Profiles of Roughness

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Road roughness is normally characterized by a summary index that applies over a length of road. Summary index measures are obtained most directly by measuring the longitudinal profile and then applying a mathematical analysis to reduce the profile to the roughness statistic. The moving average smoothing filter can be used to obtain a profile of one such roughness measure—the international roughness index (IRI). The roughness profile provides another dimension to the description of roughness, showing with maximum detail how the roughness is distributed over the length of the road. The baselength used for the IRI averaging must be considered. Specifying the baselength becomes particularly important when specifications for road quality are formulated, or when profiling accuracy is prescribed. That the variation in IRI found over the length of a road is more extreme when the baselength is short should be taken into account when reporting instrument accuracy or writing roughness specifications. Specifically, the accuracy of high-speed profiling systems should be specified according to baselength.

A standardized roughness measurement called the international roughness index (IRI) can be measured by either approach. The IRI was originally developed for the World Bank (3,4), on the basis of continuation of research that was begun in an NCHRP project (2). It is the only existing roughness index that has been demonstrated to be reproducible with a wide variety of equipment, including single- and two-track profiling systems, rod and level, and RTRRMSs. Since the World Bank published guidelines for conducting and calibrating roughness measurements, the IRI has been adopted as a standard for the FHWA Highway Performance Monitoring System (HPMS) data base (5), and is becoming a de facto standard in several countries, including the United States and Canada.

In the original World Bank guidelines, IRI roughness measuring methods were organized into the following four classifications:

Class 4—a roughness measure is not reproducible or stable with time, and can only be compared to IRI by subjective estimation. This class covers panel ratings and measures made with uncalibrated RTRRMSs.

Class 3—a measure obtained from an RTRRMS is calibrated to the IRI scale by correlation with reference measures from a Class 1 or 2 system.

Class 2—a profile-based method is used that is reproducible and stable with time, and that is calibrated independently of other roughness measuring instruments.

Class 1—a profile-based method similar to Class 2 is used. A profile-based measurement qualifies as a Class 1 measure if it is so accurate that further improvements in accuracy would not be apparent.

This classification was made to emphasize that different methods of measuring roughness on the same scale would have different levels of accuracy, where accuracy is quantified by the variation of a measure of IRI from the measure that would be obtained with a Class 1 method. The concepts of Classes 1 through 3 are repeated in the HPMS definitions (5).

Profile measuring equipment has been first viewed by many as a calibration reference for response-type systems. In fact, a primary consideration in designing the IRI was to devise a roughness index that showed maximum correlation with the RTRRMSs in use. (Other considerations, which are becoming more significant today, were that the IRI be a measure relevant to vehicle response, and measurable by existing and future profiling instruments.) However, as the profiling equipment grows more robust and becomes easier to operate, the RTRRMS is being dropped by some users due to the accuracy limitations and the great effort needed to obtain a valid
calibration. Profiling instruments are used to directly measure IRI over the road networks.

With the capabilities of profiling systems in mind, IRI can be used to quantify roughness of specific pavement events, such as intersections, railroad crossings, bridge approaches, and slab faulting. When analyzing such events, it is necessary to consider roughness over fairly short intervals, such as 50 ft or less. It will be shown that normal variations in roughness increase as the length of road being considered is reduced.

When profiling equipment is used to measure IRI, it is possible to view a profile of roughness, rather than a single index. For example, the PRORUT system owned by FHWA has this capability built in to its software (6, 7). The roughness profile is particularly relevant when roughness is used to specify (a) the quality of pavements after construction or repair, and (b) the accuracy of profiling equipment.

Using the concept of the roughness profile, this paper explores ways of dealing with the variation in roughness that exists in the road itself, over its length. The nature of these variations must be recognized and understood to specify roughness limits in roads and roughness instruments. For example, the distinction between Class 1 and 2 instruments is primarily that the first is the elevation profile, measured by most Class 1 and 2 systems. An example profile of this sort is shown in Figure 1. This particular profile was measured by the PRORUT instrument (6) on a badly damaged portland cement concrete (PCC) road as part of the 1984 Ann Arbor Road Profilometer Meeting (9). The visual appearance of the profile shape is dominated by long wavelengths that do not contribute much to vehicle vibrations. For example, the 2-in. change in elevation over 200 ft is almost imperceptible when traveling over the road. However, the spikes in the plot that occur every 80 ft or so are due to open gaps between PCC slabs, and these are apparent to traversing vehicles (and their occupants).

The IRI is a measure of slope. In the United States, it is common to apply units of in./mi to slope when it is used as a roughness numeric. The profile from Figure 1 is shown again as a slope profile in Figure 2. The conversion of the elevation profile to a slope profile is performed simply by taking the differences between adjacent elevation measures (in.), dividing by the sample interval (ft), and then converting to the desired units (multiplying by 5,280 ft/mi). As noted earlier, the true slope profile includes occurrences of infinite slope. The appearance of a measured profile of the sort shown here

**ROUGHNESS PROFILES**

Consider a roughness analysis of a single longitudinal profile of a traveled wheel track. Roughness is necessarily defined over an interval of profile. It is meaningless to talk of the roughness of a point. Instead, one must always consider roughness as a summary description of deviations that occur over an interval between two points.

Many of the basic techniques for reducing a profile to a single summary roughness have the following three steps in common (8):

Step 1. The profile is filtered spatially to remove wavelengths outside of a band of interest. Wavelengths within the band of interest are weighted by the mathematical properties of the roughness analysis algorithm. For the IRI and many other roughness analyses that have been used, this step is a linear transformation.

Step 2. The filtered profile is transformed to eliminate negative values. In most analyses, this transformation is accomplished either by squaring or taking the absolute values of the individual values.

Step 3. The processed profile is averaged to provide a summary index. If the transformation in Step 2 was squaring, a root-mean-square (RMS) value is obtained; if the transformation was absolute value, an average rectified (AR) value is obtained. (The IRI uses the latter method.)

The filtering of Step 1 is needed to remove influences of the profile measuring equipment. Without filtering, the true average elevation variance is generally determined by the length of the profile and whether it includes a hill. The true variance of slope and spatial acceleration is infinite. (A tiny crack, with a vertical wall, has an infinite slope. Infinity, of course, takes a long time to average out.)

After the processing of Step 2, the result is a profile that can be scaled with the units per length convention needed for the IRI and other roughness indices. When this scaling is done, the result is a rudimentary roughness profile that shows how the roughness is distributed over the length of the road.

There are three profiles that are relevant to the IRI scale. The first is the elevation profile, measured by most Class 1 and 2 systems. The visual appearance of the profile shape is dominated by long wavelengths that do not contribute much to vehicle vibrations. For example, the 2-in. change in elevation over 200 ft is almost imperceptible when traveling over the road. However, the spikes in the plot that occur every 80 ft or so are due to open gaps between PCC slabs, and these are apparent to traversing vehicles (and their occupants).

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**FIGURE 1** Elevation profile for faulted PCC, measured with PRORUT.

**FIGURE 2** Slope profile for same road.
is strongly influenced by the properties of the method used to obtain the measurement. This particular measurement was obtained using the PRORUT with a sample interval of about 3 in., and a low-pass (smoothing) antialiasing filter set at about a 1-ft wavelength. Thus, the amplitudes of the profile in Figure 2, which reach 5,000 in./mi, reflect a 1-ft wavelength limit. Higher amplitudes would be seen for the same road if the PRORUT had been run using a finer sample interval. (The cutoff wavelength of the PRORUT is always set automatically to about four times the sample interval.) Conversely, smaller amplitudes would be seen if the PRORUT had been run using a coarser interval.

The same slope profile was then filtered using the quarter-car analysis of the IRI. The filter has the spatial transfer function shown in Figure 3. After this filtering, the influence of the profiling system has been removed (assuming that the original measurement was valid over the range of wavelengths shown, covering about 3-ft waves to about 80-ft waves with good fidelity.) The resulting filtered profile is shown in Figure 4.

At this stage, the plotted profile amplitude differs from IRI only because it includes negative values. After the profile is rectified, the result is a plot of IRI at about 1-ft intervals down the road. Values range from 0 to 2,000 in./mi, depending on exactly which 1-ft interval is being considered. IRI would never be reported over such small intervals. As noted earlier, the typical length associated with a single IRI numeric (and virtually all other roughness indices that have been used in the past decades) ranges from 0.1 mi to several miles. In nearly all past uses before the PRORUT system, roughness statistics such as IRI were used to reduce a profile to a single numeric. However, a different method will be used now. Instead of reducing the profile, a moving average smoothing filter is used to obtain the same averaging, while retaining the representation of roughness as a continuous function of distance.

A moving average filter is applied to a point in a profile by averaging elevation over a baselength centered at the longitudinal location of the point of interest, as shown in Figure 5.

For example, consider a moving average of 100 ft, applied to a profile measured at intervals of 0.25 ft. The averaging covers 401 points. The first filtered value is the average of the first 401 profile values. The second filtered value is the average of the values going from number 2 to number 402. Each new point in the filtered profile is obtained by moving the start of the average by one sample.

Figure 6 shows how the roughness profile is smoothed by applying a moving average. The figure overlays four plots, each prepared using a moving average with a different baselength. As the baselength increases from 20 to 528 ft, the smoothing has a greater effect.

Because the moving average applies a simple unweighted average, every point shown in the plot is a valid IRI value for some interval of profile. For example, the first point for
the 528-ft average, shown at a location 264 ft into the profile, is the IRI for the interval going from 0 to 528 ft.

Note that with increasing baselength, some of the original profile is lost. Specifically, a length equal to the baselength of the moving average is lost. Figure 6 was prepared by plotting each point of the smoothed profile at the center of the averaging interval. Thus, the first value for the 528-ft average appears 264 ft from the beginning of the test site. Although not shown, the last plotted point appears 264 ft from the end of the test site. That is, half of the baselength is lost at each end.

Figure 6 shows directly how a choice of baselength influences the variation in roughness seen over a section of this road. Using a 528-ft average, the roughness ranges from 140 to 200 in./mi for 528-ft intervals lying in the first 1,268 ft of the test site. However, using a 20-ft average, the range covers about 50 to 700 in./mi. Also, when the baselength is 20 or 50 ft, the profile shows clearly that the road alternates between smooth and rough sections, with the smooth sections having a roughness level of about 100 in./mi.

This example is obviously one in which the roughness is localized and occurs mostly at the openings between the slabs of PCC. A similar plot is shown in Figure 7 for a much newer PCC road, in which the roughness is both lower and more uniformly distributed over length. In this figure, the entire measured length is included. Note that the longer averages cause the roughness profile to be shortened at the end also. Although a longer length is included in the plot than in Figure 6, the range of IRI is much less.

Roughness profiles can also be made for statistics that use the RMS averaging, although the processing and interpretation are more complicated. If a roughness profile is obtained for an RMS statistic, a choice must be made either to apply the simple moving average to the squared variable of interest and plot the profile of the squared index, or to apply the moving average to the squared variable and then plot the square root of each point.

![Image of IRI profile](image)

**FIGURE 7** Roughness profiles for new PCC road.

**CHOOSING AN APPROPRIATE BASELENGTH**

From the two examples shown in Figures 6 and 7, it is clear that different pictures of the road roughness are revealed by choosing different baselengths to prepare roughness profiles, even though all measures are on the same IRI roughness scale. Without averaging, IRI ranges from zero to about 2,000 in./mi for the faulted PCC (Figure 4) whose average over the 0.5-mi test site is about 170 in./mi. As the baselength increases (Figure 6), the IRI numbers approach the average for the entire site.

By choosing an appropriate baselength, the IRI can be used to either reveal or hide the variation in roughness over the length of the road.

When only averages of IRI numerics over long distances are considered, the detail provided by roughness profiles may not be required. However, when considering limit specifications of IRI, the choice of baselengths becomes critical. The previous examples show that the range of IRI values encountered over a length of profile increases as the baselength decreases. That is, a specification involving a specific value of IRI generally becomes more stringent when the baselength is decreased. This effect will be discussed for specifications of the pavement and for the equipment used to measure profile.

**Pavement Descriptions**

In determining what baselength to use, it is helpful to consider that the IRI analysis is a quarter-car analysis based on a simulated travel speed of 80 km/hr (49.7 mph = 73 ft/sec). The IRI filter responds to a bump after encountering it, just as a vehicle does. A singular event, such as a pothole, affects the vehicle vibration strongly for a few 10ths of a second. Lingering oscillations last about 1 sec. A baselength of 20 ft is suggested as a minimum for use with the IRI. (At the simulated speed, 20 ft corresponds to 0.27 sec.)

Ideally, the baselength used to prepare a roughness profile should correspond to the source of roughness that is of interest. If the concern is to obtain simply an average roughness over the miles of the network, a baselength of 528 ft or more is appropriate. However, if there is a need to discern specific events, a much shorter baselength is desirable. Ideally, the baselength should be smaller than the minimum distance between events, so that each event can be distinguished.

Table 1 presents the maximum roughness anywhere in the sites used for the two previous examples. For baselengths of 50 ft and longer, the measures from the site of Figure 7 are about 70 percent rougher than those from the site of Figure 6. However, for the 20-ft baselength, the maximum IRI from the faulted site jumps to being 344 percent higher.

**Pavement Specifications**

If roughness is used as a specification for pavement, the associated baselength is a major factor. Table 1 shows that (a) the maximum roughness expected in a site increases as the baselength is shortened, and (b) short baselengths can reveal highly localized roughness that might otherwise be lost in the averaging. One way to control both the overall quality of a
road and the roughness of short events is to specify roughness using two baselengths. For example, a 528-ft baselength would be used to set the overall quality (say, a maximum limit of 60 in./mi over 528 ft for new construction), and a 20-ft baselength would be used to guard against any sudden surprises (say, a maximum limit of 90 in./mi over 20 ft).

### Profile Measurement Specifications

Profile measurements are subject to error in the capabilities of the instrument and the operator. A direct way of specifying the accuracy of a profiling system is to perform the routine analyses of the profiles, and compare the results with reference measures. For example, if the profiles are mainly used to obtain IRI, then the overall accuracy of the system can be determined by comparing the IRI numerics obtained with the candidate system to those obtained by a reference.

The main difference between Classes 1 and 2 in the World Bank guidelines is in the reproducibility of a single measure of IRI. If the measure of IRI cannot be significantly improved, then the method is considered to fall in Class 1. Generally, this has been taken to mean high-precision static measurements. Profiles taken with high-speed profiling systems are not as repeatable and are considered Class 2. Also, profiles obtained statically with less precise specifications are considered Class 2.

In the 1984 Ann Arbor Profilometer Meeting, various profiling systems were compared, based on their abilities to measure IRI over 0.1-mi sections. For some of the systems, the limiting factor was the ability of the driver to follow exactly the same path in repeated tests. Even with experienced drivers operating under controlled conditions, it was common to find differences in the starting position of 50 to 100 ft laterally, and about 2 ft laterally. (Generally, each driver was repeatable to within 20 ft. However, when comparing driver A’s idea of the start to driver B’s idea, the 50 to 100 ft differences were observed.) The significance of this error can be viewed directly in the roughness profiles. In Figure 6, even a delay of 20 ft in the starting position causes a change in the IRI of up to 30 in./mi for certain 528-ft sections. (Compare the 528-ft section centered at 760 ft with that centered at 780 ft into the test site.)

When dealing with baselengths of 528 ft and less, any high-speed profiling system should be considered a Class 2 system because of the limits of the operator.

The baselength is a factor when considering the reproducibility of a roughness measurement. In past work (by this author, as well as others), comparisons are made by summary values tabulated for a number of test sites. The roughness profile provides a much better means for comparing two systems. The roughness profiles from two systems can be overlaid. If there is an offset in the starting point, it is immediately obvious. After adjusting the longitudinal positions to eliminate that source of error, the average and maximum differences observed between roughness profiles can be computed and used to define the accuracy limits of the system being validated.

There is presently not much data showing how accurate profiling systems are, or how the accuracy is influenced by measurement length. In future studies, the roughness profile should prove useful for better characterizing the performance of such systems.

### RECOMMENDATIONS

The roughness profile provides a detailed view of how roughness is distributed over the length of a road. Although a profiling system such as the PRORUT is needed to obtain a roughness profile, the profile is fully compatible with IRI numerics obtained from RTRMMS, and can be used to extend the information available about the road as new equipment becomes available. By overlaying roughness profiles for various baselengths, extra dimensions are added to the knowledge about the roughness state of a road.

When considering roughness specifications for contractors, the baselength should be considered and included explicitly in the specification. Short baselengths result in the specifications being more stringent.

When evaluating new profiling systems, or when characterizing the performance of existing systems, the roughness profile can show the reproducibility much more concisely than the methods of comparison used in the past. Also, operator error in starting the beginning of a test site is easily detected and corrected.

When baselengths of 528 ft and shorter are used to obtain IRI measurements, all high-speed profiling systems should be considered as Class 2 devices, due to limitations of the ability of the driver and the operator to cover exactly the same profile in repeated runs. With longer baselengths, it is possible that some high-speed systems could be considered as Class 1 devices.

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