analysis of data from the International Road Roughness Experiment (6).
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 1 Relationships for conversion between Qlm (Brazil road costs study), BI (TRRL Bump Integrator trailer), and CP2.5 (French/Belgian APL profilometer) scales of road roughness: (a) Brazil calibrated Mays meter, Qlm, and profile roughness, IRI; (b) Brazil calibrated Mays meter, Qlm, and APL profilometer coefficient, CP2.5; (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, Qlm.
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, CAPL25, and profile roughness, IRI; (b) APL72 profilometer short wavelength energy, \( W_{sw} \), and profile roughness, IRI; and (c) APL72 profilometer coefficient, CP2.5, and profile roughness, IRI.

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

\[
\text{BI (mm/km)} = 55 \cdot \text{QIM (counts/km)}
\]

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

\[
q = \frac{y_1/x_1}{y/x} = \frac{y}{x}
\]
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 (CP$_{25}$) 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 (3). 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 Q$_{lm}$ 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 ([1]). For the first three, PSR was related directly to the Q$_{lm}$ 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 Q$_{lm}$ = 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](image-url)
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 Q1 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:

\[ Q_{1m} = 72 \log_{10} \left( \frac{5.0}{SI} \right) \]

IRI = 5.5 \log_{10} \left( \frac{5.0}{SI} \right)

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

\[ Q_{1m} = \max \left( 136 - 33 \ SI; 0 \right) \]

IRI = \max \left( 10.5 - 2.5 SI; 0 \right)

The slope of the Q1m/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 \( Q_{1m} = 1.0 \) km/km IRI
- 2.5 PSI = 50 counts/km \( Q_{1m} = 3.8 \) km/km IRI
- 2.0 PSI = 65 counts/km \( Q_{1m} = 5.0 \) km/km IRI
- 1.5 PSI = 86 counts/km \( Q_{1m} = 6.6 \) km/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 one side of the chart, and for North American users, the equivalent reference scale in inches/mile units (IM) 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 Q1m scale, an estimated value of 70 counts/km Q1m 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, Q1m, BI, and IMo 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 Q1m, BI, 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, Q1m, CP2.5, IMo, 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 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 (Q1m, BI, Qm, and CP2.5), 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.
<table>
<thead>
<tr>
<th>IRI (m/km)</th>
<th>QHm (count/km)</th>
<th>Bt (mm/km)</th>
<th>CP2.5 (mm)</th>
<th>WSW</th>
<th>CAPL25</th>
<th>SI (PSI)</th>
<th>IM1 (in/mile)</th>
<th>IRI m/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

Notes:
- On the 3-line scales, the center line represents the estimated value, and the left and right margins represent the low (15th percentile) and high (85th percentile) limits of individual values about the estimated value.

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

2. QHm — Quarter-car Index of calibrated Maymeter, Brazil-UNDP Road Costs Study
   \( QHm = C_{Hm} / 13 + 0.37 / \text{IRI} \) \( \text{IRI} < 17 \)
3. Bt — Bump Integrator trailer at 32 km/h. Transport and Road Research Laboratory, UK
   \( Bt = 0.0032 \times \text{IRI} + 0.37 / \text{IRI} \) \( \text{IRI} < 17 \)
4. CP2.5 — Coefficient of planarity over 2.5m baseweight for APL72 Profilometer, Centre de Recherches Routiers, Belgium:
   \( \text{IRI} = CP2.5 \div 1.24 / \text{IRI} \) \( \text{IRI} < 11 \)
5. WSW — Short Wavelength Energy for APL72 Profilometer, Laboratoire Central des Ponts et Chaussées, France
   \( \text{IRI} = 0.79 \times \text{WSW} + 0.69 \times \text{IRI} \) \( \text{IRI} < 9 \)
6. CAPL25 — Coefficient of APL25 Profilometer, Laboratoire Central des Ponts et Chaussées, France:
   \( \text{IRI} = 0.45 \times \text{CAPL25} \times 10^{1.6} \) \( \text{IRI} < 11 \)
7. SI — Serviceability Index, American Association of State Highway and Transportation Officials:
   \( \text{IRI} = 5.5 \times (50 / \text{SI}) \times 0.25 \) \( \text{IRI} < 12 \)
8. IM1 — Inches/mile equivalent of IRI from Reference Quarter-Car Simulation of 50 mile/hr (see 'IRI-reference' in Gillespie, Sayers and Segel NCHRP report 228, 1980; and 'IRI' in Sayers, Gillespie and Queiroz, World Bank Technical Paper 45, 1986):
   \( \text{IRI} = IM1 / 0.35 \)

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

REFERENCES