Two Quarter-Car Models for Defining Road Roughness: IRI and HRI

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There is now a movement in the United States toward standardizing road roughness measurements by using a scale called the International Roughness Index (IRI). The IRI was defined by the World Bank (based on earlier work performed for the NCHRP) and is required by the Federal Highway Administration (FHWA) for the roughness database of the Highway Performance Monitoring System (HPMS). The IRI is defined as a roughness description for a single wheeltrack profile, obtained by using a quarter-car model with certain specified parameter values. A related roughness measure is obtained by using both wheeltrack profiles as inputs to the same computer algorithm used for the IRI. This analysis is mathematically equivalent to a half-car model and produces a roughness measure called the half-car roughness index (HRI). There is currently a mixture of IRI and HRI data being measured in the United States. The two analytic methods are so similar in concept that many practitioners are not aware of the difference between them. As a result, there has been occasional confusion and error when data are reported. The purpose of this paper is to identify and discuss the differences and similarities between IRI and HRI. The paper also summarizes technology used to measure IRI and HRI.

The past few years have seen a rapid expansion of the options available for measuring road roughness and longitudinal road profile. PSI, IN/MI, ARV, ARS, "Golden Car," IRI, RMSVA, M0, QI, RI, and PI are only a few of the names and acronyms that have crept into the literature as new measures are introduced and old measures are better understood. As methods have improved and the transition has begun toward standardization, there has understandably been confusion because the language has lagged behind the technology. For example, many users do not even have a name for their roughness measure; it is referred to simply by units, such as "in./mi."

The bulk of the roughness data collected in the United States is obtained with vehicles that are equipped with roadmeter devices, such as the Mays Ride Meter, the PCA meter, or a generic equivalent. The roadmeter accumulates vibrations as the vehicle responds to road roughness when driven at highway speeds. The measure from the roadmeter can be scaled to approximate an accumulated suspension movement for the vehicle, and then normalized by the distance traveled to obtain a roughness measure with units of slope, such as inches/mile or meters/kilometer. The vehicle and roadmeter together are called a response-type system.

The measures from almost any response-type system can be reported with the same engineering units (e.g., inches/mile), leading to a false sense of standardization among first-time users of these devices. In practice, the "roughness" measures are not highly reproducible when different vehicles, operating conditions, or times are being considered. Several large research programs have addressed this problem and clarified the relationships between alternative measurement methods (*1–3*). The research has shown that measures from dissimilar systems correlate with a variety of numerics that can be computed from measured profiles. Time stability and reproducibility are obtained by calibrating the measures from a response-type system to a rigorously defined mathematical function of profile. The key advantage of this method is that the profile-based reference measure is independent of the particular equipment used to measure the profile.

Profile-based numerics that are highly correlated with measures from response-type systems are now used (1) to calibrate response-type systems so that their measures are converted to a standard scale and (2) as a means for defining roughness for direct measurement using a high-speed profiling system. A review of the high-speed profiling systems that were used in the 1987 Federal Highway Administration (FHWA)/ Colorado Profiling Seminar (*4*) indicates that most of the systems report roughness using an analysis based on the IRI. Some of the profiling systems, however, use a nearly identical analysis method that is not the same as IRI; it is called the half-car roughness index (HRI) in this paper.

Currently, a mixture of IRI and HRI data is being measured with existing profiling systems in the United States. The purpose of this paper is to clarify the distinctions and similarities between the IRI analysis, the HRI analysis, and physical response-type systems.

Before delving into details of the analysis methods, several other popular roughness concepts are mentioned in the context of IRI and HRI.

- Present Serviceability Index (PSI) is the name of an estimate of panel rating for data from the original AASHTO experiment (*5*). Although numerous state agencies convert roughness data to units called "PSI" (a scale ranging from 0 to 5) based on correlations linked to the original experiments, no standardized PSI roughness scale is in existence. At the theoretical level, the problem with PSI is that there is no rigorous mathematical definition of PSI that can be used to validate equipment. At the practical level, the problem is that existing versions of "PSI" do not agree; different agencies measuring the same road at the same time have shown differences of more than 1 full PSI unit (*1*). A conversion between IRI and an average of several versions of PSI has been derived from several independent sources by Paterson (*6*) to provide an approximate link to the old PSI concept.

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- Recent NCHRP research on rideability has resulted in a new roughness statistic called profile index (PI) that has been correlated to panel ratings (*7*). PI is generally not well correlated with measures from response-type systems and, to the author's knowledge, has not yet been used outside of a few research projects.
- Rigid pavements are commonly evaluated immediately after curing with devices called profilographs. The measures from profilographs are also reported with units of slope (typically in./mi). However, the profilograph "in./mi" has little in common with the "in./mi" of the response-type system. Measures from different profilographs are not compatible. The development of calibration practices for these devices is a present research topic.

The preceding roughness measures are mentioned only to note that they are fundamentally different from the IRI and HRI, such that equivalences with the IRI and HRI roughness scales do not exist.

DEFINITIONS OF TERMS

Before discussing the physics of a moving vehicle responding to road roughness, it is important to distinguish between measures and methods, physical systems and mathematical models, and different models.

- A response-type system is a physical, mechanical system consisting of a vehicle that is instrumented with a roadmeter.
- ARS (average rectified slope) is the generic name of a measure that can be obtained from a response-type system or a vehicle model. This numeric is often left nameless, with users calling the measure by the name of the units, such as "in./mi." "ARS" is the name of the numeric, and "in./mi" are the units of ARS. (Of course, ARS could just as well be reported with other units, such as m/km, in./fathom, and so forth.)
- IRI (International Roughness Index) is a roughness scale defined as a specific mathematical property of a longitudinal profile. (The mathematical definition is presented later.) IRI can be obtained directly with a profile measurement system and suitable computer software. Alternatively, IRI can be estimated by transforming the measurement from a response-type system using a valid calibration equation.
- HRI (half-car roughness index) is a roughness scale similar to IRI except that it is defined as a specific mathematical property of a pair of longitudinal profiles.
- A quarter-car model is a mathematical model of a vehicle that represents a body and a single wheel.
- A half-car model is a mathematical model of a vehicle that represents a body and a single axle with two wheels.
- The Golden Car is a set of four parameter values that can be used with either of the preceding two models.
- The IRI analysis is the algorithm used to compute IRI from a longitudinal profile. This analysis produces the ARS from a quarter-car model using the Golden Car parameter values and a simulation speed of 49.7 mph (80.0 km/h).
- The HRI analysis is the algorithm used to compute HRI from two longitudinal profiles. This analysis produces the ARS from a half-car model using the Golden Car parameter values and a simulation speed of 49.7 mi/h (80.0 km/h). It is later shown that HRI is also obtained if the two profiles are first averaged into a single modal profile, which is then used as input to the IRI analysis.

HISTORY OF IRI AND HRI

The quarter-car model underlying the IRI and HRI analyses is widely used by vehicle analysts as a simple means to study alternative vehicle designs. The model also has a long history of use for characterizing road roughness, as summarized below.

In the late 1960s, General Motors (GM) developed a high-speed profiling system that could measure "true profile" over a range of wavelengths affecting vehicle vibrations (*8*). One of the first uses of profile data from that type of system was to use a quarter-car model to replicate the Bureau of Public Roads (BPR) Roughometer, a response-type system (*9*). The BPR Roughometer is a one-wheeled trailer with a roadmeter that represents an early attempt to standardize roughness measurements (*10*). Interestingly, two of the first profiling systems made outside of GM used different vehicle parameter values to describe the BPR Roughometer. Both sets of parameter values were measured in the laboratory for different BPR Roughometers and are listed by Gillespie et al. (*1*). This disparity illustrates the difficulty in standardizing roughness measures by standardizing hardware.

Early commercial versions of the GM-type profiling system included a quarter-car model as a means to summarize roughness of the measured profiles. The model was used with two sets of parameter values: one set for the BPR Roughometer and one set for a 1968 Chevrolet Impala (*11*).

Extensive tests in an NCHRP project using a four-wheel road simulator and a response-type system showed that a half-car model provided as good a reference as more comprehensive vehicle models. Copious computer simulations conducted in that study were used to select a set of parameter values for the model that would maximize the correlation for a variety of response-type systems based on the full spectrum of vehicles available in the United States. This set of parameter values is shown in Figure 1 and has sometimes been called the Golden Car vehicle parameter values. The same set now

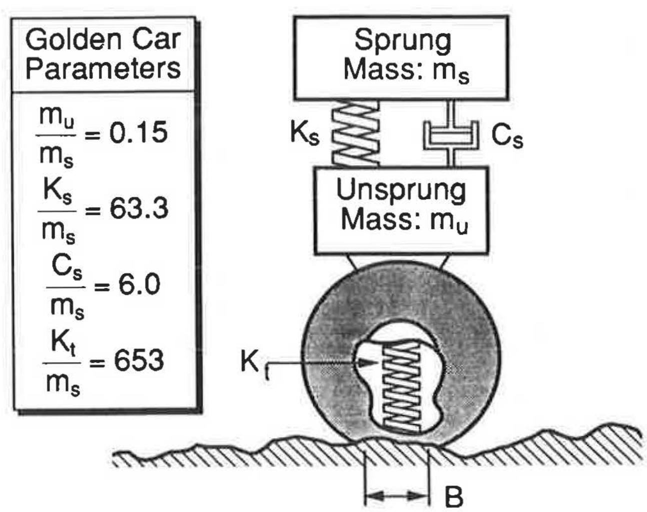

FIGURE 1 Quarter-car model.

appears (ASTM E1170) for a simulated response-type system identified as "Ride-Meter Vehicle-Mounted."

When the half-car model was tested in the NCHRP project with the Golden Car parameter values, the correlations between the profile-based measures and the various response-type systems were better than the correlations between the different response-type systems.

The calibration reference proposed in the NCHRP report is nearly identical to the HRI. The difference is that the NCHRP report did not specify a standard speed. (As defined later in this paper, the HRI applies only for a simulation speed of 49.7 mph (80 km/h).)

The International Road Roughness Experiment (IRRE) was initiated by the World Bank, funded by several countries, and held in Brasilia in 1982 to establish correlation and a calibration standard for roughness measurements (*2*). In this study, it became clear that nearly all roughness measuring equipment throughout the world was capable of producing measures on the same scale, if that scale were suitably selected. Accordingly, the IRI was developed to encourage standardization. The main criteria in designing the IRI were that it be relevant, transportable, and stable with time. To ensure transportability, it must be measurable with a wide range of equipment, including response-type systems. Numerous roughness definitions were considered by applying them to the large amount of test data obtained in the IRRE. The half-car analysis and Golden Car parameters from the NCHRP project were considered a candidate reference. However, some of the instruments measured the roughness in only one wheeltrack; therefore, a quarter-car model (together with the Golden Car parameter values) was also used.

With the half-car model, a single ARS number is obtained that describes both the left- and right-hand wheeltrack profile conditions as seen by a vehicle. With the quarter-car model, an ARS roughness level is determined separately for the left- and right-hand profiles. The ARS values obtained by simulating a quarter-car model over the two wheeltracks are averaged for comparison with the ARS measure obtained from instrumented passenger cars or two-wheeled trailers. Almost identical correlations with the response-type systems were obtained with the quarter-car and half-car models.

After all of the candidate roughness numerics were considered, the best correlations with the response-type systems were obtained with the quarter-car and half-car models, which gave essentially the same level of correlation. The single-track analysis was selected for the IRI, because it was measurable by a much wider range of equipment. The IRI was one of the few profile analyses that was well suited to all profiling methods that were in use at that time, including rod and level, profilometers based on the GM design, and the French APL trailer. (Some high-speed profiling systems do not measure both wheeltrack profiles and, therefore, cannot easily produce HRI.)

As a part of the IRRE, averages of the two IRI numerics for each test section were compared with HRI, as shown in Figure 2. The data showed the correlation between IRI and HRI to be almost perfect. Consequently, the two were equal in performance as a calibration reference for response-type systems.

Fairly complete guidelines were prepared by the World Bank for the calibration and use of road roughness measuring equipment using the IRI scale (*12*). Since then, the IRI has been adopted as a standard in several countries and is currently being evaluated as a candidate standard in many more.

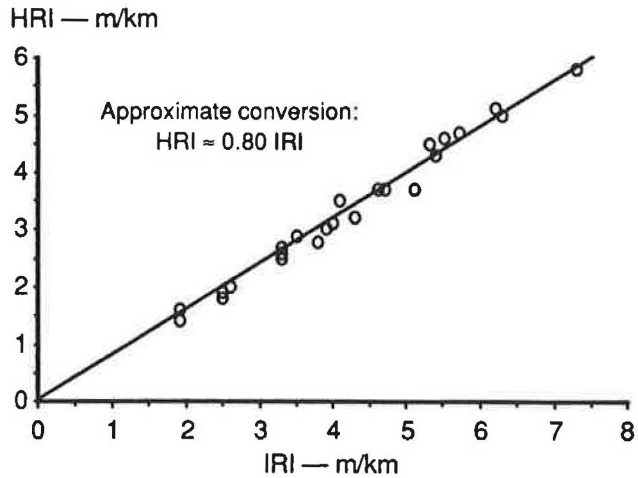

FIGURE 2 HRI—IRI correlation.

In the United States, the IRI has been established by the FHWA as a standard for the Highway Performance Monitoring System (HPMS) database. A condensed (and modified) version of World Bank Guidelines was prepared to help guide states in obtaining valid measures on the IRI scale (*13*). At the time of this writing, several ASTM task groups are incorporating the IRI into ASTM standards involving roughness measurement.

MATHEMATICAL DERIVATIONS

The roughness measure from a response-type system is conventionally divided by the length of the road measured to obtain a measure with units of roadmeter output per units of distance (*1, 14*). For an ideal roadmeter that accumulates displacement perfectly, the accumulation process consists of an integration of the absolute value of the derivative of suspension deflection − deflection velocity. That is, the ARS computed from a vehicle model is defined as

$$\text{ARS} = \frac{1}{L}\int_0^T |\dot{z}_u - \dot{z}_s|\, dt \tag{1}$$

where

ARS = average rectified slope,
T = time duration of test,
L = length of test,
$\dot{z}_u$ = vertical velocity of the unsprung mass (axle), and
$\dot{z}_s$ = vertical velocity of the sprung mass (vehicle body).

Most roadmeters have significant quantization and hysteresis properties that prevent them from measuring the true displacement and the true ARS (*1*). Nonetheless, for the sake of simplicity, the name "ARS" is used here also to describe the measure from a response-type system.

The vehicle models underlying the IRI and HRI roughness scales are defined by differential equations that relate motions of the simulated vehicle to road profile inputs. Even though the equations of motion for these models have been published time and time again, they are derived below to show how the quarter-car equations are used to simulate a half-car equipped with an idealized roadmeter.

Figure 1 shows a quarter-car model, in which the vertical movements of the body are represented by an element called the unsprung mass. The model includes the major dynamic effects that determine how roughness causes vibrations of the car body. It includes tire compliance, suspension stiffness and damping, and two masses. The equations are derived from Newton's second law, force = mass × acceleration. For the sprung mass, the vertical acceleration is related to vertical forces according to the relationship

$$m_s (\ddot{z}_s - g) = f_{susp} - f_g \qquad (2)$$

where

- $\ddot{z}_s$ = vertical acceleration (Time derivatives are indicated by dots over a variable. The two dots over z_s indicate a double derivative of the sprung mass position (z_s) with respect to time. The sprung mass velocity is written later as $\dot{z}_s$.);
- m_s = sprung mass (portion of mass of car body supported by one wheel);
- g = gravitational constant;
- f_{susp} = suspension force in addition to static load due to gravity; and
- f_g = static load due to gravity = $m_s g$.

The gravitational force and acceleration are constants that can be removed from the equation, leaving

$$m_s \ddot{z}_s = f_{susp} \qquad (3)$$

For the simplified mechanical system shown in the figure, the suspension force is the sum of a spring force and damper force. Using simple linear spring and damping components, k_s and c_s, respectively, gives

$$f_{susp} = k_s (z_u - z_s) + c_s (\dot{z}_u - \dot{z}_s) \qquad (4)$$

Combining Equations 2 and 3, an equation of motion is obtained:

$$m_s \ddot{z}_s + c_s (\dot{z}_s - \dot{z}_u) + k_s (z_s - z_u) = 0 \qquad (5)$$

A similar equation is obtained for the unsprung mass by considering the force from the suspension and also the tire (modeled as a linear spring with rate k_t):

$$m_u \ddot{z}_u + c_s (\dot{z}_u - \dot{z}_s) + k_s (z_u - z_s) = k_t (z_p - z_u) \qquad (6)$$

In Equation 6, m_u is the unsprung mass, defined as the mass of the wheel, tire, and half of the axle. Equations 5 and 6 are the equations of motion for the quarter-car model shown in the figure. As input, this model requires wheeltrack elevation as a function of time, designated by the variable z_p. As output, it predicts the displacement, vertical velocity, and vertical acceleration of the sprung and unsprung masses. The actual roughness index is the ARS as defined in Equation 1.

Figure 3 shows a more comprehensive vehicle model in which two inputs are allowed, corresponding to the left- and right- hand sides of the vehicle. With the gravitational terms removed, the vertical forces acting on the sprung and unsprung masses can again be set equal to mass × acceleration, with the results

$$2 m_s \ddot{z}_s + 2 c_s (\dot{z}_s - \dot{z}_u) + 2 k_s (z_s - z_u) = 0 \qquad (7)$$

$$2 m_u \ddot{z}_u + 2 c_s (\dot{z}_u - \dot{z}_s) + 2 k_s (z_u - z_s) = k_t (z_{p,right} + z_{p,left} - 2 z_u) \qquad (8)$$

where

- $z_{p,right}$ = road profile elevation on right-hand side and
- $z_{p,left}$ = road profile elevation on left-hand side.

As before, the sprung and unsprung masses correspond to the masses associated with one wheel. Note that the roll angles of the body and axle do not appear in either equation. Newton's second law, applied to a rigid body, involves only the vertical movements of the center of mass points for the two bodies and the vertical forces. This may appear surprising because the left- and right-hand spring, damper, and tire forces are all affected by roll of the vehicle body and axle. Indeed, the roll motions can influence the motions of every point in the bodies except for the center-of-mass points. However, noting that ARS is defined solely from the movements of these two points, it can be seen that Equations 7 and 8 are sufficient for computing the ARS of a half-car.

Note that Equations 7 and 8 (half-car) are nearly identical to Equations 5 and 6 (quarter-car). After canceling the factors of 2 in the half-car model, the equations are made identical

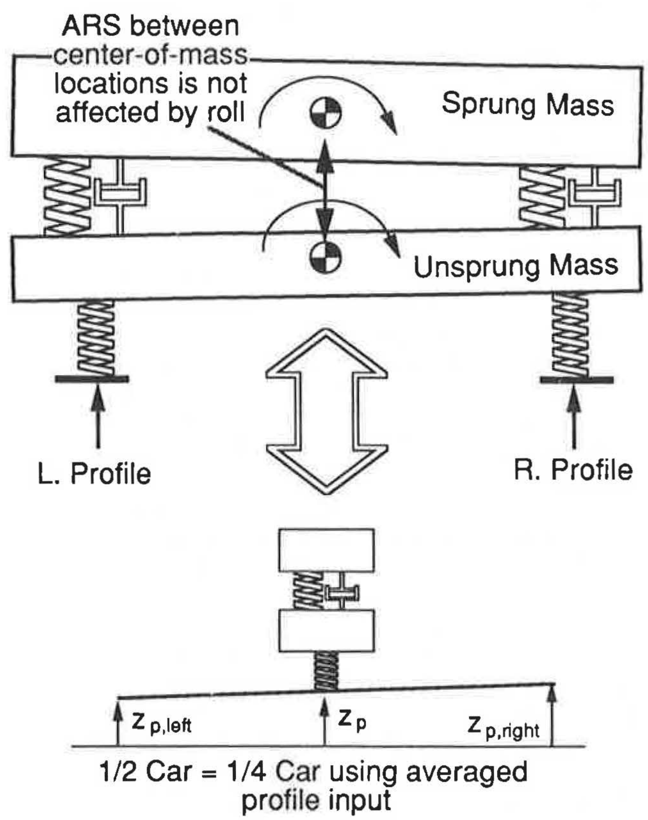

FIGURE 3 Half-car model.

by the substitution

$$z_p \leftarrow \frac{z_{p,\text{right}} + z_{p,\text{left}}}{2} \tag{9}$$

A geometric interpretation of the equivalence of the equations is shown in Figure 3. The prediction of the vertical movements of the center-of-mass locations of the sprung and unsprung masses using the half-car model is exactly the same as would be obtained using a quarter-car model, using as input the point-by-point average of the individual wheeltrack profiles.

The IRI analysis is a special case of the quarter-car model (Equations 5 and 6). It specifies the Golden Car parameter values shown in Figure 1, a simulated travel speed of 49.7 mph (80 km/h), and the ARS averaging (Equation 1). IRI is usually reported with units of m/km = mm/m, or in./mi. (Note: in./mi = m/km × 63.36.)

When the same process is applied to an averaged profile, the resulting ARS value is designated HRI.

To summarize, the IRI and HRI indices are both obtained by using the quarter-car analysis. The distinction is that the IRI is obtained by applying the quarter-car to a single wheeltrack profile (either $z_{p,\text{left}}$ or $z_{p,\text{right}}$), whereas the HRI is obtained by applying the quarter-car to a point-by-point average of two wheeltrack profiles [$z_p = (z_{p,\text{right}} + z_{p,\text{left}})/2$].

DIFFERENCES AND SIMILARITIES

A roughness index can be considered to derive from three considerations. These are listed below, in the context of the IRI and HRI.

1. How is the three-dimensional road surface measured for input to an analysis? Within the scope of this paper, this reduces to two options:
   a. Measure the longitudinal profile for a single wheeltrack, and use that profile as input to the roughness analysis (IRI).
   b. Measure a point-by-point average of the profiles in two traveled wheeltracks, and use that averaged profile as input to the roughness analysis (HRI).
2. How are wavelengths in the profile weighted? In other words, how is the profile spatially filtered? For both the IRI and HRI, the filter is the quarter-car model, using the Golden Car parameter values and a simulation speed of 49.7 mph (80 km/h).
3. What averaging method is used to accumulate the filtered profile to produce a single roughness numeric? For both the IRI and HRI, ARS (Equation 1) is used.

The IRI and HRI analyses differ only in how a profile is defined for input to the quarter-car filter. Ultimately, any similarities and differences between IRI and HRI derive from the similarities and differences in the two types of profiles. A detailed presentation of the relationships between the roughnesses in a single wheeltrack profile is available elsewhere (*15*). A few essential points are repeated below, to establish limits for relationships between the roughness of individual wheeltracks and an averaged profile.

Theoretical Relations Between Averaged Profiles and Wheeltrack Profiles

Profiles can be viewed in the frequency domain, as "amplitude" versus wavenumber (wavenumber = 1/wavelength), using the power spectral density (PSD) function. Correlations between profiles can also be viewed as a function of wavenumber, using the coherence function. When viewed in this way, the correlation between the left- and right-hand wheeltrack profiles changes drastically with wavenumber. For very long wavelengths, there is perfect coherence because the left- and right-hand wheeltracks must go up and down together (in-phase) over hills and valleys. (This hypothesis can be false only for an unrealistic condition in which the elevations of the left- and right-hand wheeltracks differ by several feet or more.) Hence, the average of the two profiles is equal to the individual wheeltrack profiles:

$$G_p(\nu) = G_{p,\text{left}}(\nu) = G_{p,\text{right}}(\nu) \tag{10}$$

valid for very long wavelengths, $\nu \to 0$

where

G = PSD amplitude at a given wavenumber, and
ν = wavenumber = 1/wavelength.

For very short wavelengths, the coherence approaches zero because the profile features contributing to texture have no point-by-point relationship. That is, they have random phase. (This hypothesis can be false only for the unrealistic condition in which the texture details in one wheeltrack are systematically related to corresponding details in the other wheeltrack. For most types of pavement, when the right-hand profile goes up over a tiny bump in the texture with a length of 0.1 in., the left-hand profile is equally likely to be going up or down.)

The mean-square value for the sum of two uncorrelated, zero-mean random variables is the sum of their variances. To prove this, consider two random variables X_1 and X_2 with variances $\sigma^2_{X_1}$ and $\sigma^2_{X_2}$, mean values of zero, a correlation coefficient $r = 0$, and their sum, Y:

$$Y = X_1 + X_2 \tag{11}$$

The expected value of Y^2, designated by the "expected value" operator, E, is

$$E[Y^2] = E[(X_1 + X_2)^2] = E[X_1^2 + 2\,X_1\,X_2 + X_2^2] = E[X_1^2] + E\,[2\,X_1\,X_2] + E[X_2^2]$$

$$= \sigma^2_{X_1} + 2\,\cancel{r}^{\,0}\,(\sigma_{X_1}\sigma_{X_2})^{1/2} + \sigma^2_{X_2}$$
$$= \sigma^2_{X_1} + \sigma^2_{X_2} \tag{12}$$

Because the PSD function is a distribution of variance over wavenumber, the same relationship holds for the sum of two random signals whose coherence function is zero. Thus,

$$G_p(\nu) = \frac{1}{4}G_{p,\text{left}}(\nu) + \frac{1}{4}\,G_{p,\text{right}}(\nu) \tag{13}$$

valid for very short wavelengths, $\nu \to \infty$

A factor of 4 appears because the averaging involves division by 2, and $2^2 = 4$.

In the case of wheeltrack profiles with the same overall roughness levels (the mean-square values of the two uncorrelated random variables are the same), the mean-square of the sum is twice the mean-square of one side:

$$G_p(\nu) = \frac{1}{2} G_{p,\mathrm{left}}(\nu) = \frac{1}{2} G_{p,\mathrm{right}}(\nu) \tag{14}$$

valid for very short wavelengths, $\nu \rightarrow \infty$

The square roots of the relations of Equations 10 and 14 indicate the limiting relationship between nonsquared roughness values of individual wheeltracks and an averaged profile. For very short wavelengths, the roughness amplitude of the averaged profile is $(1/2)^{1/2} = .707$ of the amplitude of a single wheeltrack profile.

In summary, the limiting relationships between roughness of an averaged profile and individual wheeltrack profiles are:

- For very long wavelengths, the roughness is the same.
- For very short wavelengths, the roughness of the averaged profile is 29 percent lower (0.707) than the roughness of an individual wheeltrack profile.
- Between the "very long" and the "very short" wavelengths, the averaged profile exhibits roughness lower than the average of the roughness values for the individual wheeltrack profiles, by an amount lying between 0 and 29 percent.

Therefore, a bracketing relation is expected between IRI and HRI:

$$.71 \frac{\mathrm{IRI}_{\mathrm{left}} + \mathrm{IRI}_{\mathrm{right}}}{2} < \mathrm{HRI} < \frac{\mathrm{IRI}_{\mathrm{left}} + \mathrm{IRI}_{\mathrm{right}}}{2} \tag{15}$$

Physically, the foregoing results mean that some of the roughness in the left- and right-hand wheeltracks cancels. The roughness that cancels causes roll motions in a vehicle, which are not detected by a roadmeter located at the center.

Relations Between the Two Types of Profile on Real Roads

Virtually all of the wavelengths contributing to IRI and HRI lie between the limits deduced in the preceding theoretical analysis. The exact relationship between the types of profile is itself a property of a road surface. The data collected in the Brazilian experiment (the IRRE) covered asphalt, surface treatment, gravel, and dirt roads. Figure 2 shows that excellent correlation was found for that range of conditions. An empirical relation between the two was derived from paved test sites used for the Brazil experiment:

$$\mathrm{HRI} \approx 0.80 \frac{\mathrm{IRI}_{\mathrm{left}} + \mathrm{IRI}_{\mathrm{right}}}{2} \tag{16}$$

When the unpaved roads are also included, a slightly lower ratio of 0.76 was found (*2*), indicating slightly less coherence between the two wheeltrack profiles.

A similar analysis has not been performed for rigid pavements. Measurements show that the relationships between the two types of profiles are substantially different for PCC roads (*15*). A significant part of the roughness was derived from misalignment at the joints between slabs. This type of roughness tends to appear identically in both the left- and right-hand wheeltrack profiles. Even when the roughness is greater in one wheeltrack, the disturbance occurs in the same place in both, so they are in phase and thus highly correlated. The effect on vehicles is that they receive less roll input for the amount of roughness on PCC roads than on asphalt roads. Consequently, the HRI is closer in amplitude to the average of the two IRI values, and a ratio of approximately 0.90 is expected.

Practical Interpretation of the Differences Between HRI and IRI

The (slight) difference between IRI and HRI is partly derived from seeing roughness from the perspective of different points in a vehicle. The IRI more closely indicates vehicle response at the wheels, while the HRI more closely indicates response of the vehicle at its center. Thus, the IRI could be viewed as a marginally better indicator of vehicle suspension wear, pavement loading, and adhesion utilization, because these measures all depend mainly on the dynamic response of a single wheel. HRI unquestionably offers a better representation of a two-track vehicle (passenger car or two-wheeled trailer) equipped with a roadmeter when the roadmeter is mounted over the center of an axle. It is not clear which is the better indicator of cargo damage and ride quality, as this depends on how the roll dynamics contribute to the vibrations of the sprung mass away from the centerline of the vehicle.

IRI might be viewed as a potentially more useful roughness index simply because it can provide roughness levels separately for left- and right-hand wheeltracks, to show how one side of a lane has deteriorated more than the other. The HRI cannot be used for this purpose; neither, however, can most response-type systems now in use. The potential advantage of the IRI mainly applies to high-speed profiling systems.

The major practical consideration is simply which is more convenient to measure and to relate to other data. Some profiling systems can measure IRI but not HRI; others can measure HRI but not IRI. An agency that has been measuring a reproducible index for the past 5 years will probably prefer to continue using that index unless there is a truly compelling reason to switch.

Automated Profiling Systems

In 1984, a profilometer meeting was held in Ann Arbor, Michigan, for the purpose of determining the performance capabilities of numerous profiling systems in use at that time (*16*). Nearly all of the high-speed profilometers in use in North America participated. At that time, only a few of the systems had software to compute quarter-car numerics routinely. Since then, software options have been added, and other profiling systems have been developed. The situation today is that nearly all of the automated profiling systems used in North America include some form of quarter-car analysis, and they are most commonly used to measure IRI or HRI (*4*). Some of these systems are listed in Table 1 to indicate whether they currently measure IRI and/or HRI.

The table also indicates the principles upon which the systems operate. Reference is made to four designs, which have been used or demonstrated in the United States.

TABLE 1 SUMMARY OF AUTOMATED PROFILING SYSTEMS AND ASSOCIATED QUARTER-CAR ANALYSES

Profiling System	Developer	Design	Quarter-car
APL	French Bridge and Pavement Laboratory (LCPC) and MAP Sarl, Illfurth, France	.APL	IRI
Dipstick	Edward W. Face Company Norfolk, VA	Static Level	IRI
ARAN with profile option	Highway Products International Paris, Ontario, Canada	2-accel.	HRI
PURD with profile option	Highway Products International Paris, Ontario, Canada	2-accel.	HRI
690 DNC Profilometer	K. J. Law Engineers, Inc. Farmington Hills, MI	GM	IRI, HRI
8300 Roughness Surveyor	K. J. Law Engineers, Inc. Farmington Hills, MI	GM	IRI
S. Dakota Profiling System	S. Dakota DOT Research Program Pierre, SD	GM	IRI
PRORUT	Univ. of Mich. and FHWA McLean, VA	GM	IRI
Laser Road Surface Tester (RST)	Swedish National Road and Traffic Institute (VTI) and Infrastructure Management Services (IMS), Arlington Heights, IL	GM	IRI

- GM-type inertial profiling system: This is the design developed by Spangler and Kelly at General Motors Research Laboratories around 30 years ago (*8*). In this design, the vertical motions of the moving vehicle are sensed with an accelerometer and processed to obtain the vertical position of the vehicle relative to an inertial reference. The distance between the vehicle and the ground surface is also measured and is subtracted from the inertial height of the vehicle. Originally, vehicle-to-ground distance was measured with an instrumented follower wheel. In most modern systems, this distance is measured with a noncontacting transducer.
- Two-accelerometer inertial profiling system: This design by Sayers and Gillespie (*17*) requires two accelerometers installed in a vehicle with a beam axle. One of the accelerometers is mounted on top of the axle at the center. The second accelerometer is mounted in the body of the vehicle, directly above the center of the axle. The two accelerometer signals are processed to cancel the suspension effects, so that the linear spring properties of the tires are used to sense the vehicle-to-ground distance required to measured profile.
- French APL inertial profiling trailer (*18*): In this design, an isolated rotational pendulum provides an inertial reference. The pendulum is supported by a one-wheeled trailer. Profile is measured directly as a displacement of a linkage relative to the pendulum.
- Proprietary "Dipstick" static leveling method, originally used for measuring floor flatness in constructions.

The GM, APL, and Dipstick designs measure a single profile and are well suited for obtaining IRI measures. To measure HRI, the vehicle-based systems must include separate sets of transducers for the right- and left-hand wheeltracks. The outputs of each set of transducers must be precisely synchronized and averaged at every profile measurement point to obtain HRI. (For the static Dipstick method, HRI would be obtained by measuring the two wheeltrack profiles consecutively and using new software to perform the point-by-point averaging of the two profiles.) The two-accelerometer design inherently measures the average of the two profiles traversed by the tires of the test vehicle and is thus well suited for measuring HRI.

SUMMARY AND CONCLUSIONS

Most of the automated profiling systems used in North America include a quarter-car analysis as a means of summarizing roughness. Systems that measure a single wheeltrack profile can measure roughness on the IRI scale. Systems that can measure the point-by-point average of the two traveled wheeltracks can measure roughness on the HRI scale. The HRI from two wheeltrack profiles is always lower than the average of the IRIs from the two wheeltracks, because some of the roughness is canceled in the HRI analysis. Most of the time, the IRI and HRI measures are very highly correlated. Existing data for asphalt roads suggest an approximate relationship:

$$\text{HRI} \approx 0.8 \text{ IRI}$$

There are subtle theoretical differences in how the two are interpreted. The distinctions are so slight, however, that the choice of which to measure should be largely determined by practical considerations.

There has been confusion between the two because of limits in terminology; the name "quarter-car" alone does not distinguish which version is used. (For example, the data from at least one of the profiling systems involved in the 1987 Colorado Profiling Seminar are labeled incorrectly in the final report.) Users of a quarter-car analysis should be aware of which type they are using and should clarify this when reporting roughness data to others. As defined by the World Bank, the name "IRI" refers to ARS as computed with a quarter-car model for a single wheeltrack profile using the "Golden Car" parameter values and a simulation speed of 49.7 mph (80 km/h). The name "HRI" is suggested for use of the same analysis applied to an averaged profile.

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Publication of this paper sponsored by Committee on Surface Properties–Vehicle Interaction.