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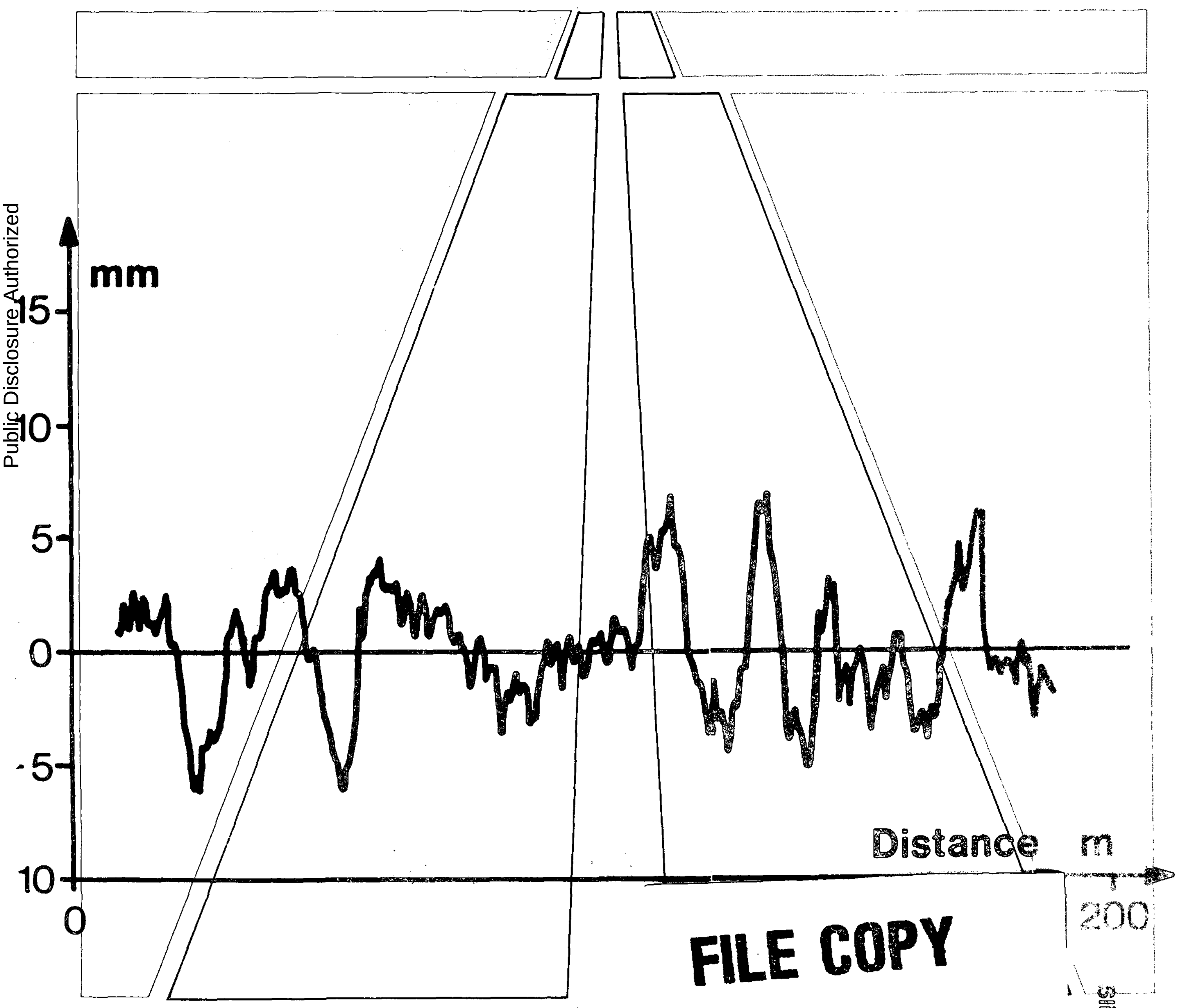
Guidelines for Conducting and Calibrating Road Roughness Measurements

Michael W. Sayers, Thomas D. Gillespie, and William D. O. Paterson



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Michael W. Sayers is assistant research scientist and Thomas D. Gillespie is research scientist at the Transportation Research Institute of the University of Michigan in Ann Arbor. William D. O. Paterson is senior highway engineer with the Transportation Department of the World Bank.

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ABSTRACT

Road roughness is gaining increasing importance as an indicator of road condition, both in terms of road pavement performance, and as a major determinant of road user costs. This need to measure roughness has brought a plethora of instruments on the market, covering the range from rather simple devices to quite complicated systems. The difficulty is the correlation and transferability of measures from various instruments and the calibration to a common scale, a situation that is exacerbated through a large number of factors that cause variations between readings of similar instruments, and even for the same instrument. This need to correlate and calibrate led to the International Road Roughness Experiment (IRRE) in Brazil in 1982, which is documented in a companion volume in this Series, entitled The International Road Roughness Experiment: Establishing Correlation and a Calibration Standard for Measurements (World Bank Technical Paper Number 45).

This paper defines roughness measurement systems hierachically into four groups, ranging from profilometric methods (2 groups) - being accurate and most amenable to detailed analysis - through response-type road roughness measuring systems (RTRRMS's) - representing the most widely used, practical and fast instruments - to subjective evaluation - allowing assessments to be made without use of instruments. The general planning of road roughness measurement programs is outlined, as well as the criteria for selection of measurement system to meet the objective. The procedures for carrying out surveys in the four groups of systems are explained, including instrument characteristics, the need for adequate checking and verification, and the importance of travelling speed, as well as the methodology for data analysis.

The international Roughness Index (IRI) is defined, and the programs for its calculation are provided. The IRI is based on simulation of the roughness response of a car travelling at 80 km/h - it is the Reference Average Rectified Slope, which expresses a ratio of the accumulated suspension motion of a vehicle, divided by the distance travelled during the test. The report explains how all roughness measurements can be related to this scale, also when travelling at lower speeds than 80 km/h. The IRI therefore emerges as a scale that can be used both for calibration and for comparative purposes.

ACKNOWLEDGEMENTS

These guidelines have their technical foundations in the published findings of two major research projects:

The international Road Roughness Experiment (IRRE) [1], held in Brasilia in 1982, and funded by a number of agencies, including the Brazilian Transportation Planning Company (GEIPOT), The Brazilian Road Research Institute (IPR/DNER), the World Bank (IBRD), the French Bridge and Pavement Laboratory (LCPC), and the British Transport and Road Research Laboratory (TRRL); and

The NCHRP (National Cooperative Highway Research Program) Project 1-18, documented by NCHRP Report No. 228 [2].

Per Fossberg (IBRD) and Cesar Queiroz (IPR/DNER) are acknowledged for their contributions in the development of these guidelines. Also, grateful acknowledgement is extended to Clell Harral (IBRD), who conceived the idea of the IRRE and arranged for the participation of the various agencies and the subsequent preparation of these guidelines.

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CHAPTER 1

SCOPE

This document presents guidelines for use by personnel in highway organizations responsible for setting up or operating road roughness monitoring programs. It provides guidance on:

* Choosing a method for measuring road roughness;

* Calibrating the measurement equipment to a standard roughness scale;

* Using procedures that ensure reliable measurements in routine daily use.

The suggestions and procedures presented here are intended to guide the practitioner in acquiring road roughness data from which to build a roughness data base for a road network. Adherence to these guidelines will help ensure:

* That the roughness data indicate road condition as it affects using vehicles in terms of ride quality, user cost, and safety;

* That data acquired in routine measurement operations will be related to a standard roughness scale, and that erroneous data can be identified prior to entry into the data base;

* That the roughness data can be compared directly to data acquired by other highway organizations also following the guidelines; and

* That the roughness measures have the same meaning on all types of roads used by highway trucks and passenger cars, including asphalt, concrete, surface treatment, gravel, and earth surfaces.

The procedures presented in this document are primarily applicable to roughness measurements of two types:

* Direct measurement of roughness on the standard scale, derived from the longitudinal profile of the road

* Estimation of the standard roughness measure, using calibrated response-type road roughness measurement systems (RTRRMSs)

CHAPTER 2

PLANNING A ROUGHNESS MEASUREMENT PROJECT

The design of a project for surveying the roughness of a road network should start with a clear understanding of the objectives to be achieved from the measurement effort. A substantial investment of manpower and money can be consumed in a typical project, thus it is desirable to design the program carefully. The design itself is a synthesis process taking into account the project goals, the resources available, and the environment of the project. Perhaps the most critical element in the design is the selection of a roughness measurement method that is practicable, yet suitably accurate for the purposes of the project. This section reviews the various measurement methods available, classified according to how directly they measure roughness on a standard scale (Generally, the more direct methods are also the most accurate). In addition, it explains the types of errors to be anticipated, and their importance to various kinds of measurement projects.

2.1 Overview of the IRI Road Roughness Scale

In order to address specifics of roughness measurement, or issues of accuracy, it is first necessary to define the roughness scale. In the interest of encouraging use of a common roughness measure in all significant projects throughout the world, an International Roughness Index (IRI) has been selected. The IRI is so-named because it was a product of the International Road Roughness Experiment (IRRE), conducted by research teams from Brazil, England, France, the United States, and Belgium for the purpose of identifying such an index. The IRRE was held in Brasilia, Brazil in 1982 [1] and involved the controlled measurement of road roughness for a number of roads under a variety of conditions and by a variety of instruments and methods. The roughness scale selected as the IRI was the one that best satisfied the criteria of being time-stable, transportable, and relevant, while also being readily measurable by all practitioners

The IRI is a standardized roughness measurement related to those obtained by response-type road roughness measurement systems (RTRRMS), with recommended units: meters per kilometer (m/km) = millimeters per meter (mm/m) = slope x 1000. The measure obtained from a RTRRMS is called either by its technical name of average rectified slope (ARS), or more commonly, by the units used (mm/km, in/mi, etc.). The ARS measure is a ratio of the accumulated suspension motion of a vehicle (in, mm, etc.), divided by the distance travelled by the vehicle during the test (mi, km, etc.). The reference RTRRMS used for the IRI is a mathematical model, rather than a mechanical system, and exists as a computation procedure applied to a measured profile. The computation procedure is called a quarter-car simulation (QCS), because the mathematical model represents a RTRRMS having a single wheel, such as the BI Trailer and BPR Roughometer. When obtained from the reference simulation, the measure is called reference ARS (RARS). This type of measure varies with the speed of the vehicle, and therefore, a standard speed of 80 km/h is specified in the definition of the IRI. Thus, the more technical name for the IRI is $RARS_{80}$, indicating a measure of average rectified slope (ARS) from a reference (R) instrument at a speed of 80 km/h.

The mathematical vehicle model used to define the IRI is the same as that described in the 1981 NCHRP Report 228 [2], with the single difference that the IRI is computed independently for each wheeltrack. (The model in NCHRP Report 228 was computed for two wheeltracks simultaneously, thus replicating the performance of a RTRRMS based on a passenger car, or a two-wheel trailer.) The IRI version is more transportable, and was demonstrated as yielding RTRRMS accuracy just as high as the NCHRP version for all types of RTRRMSs.

The IRI is defined as a characteristic of the longitudinal profile of a travelled wheeltrack, rather than as a characteristic of a piece of hardware, in order to ensure time stability. Thus, direct measurement of the IRI requires that the profile of the wheeltrack be obtained.

The particular profile characteristic that defines the IRI was demonstrated to be directly measurable by most profilometric methods (more than any of the other profile-based roughness numerics that were considered in the IRRE). At the same time, the IRI profile characteristic is so highly compatible with the measures obtained by RTRRMSs that these instruments can be calibrated to the IRI scale to achieve the best (or close to the best) accuracy that is possible with this type of instrument. The IRI is also strongly related to the subjective opinions about road roughness that can be obtained from the public. Because the IRI is (1) measurable by many profilometric methods, (2) highly correlated with the measures from RTRRMSs, and (3) highly correlated with subjective opinion, it is a highly transportable scale.

Figure 1 shows the approximate range of IRI roughness on different types of roads.

It should be recognized that the IRI is a numeric that summarizes the roughness qualities impacting on vehicle response, but which may not be the most appropriate for other applications. More specifically, the IRI is appropriate when a roughness measure is desired that relates to:

* overall vehicle operating cost

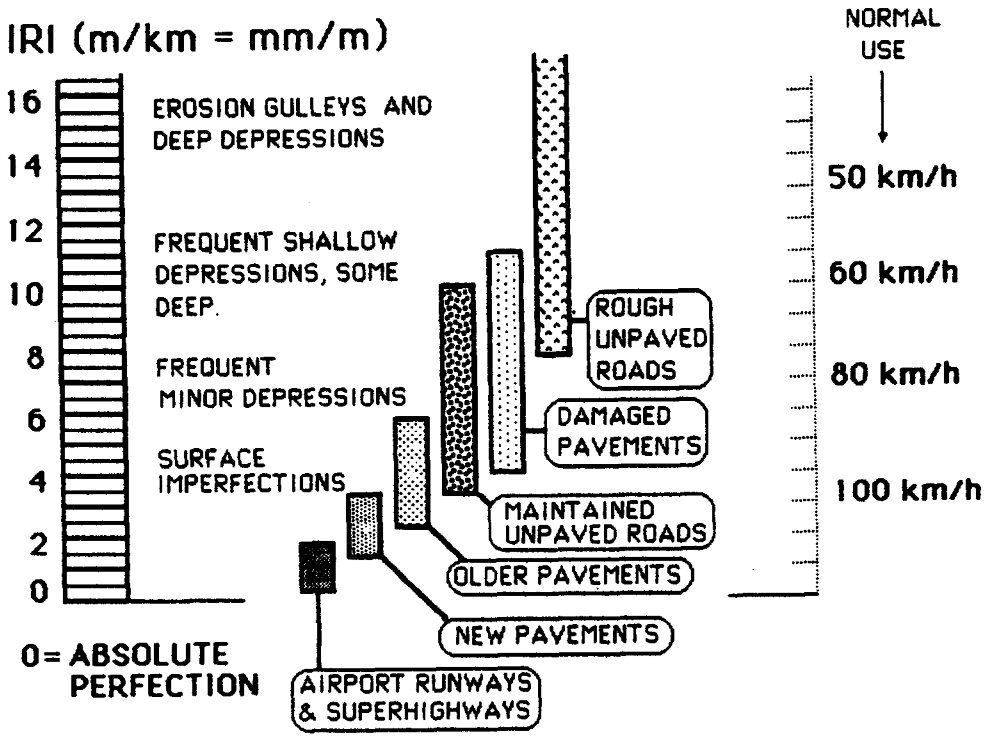

Fig. 1. The IRI roughness scale.

* overall ride quality

* dynamic wheel loads (damage to the road from heavy trucks; braking and cornering safety limits available to passenger cars)

* overall surface condition

The IRI is also recommended whenever the measurements will be obtained using a RTRRMS at highway speeds (50 - 100 km/h), regardless of the use made of the data.

However, when profilometric methods are used to measure wheeltrack roughness, then other measures may serve as better indicators for some qualities of pavement condition, or for specific components of vehicle response encompassed by the IRI. These guidelines address only the measurement and estimation of the IRI.

2.2 Roughness Measurement Methods

The many approaches for measuring road roughness in use throughout the world can be grouped into four generic classes on the basis of how directly their measures pertain to the IRI, which in turn affects the calibration requirements and the accuracy associated with their use.

2.2.1 Class 1: Precision profiles. This class represents the highest standards of accuracy for measurement of IRI. A Class 1 method requires that the longitudinal profile of a wheeltrack be measured (as a series of accurate elevation points closely-spaced along the travelled wheelpath) as a basis for calculating the IRI value. For static profilometric methods, the distance between samples should be no greater than 250 mm (4 measures/meter) and the precision in the elevation measures must be 0.5 mm for very smooth pavements. (Less precise measurements are acceptable for rougher surfaces, as specified in Section 3.2.) High-speed profilometers offer a potential means for measuring IRI quickly; however, the profilometer must be validated at some time against an established procedure such as rod and level to prove its accuracy. At the present time, only rod and level (Section 3.3.1) and the TRRL Beam (Section 3.3.2) methods have been demonstrated to be valid Class 1 methods for determining IRI over a broad range of roughness levels and road types for the 320 m site length used in the IRRE.

Methods in this class are those that produce measures of such high quality that reproducibility of the IRI numeric could not be improved. While this definition might at first appear to imply an unreachable ideal, there is usually a practical limit to the repeatability that can be obtained in measuring road roughness, even with a "perfect" method and/or instrument. The practical limit results from the inability to measure roughness repeatedly in exactly the same wheeltrack. Therefore, a method qualifies as Class 1 if measurement error is negligible in comparison with the uncertainty associated with trying to locate exactly the same wheeltrack twice.

In the IRRE the methods found to qualify as Class 1 had negligible measurement error for sites 320 m long, when the wheeltracks were marked with painted reference spots spaced at about 20 m intervals. The repeatability under these conditions is about 0.3 m/km IRI on paved roads, and about 0.5 m/km for all other road types. For wheelpaths marked even more precisely, methods described in these guidelines as Class 1 could perhaps not qualify as Class 1 (although it is uncommon to have an application where such a high level of accuracy is needed). On the other hand, less stringent specifications might be suitable if longer test sites were used, or if the wheeltracks were not marked at all.

In many cases, a method that yields this level of accuracy will have an associated disadvantage of requiring a great deal of effort to make the roughness measurement (for example, by the rod and level method). The accuracy obtained using a Class 1 method by definition matches or exceeds the requirements of a given application, and thus the Class 1 method is viewed as having primary utility for validating other methods, or when special high-accuracy data are required.

2.2.2 Class 2: Other profilometric methods. This class includes all other methods in which profile is measured as the basis for direct computation of the IRI, but which are not capable of the accuracy required for a Class 1 measurement. Though the hardware and methods used for profile measurement are functionally verified by an independent calibration process, they are limited to accuracy or bandwidth less than that needed to qualify as a Class 1 method. Consequently, the IRI value computed from a Class 2 profile measurement may not be accurate to the practical limit due to random or bias errors over some range of conditions. This class presently includes IRI values computed from profiles measured with high-speed profilometers and with static methods that do not satisfy the precision and/or measurement interval requirements specified in Section 3.2.

At the present time, the APL Trailer (Section 3.3.3) is the only dynamic profilometer that has been experimentally validated over the range of roughness covered in the IRRE. The GMR-type Inertial Profilometer with follower wheels has been validated for roads with roughness levels less than an IRI value of about 3 m/km [2], above which errors are introduced due to bounce of the follower wheels. This type of design is no longer commercially available in the United States, however, as the follower wheels have been replaced with non-contacting sensors to eliminate the bounce problem. Two high-speed profilometers are presently sold by K.J. Law, Inc. (Section 3.3.4), and both are designed to provide the IRI roughness during measurement. Both are considered as Class 2 systems at this time, although their accuracy and range of operation have not been verified against rod and level yet. Tests with these and other profilometers have been performed, but the analyses of the data have not yet been completed sufficiently to quantify their ability to measure IRI[1].

High-speed profilometers have the disadvantage of being the most expensive and complex instrumentation systems used to measure road roughness, and generally require operators with engineering training. Yet, they offer a great advantage in being able to obtain high-quality measurements rapidly, without requiring that great effort be spent in maintaining calibration. Detailed procedures for operating a profilometer to measure IRI are highly specific to the design of the profilometer; hence, the manufacturer should be consulted. Sections 3.3.3 and 3.3.4 briefly describe several of the high-speed profilometers that have been used to measure IRI.

2.2.3 Class 3: IRI estimates from correlation equations. By far, the majority of road roughness data that is collected throughout the world today is obtained with RTRRMSs. The RTRRMS measure depends on the dynamics of a vehicle to scale the measurements to yield roughness properties comparable to the IRI. The dynamic properties are unique for each vehicle, however, and change with time, Thus, the "raw" measures of ARS obtained from the RTRRMS must be corrected to the IRI scale using a calibration equation that is obtained experimentally for that specific RTRRMS. Because the dynamics of a vehicle change easily, very rigorous maintenance and operating procedures must be employed for the vehicles used, and control testing must be made a routine part of normal operations. When changes occur, there is no simple correction that can be applied; instead, the entire roadmeter-vehicle system must be re-calibrated.

This class also includes other roughness measuring instruments capable of generating a roughness numeric reasonably correlated to the IRI (e.g., a rolling straightedge). The measures obtained can be used to estimate IRI through regression equations if a correlation experiment is performed. This approach is usually more trouble than it's worth

[1] In 1984 a Road Profilometer Meeting was held in Ann Arbor, Michigan, to determine the performance characteristics of a number of profilometers, including both of the current non-contacting systems from K.J.Law, Inc. (USA), the Swedish VTI laser system, the APL Trailer, and several non-commercial systems. The study, which was funded by the U.S. Federal Highway Administration (FHWA) and conducted by UMTRI, is still underway [3].

(better measures can be obtained with less effort), unless there is a need to convert a large amount of past data to the IRI scale.

A method for measuring roughness qualifies as Class 3 if it uses the "calibration by correlation" approach described in Section 4.2, regardless of what type of instrumentation or vehicle is used to obtain the uncorrected roughness measure. While most Class 3 methods will employ a roadmeter that accumulates suspension motion to measure ARS as described in Section 4.1, other systems are in use that employ accelerometers or other types of instrumentation. However, the roadmeter-based RTRRMS that measures ARS most closely matches the IRI concept, and these guidelines concentrate on the calibrated RTRRMS as the principle Class 3 method.

Unless a RTRRMS is calibrated by correlation, it does **not** qualify as a Class 3 method. Without the calibration, there is no verifiable link between the measures obtained with any two RTRRMSs, nor to the IRI scale.

The reproducibility associated with a calibrated RTRRMS is about 0.5 m/km (14%) for paved roads for sections 320 m long, and about 1.0 m/km (18%) for unpaved surfaces of that length. These accuracy figures are only approximate averages, as the errors generally vary both with roughness and surface type. Better accuracy is possible by using longer test sections.

2.2.4 Class 4: Subjective ratings and uncalibrated measures. There are situations in which a roughness data base is needed, but high accuracy is not essential, or cannot be afforded. Still, it is desirable to relate the measures to the IRI scale. In those cases, a subjective evaluation involving either a ride experience on the road or a visual inspection could be used. Another possibility is to use the measurements from an uncalibrated instrument. Conversion of these observations to the IRI scale is limited to an approximate equivalence, which can best be established by comparison to verbal and/or pictorial descriptions of roads identified with their associated IRI values, as described in Section 5.0. Essentially, the estimates of equivalence are the calibration, however approximate, and they may be considered to be "calibration by description."

When these subjective estimates of roughness are converted to the IRI scale the resolution is limited to about six levels of roughness with accuracy ranging from 2 - 6 m/km (about 35%) on the IRI scale. (Roughness accuracy, expressed either in absolute units of m/km or as a percentage, will generally vary with roughness level and surface type.)

Note that unless a valid calibration by correlation is used with a RTRRMS, there is no way to link the measure to the standard scale. Thus, an uncalibrated RTRRMS falls within Class 4.

2.3 Factors Affecting Accuracy

Roughness data are normally utilized in applications representing two extremes: (1) statistical analyses involving roughness measurements on major segments of a road network, and (2) individual studies related to roughness at specific road sites. The roughness data will necessarily include some errors arising from random and systematic effects. The significance of these errors depends on the nature of the application for which the data are intended.

An example of the first type of application is a road-user cost study, in which the data base of operating costs for a fleet of vehicles is regressed against the data base of roughness for the roads on which those vehicles were operated. In that case, the need is to determine levels of roughness for comparison with trends of costs, using regression methods. Random errors in individual roughness measurements, caused by poor precision or a peculiar road characteristic, will tend to average out if the study includes a large number of road sites. Thus, random error is not of great concern for this type of study. On the other hand, systematic errors will bias the cost relationships obtained. Therefore, steps should be taken to keep the systematic errors to minimal levels. The results of the study will not be transportable unless a standard roughness scale is used, and steps are taken to ensure that the roughness data more or less adhere to that scale.

Studies that involve monitoring roadway deterioration or the effects of maintenance are examples of the second type of application. In these cases, it is of interest to maintain a continuing record of small changes in the roughness condition at specific road sites. Random errors in measurement will reduce the certainty with which the trends of interest can be discerned. A constant bias in the data can be determined and corrected in order to compare roads or apply economic criteria, but it is perhaps even more critical to ensure that the bias does not change with time. Thus, for measurements to be used for these applications, the practitioner should employ procedures that will minimize random errors while also maximizing time-stability. This normally translates into using the same equipment and personnel for regular monitoring of a road site, utilizing repeat tests to improve repeatability, and carefully maintaining the calibration of the equipment.

The end use of the roughness data in applications such as these has a direct impact on the accuracy that will be necessary in the measurement procedures. In turn, the accuracy determines how much effort must be devoted to obtaining good data. Each application will have peculiar sensitivity to different error sources. In order to make rational decisions about the quality of the measurements to be obtained, it is helpful to realize that inaccuracy in roughness measurements will arise from three types of error sources.

2.3.1 Repeatability error. When repeated measurements are made with an instrument, exact agreement cannot be expected because the measurement process includes random effects that vary from measurement to measurement. The level of repeatability may not always be evident, because instruments often involve a quantization of the output that masks the effects of small variations. In these cases, the repeatability should be assumed to be no better than at least half the quantization size. For example, an RTRRMS that produces counts corresponding to 3.0 mm has a repeatability error of at least 1.5 mm.

When measuring road roughness by carefully surveying the longitudinal profile, the precision is limited by: (1) the instrumentation used to measure the profile, (2) the random locations of the specific points along the wheeltrack where the elevation measures are taken, and (3) the partly-random selection of the lateral position of a traveled wheeltrack. The first two errors are reduced by specifying higher quality profile measurements (i.e., more accurate elevation measurements and more closely spaced survey points). When these error sources are controlled, then the imprecision associated with identifying the wheeltrack location becomes the most significant factor, accounting for variations up to 5% when the wheeltrack length is 320 m.

When measuring roughness with a RTRRMS, repeatability is affected by the partly-random variation in lateral position of the RTRRMS on the road, and also by other random factors such as variations in its operating speed and small changes in the vehicle dynamics that occur even over a short time. These sources of variability can be kept to the same level as for direct profile measurement with careful operation.

Repeatability errors are basically random in nature, and can thus be controlled by extending the measurement process so that the random errors cancel out due to averaging. This can be accomplished most simply by using test sections of sufficient length.

A second form of averaging is obtained by making repeated measurements on the same test site. In this way, repeatability error can be reduced on shorter sections that are not long enough for sufficient averaging. In general, the repeatability error is inversely proportional to the square root of the total length covered, where the total length is the site length times the number of repeat measurements. Thus, the error expected on a 1.6 km test site is approximately the same as would be obtained on a 320 m test site after five repeats (5 x 320 m = 1.6 km). As a rule of thumb, a total length of 1.6 km (1.0 mile) or longer is recommended to minimize repeatability error for instruments used at highway speeds.

Another means for increasing the averaging for a RTRRMS instrument is to use a lower speed for a given length of test site; however, this approach is not recommended, because changing the speed also changes the meaning of the roughness measure for the RTRRMS and increases other errors.

2.3.2 Calibration error. Systematic errors exist in instruments. These cause the measurements of one to be consistently different from those of another, or cause one instrument to vary with time. This can be corrected by calibration, so that the roughness measurements are rescaled to cancel systematic differences bringing the measures to a common scale. However, if the calibration does not cover all of the variables that affect the measurement, then the rescaling may not be correct, and a calibration error remains.

Profilometric methods (Classes 1 and 2): Calibration error is minimal when direct profile measurements are used to obtain the IRI. The instruments that measure the profile are calibrated at the factory, and do not change much when given reasonable care. Nonetheless, systematic errors can appear in profile-based measures when (1) the profile elevation measures contain errors (usually making the profile seem rougher than it is), (2) when profile measures are spaced too far apart such that some of the roughness features are missed (making the profile seem smoother), and (3) when profile measures are subjected to a smoothing or a waveband limitation as occurs with a dynamic profilometer (making the profile seem smoother). The specifications and procedures recommended in Sections 3.2 and 3.3 were designed to hold these effects to negligible levels.

RTRRMSs (Class 3): Calibration by correlation with a reference (Section 4.2) is required for a RTRRMS for many reasons, including these important three:

1) The overall dynamic response of any particular RTRRMS vehicle will differ to some degree from that of the reference. This effect can cause the "raw" ARS measure from the RTRRMS to be higher or lower than corresponding IRI values, depending on whether the RTRRMS is more or less responsive than the reference.

2) The roadmeter in the RTRRMS generally has freeplay and other forms of hysteresis that cause it to miss counts, resulting in lower roughness measures.

3) The RTRRMS suspension motions include effects from factors other than road roughness, such as tire out-of-roundness. This induces higher roughness measures.

The systematic error sources in a RTRRMS interact, and are nonlinear. Their effect can change with roughness, surface type, temperature, and other environmental factors. The only way they can be taken into account is through correlation with measures of IRI obtained with a reference method (Class 1 or 2). This operation is essentially a "calibration by correlation." The procedure described in Section 4.2 is designed to eliminate calibration error from RTRRMS measurements.

2.3.3 Reproducibility error. When measuring a complex quality such as road roughness with a method other than direct profile measurement, it is possible (and common) for two different instruments to rank several roads in a different order by roughness. An error exists that is random with road selection, but is systematic for the instrument. Even though the measures obtained with one instrument (or method) may be highly repeatable, they are not reproduced when measures are obtained using a different instrument. The problem is that the two measuring methods have differences that are more complex than simple scale factors. While repeatability errors can be controlled using repeated tests and averaging, and calibration errors can be controlled by valid calibration methods, reproducibility errors will always exist when the measuring instrument differs from the reference.

When measures are obtained from Class 1 profile measurement, reproducibility error from the instrument is essentially non-existent, and uncertainty exists only because of the repeatability limits. Repeatability controls can therefore be used to improve the overall accuracy.

But when measures are obtained from a RTRRMS, there is no method of test design or data processing that can resolve the differences among instruments that causes one to measure high on one road and low on another, relative to the IRI. What can be done, however, is to adopt a procedure that matches the characteristics of the RTRRMS to the reference to the closest degree possible. The guidelines for selecting and operating a RTRRMS (Sections 4.1 and 4.3) were written with this in mind.

Another step that can be taken for any measurement method is to measure roughness for longer road sites. Since the reproducibility error is random for each road section, it can be reduced somewhat through the averaging that occurs when longer road sites are used. Unlike the repeatability error, this error does not necessarily decrease with the square root of length.

Reproducibility is not improved by repeating measures on the same site, since the effect is systematic for that site.

2.4 Planning the Measurement Project

The execution of a high-quality road-roughness measuring program is critically dependent on establishing well-thought-out procedures that are adhered to in a strict and consistent fashion throughout the project. This section outlines the planning needs for the three main kinds of roughness measurement projects, to aid the planner in appreciating the logistics that are involved.

2.4.1 Long-term network monitoring. Long-term roughness monitoring programs are an integral part of network condition evaluation surveys and pavement management systems. Typical objectives include:

1) Summary of network condition on a regular basis for evaluation of policy effectiveness

2) Input into a network-level economic analysis of pavement design standards, maintenance policy, and transportation costs

3) Quantifying project condition for prioritizing maintenance and rehabilitation programs.

To meet these objectives, the measurements will usually be continuous over links of the network and the total length will exceed 1000 km (or even 10,000 km). It is essential that measures made in different areas of the network be directly comparable, and that the measures be consistent over time. However, the accuracy requirements for individual roughness measurements will generally not be as demanding as for other types of projects, because data averaging will reduce the effects of random errors. Of the three sources of error described in Section 2.3, the calibration error is the most critical to control.

When planning a long-term monitoring program, one should consider:

a) Type of roughness measuring instruments: The rapid collection and automatic processing of data are paramount considerations to facilitate storage in a data bank, and streamline analysis. Only instruments that can be operated at the higher speeds should be considered. (The instrument should operate at least at a speed of 50 km/h, and preferably at 80 km/h or faster.) Any type of RTRRMS is suitable. A high-speed profilometer is also suitable and can provide useful descriptive numerics in addition to IRI.

b) Number of instruments: When the network is very large or spread-out, more than one instrument may be required. If this is the case, a fleet of RTRRMSs might be more affordable than a fleet of profilometers. The vehicles used for RTRRMSs preferably should be of the same make for the sake of interchangeability, although this is not essential when sound calibration procedures are followed.

c) Calibration sections (for RTRRMSs only[2]): A series of eight to twenty calibration sections will be needed at a central location and possibly at distant regional locations to permit full calibration of the test vehicles at regular intervals (Section 4.2).

d) Control sections: A small number of control sections (three to five) will be needed in every region where the instruments will operate to permit control checks on a daily or weekly basis (Section 4.3.4).

e) Measurement speed (for RTRRMSs only[3]): This may be a compromise of conflicting considerations. The standard speed of 80 km/h is likely to be applicable in the majority of situations. Severe road geometry or congestion will dictate a lower speed of 50 or 32 km/h on some links, but this should not influence the choice for the majority of the survey. The simultaneous collection of other data during the survey may influence the choice.

f) Data processing and reporting: Data collection must include location and other event markers for reconciliation with other pavement management data. Computerization at the earliest possible stage and use of standard coding forms where necessary should be considered to facilitate data entry. Measurements should be recorded at intervals of no more than 1 km. Reporting will usually comprise mean values either by link or homogeneous section of 10 km or longer, with summary histograms of roughness distribution by road length. These reporting units should coincide with at least the major changes in traffic volumes to facilitate estimates of vehicle operating costs. For efficiency, the data can be managed so as to permit separating the more detailed reporting requirements of simultaneous project evaluation and prioritization studies.

2.4.2 Short-term project monitoring. Evaluation of specific rehabilitation or betterment projects involves either short-term observations over periods up to 3 years or one-shot roughness measurements. Typically, the sites will range from 5 to 50 km in length and will not necessarily be contiguous. Careful consideration should be given to the detail and accuracy required, as accuracy requirements can sometimes be more stringent than for long-term network monitoring

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[2] Profilometers are calibrated at the factory or in a laboratory.

[3] Speed requirements for profilometers are specific to the profilometer design.

(Section 2.4.1). On the other hand, if only approximate roughness measures are needed, considerable economy can be achieved.

If a history of surface roughness is desired, then the instrument should be capable of providing repeatable measures over a period of time, and it will be important to maintain calibration error to small levels. Also, if high accuracy is desired, repeated measurements can be averaged to reduce the repeatability error that might otherwise mask small changes in roughness. In general, efficiency in data acquisition is not critical for short-term projects, and therefore emphasis should be placed on obtaining data with quality as high as possible from the instrumentation.

In some cases, transportability of the data (obtained by using the standard IRI scale) may not be as critical as maintaining a high standard of internal consistency. In practice, however, the careful controls needed to maintain internal consistency will often result in adherence to the IRI scale anyway (particularly for RTRRMSs).

a) Profilometric Methods (Classes 1 and 2): Profilometric methods are suitable and can optionally provide useful descriptive numerics in addition to IRI, which can be used to diagnose the nature and probable sources of distress. (For example, the APL 72 system normally provides three waveband roughness indices. The predominantly long wavelength roughness indicates subgrade or foundation instability, whereas short wavelength roughness indicates base or surfacing distress.)

If a profilometer is available, it can probably be applied with little modification in procedure, requiring only a more detailed reporting format and possibly more careful marking of test sites. If no roughness measuring instrumentation is available, a profilometer might be imported temporarily with less overall cost than the purchase of less sophisticated systems that require extensive calibration effort.

b) Calibrated RTRRMS (Class 3): These methods need to be under rigorous control to be satisfactory when high accuracy is desired. If possible, a single instrument should be used to perform all of the measurements in order to minimize reproducibility error. The complete calibration (see Section 4.2) may need to be repeated more frequently than for other applications, as even small changes in the response properties of the RTRRMS may mask the desired roughness information.

If a fully equipped RTRRMS is available (from a long-term project), it can possibly be applied with little modification in procedure, requiring only more detailed measurement and reporting formats. However, if the accuracy requirements are significantly more stringent than for the other project, then the procedures will need to be modified accordingly by controlling the vehicle condition more carefully (Section 4.1) and by applying calibrations more frequently (Section 4.2). If the primary calibration sites for the test vehicle are distant (over 100 km) from the project, a series of three to six control sites should be established nearby (Section 4.3.4).

If measures from one RTRRMS are to be compared for different sites, it is absolutely essential that all of the measurements be made at the same speed. If it is not possible to perform measures at 80 km/h, then the highest speed that can be used at all sites should be chosen. In selecting a non-standard speed, the reproducibility error may be worse for comparing data from different RTRRMSs, but it will be better for comparing data obtained with the single RTRRMS used in the study. Thus, the data will be internally more consistent, at the expense of transportability.

If a system has to be set up for the project, minimum requirements can be established suiting either an imported temporary system or the beginnings of a system that might later be expanded.

c) Uncalibrated measures or subjective ratings (Class 4): If low accuracy and precision are acceptable, as often applies in the early stage of a project or in areas of poor access, a RTRRMS with approximate calibration or a subjective evaluation method (Class 4) can be used quickly with high utility and low set-up costs.

d) Data processing and reporting: Readings should usually be taken at 0.1 or 0.2 km intervals. Reporting will usually include longitudinal-profile bar graphs with 95th percentile values and means over homogeneous lengths, or a coding that highlights critical sections. The presentation should aid the prioritization, planning, and design of rehabilitation and betterment projects.

2.4.3 Precise monitoring for research. Research studies which aim to quantify relatively small changes in roughness of roads over short- to medium-term periods of three to six years require a high accuracy and precision of measurement. Many such studies are being instituted in countries seeking to calibrate or establish road deterioration predictive functions for use in pavement management and economic evaluation analyses. Usually the sections are short, of 1 km length or less, and may be widely scattered throughout a region and between regions in order to meet experimental design requirements of traffic, pavement, and climate permutations.

Where such studies involve short road sections, preference should be given to profilometric methods (Classes 1 and 2), including static methods (e.g., rod and level) if a high-speed profilometer is not available or is not sufficiently accurate. RTRRMS Class 3 methods have often been used for this application, but generally lack adequate precision and give rise to uncertainty in the trend data. It should be noted that profile measures can also be processed to yield a variety of surface condition indicators other than the IRI, whereas RTRRMSs are capable of only the single type of measurement.

A trade-off on the frequency of measurement is possible: Class 1 or 2 measures need be made only annually and in conjunction with major maintenance activities, because of their higher accuracy. However, Class 3 RTRRMS measures should be made at least two to three times per year, in order to ensure confidence in the data trends. Portability of the system is important: Class 3 methods require the establishment of supporting control sections in distant regions, whereas Class 1 or 2 systems do not.

Data processing and analytical methods will usually be project-specific; thus, these topics are not addressed here. Reporting should include computation of the IRI for the purposes of transferability, even if other numerics are used more directly in the research.

CHAPTER 3

MEASUREMENT OF IRI USING PROFILOMETRIC METHODS (CLASSES 1 & 2)

3.1 Description of Method

Class 1 and 2 measurements of the IRI can only be obtained from a longitudinal profile of a road. A longitudinal profile is a vertical section along the wheeltrack, which indicates the elevation of the surface as a function of longitudinal distance. The profile is described by the set of elevation values, spaced at close intervals along the wheeltrack. In order to summarize the hundreds or thousands of numbers that constitute a profile, an analysis procedure is performed that calculates the IRI as a single statistic quantifying the roughness. The calculations are usually performed using some form of digital computer. A programmable pocket calculator can also be used, although the computations are tedious and there is a higher potential for error. Nearly all microcomputers are suitable for calculating IRI, and offer the advantages of being cheap, readily available, and easily programmed.

Because the IRI applies to a particular wheelpath along the road, the persons responsible for measuring the profile should have a clear idea of where the wheelpath is located in the lane. Whenever repeated measures are to be made using static methods, the wheelpath should be clearly marked on the road surface so that the various measures will be over the same path. When a high-speed profilometer is used in survey work, the operators should follow a consistent practice for locating the profilometer laterally in the travelled lane. Most measurements made with high-speed profilometers are made in either the center of the travelled lane, or in the two travelled wheelpaths. Generally, the results are not equivalent except on new roads and sometimes on Portland Cement concrete (PCC) roads. In order for results to be comparable when different operators perform the measurements, the criteria for selecting the wheeltrack(s) to be measured should be well established.

The two wheelpaths followed by the tires of vehicles in the normal traffic stream will provide measurements that are most representative of the road roughness affecting traffic, therefore it is recommended that measures be made in the travelled wheeltracks.

3.2 Accuracy Requirements

The IRI analysis can only be applied to existing information--it cannot supply information about the road that was not included in the profile measurement. Thus, there are minimum requirements that must be satisfied in order to obtain a valid IRI measure using a profilometric method. Table 1 summarizes the requirements for the two primary

TABLE 1. Accuracy requirements for Class 1 and 2 profilometric measurement of IRI

Roughness range	Maximum convenient sample interval between points (mm)1/		Precision of elevation measures (mm)2/	
IRI (m/km)	Class 1	Class 2	Class 1	Class 2
1.0 - 3.0	250	500	0.5	1.0
3.0 - 5.0	250	500	1.0	1.5
5.0 - 7.0	250	500	1.5	2.5
7.0 - 10.	250	500	2.0	4.0
10 - 20	250	500	3.0	6.0

1/ For tapes marked in foot units, the maximum convenient intervals are respectively Class 1: 1 ft.
Class 2: 2 ft.

2/ Precision Class 1 yields less than 1.5% bias in IRI.
Precision Class 2 yields less than 5% bias in IRI.

Note: Precision Class 2 is adequate for the calibration of response-type systems (RTRRMS's).

parameters involved in profile measurement: sample interval and precision of the elevation measurements.

a) Precision. Note that the precision needed is a function of roughness. Although the roughness is not known until the profile is measured and IRI is calculated, with experience the practitioner will be able to judge when the roughness is high enough that the precision requirements can be relaxed. The values shown in the table are computed using the experimentally obtained relationships:

Class 1 precision (mm) $\leq$ .25 * IRI (m/km)

Class 2 precision (mm) $\leq$ .50 * IRI (m/km)

b) Sample interval. The sample intervals shown in the table are valid for all types of road surfaces except those cases where the roughness is extremely localized and would be "missed" by using the sample intervals shown. Examples of localized roughness are tar strips, patches, and small potholes. Since the IRI analysis cannot provide any information that is not contained in the profile measurement, it is absolutely essential that the profile elevation be measured at intervals that are sufficiently close to "capture" the relevant sources of roughness. When automated profilometers are used, an interval of 50 mm is recommended to ensure that all relevant roughness features are detected. (Even this interval may not be sufficient to detect tar strips in a new PCC surface, however.)

c) Waveband. A complete road profile includes features ranging over a broad spectrum (from hills and valleys on the large scale, down to the small features of surface texture). No instrument in present use measures the complete profile. For technical reasons, profilometric instruments cover only a limited range of the spectrum of wavelengths that hopefully includes the road qualities of interest. A further reduction in profile content occurs during the computation of IRI.

The IRI analysis acts as a filter, eliminating all profile information outside of the 1.3 - 30 m waveband (hills and valleys, texture). Wavelengths outside this band do not contribute to the roughness seen by road-using vehicles at speeds near 80 km/h. Because different profilometric methods will often include some wavelengths outside of this range, plots of unprocessed profiles can appear quite different even though they are obtained from the same road and yield the same value of IRI. A profilometer can qualify as a Class 2 method for measuring IRI if it senses wavelengths over the range 1.3 - 30 m.

Because different analyses apply different "filters" to a measured profile, a profilometric method will generally be valid for some applications but not for others. Thus, accuracy requirements determined for other applications are not necessarily valid for measurement of IRI.

3.3 Measurement of Profile

3.3.1 Rod and Level Survey. The most well-known way to measure profile is with conventional surveying equipment. The equipment consists of a precision rod marked in convenient units of elevation (typically major divisions are cm or ft), a level that is used to establish a horizontal datum line, and a tape used to mark the longitudinal distance along the wheelpath. This equipment is widely available, and can usually be rented or purchased at a cost that compares very favorably with other roughness measuring equipment. However, the method requires a great deal of labor, and is generally best to use when only a few profiles are to be measured. Detailed instructions for using a rod and level are beyond the scope of these guidelines; however, the measurement of a road profile is not a routine application of these instruments, and therefore an overview of the procedure is provided below along with guidance specific for this application.

a) Equipment. In order to measure relative elevation with the required precision for paved roads, it is necessary to obtain precision instrumentation used in construction, as the rod and level equipment used for routine land surveying work cannot provide the required accuracy. With the precision instrumentation, in which the rod and level are calibrated together, the level usually includes a built-in micrometer to interpolate between marks on the rod.

Note that the accuracy requirements in Table 1 are straightforward with regard to rod and level: the elevation precision is generally equivalent to the resolution with which the rod can be read through the level, while the sample interval is the distance (marked on the tape) between adjacent elevation measures. When a tape is marked in meters, an interval of 0.25 m is convenient for Class 1 measures, and an interval of 0.50 m is convenient for Class 2 measures. When the tape is marked in feet, an interval of 2 ft (610 mm) can be used for Class 2 measures, while the largest convenient increment for Class 1 measures is 0.5 ft (152.4 mm).

b) Field measurements. The exact methodology adopted to measure and record the elevation points is not critical, and can be matched to the local situation regarding available time, equipment, and manpower. Recent improvements in procedure developed by Queiroz and others in Brazil in obtaining rod and level profiles for the explicit purpose of measuring roughness have proven helpful, and are suggested here.

It is best if the survey crew includes at least three persons: a rod-holder, an instrument-reader, and a note-taker. When available, a fourth member is desirable to act as relief, so that the four can rotate positions to reduce fatigue. A metal tape is laid down in the marked wheeltrack as a reference for the rod-holder, and held in place with weights or adhesive tape. (It is a good idea to mark the measurement intervals on the tape with paint ahead of time, to reduce the chance of error on the part of the rod-holder.) The levelling instrument should be placed at one end of the tape, directly in line. Unless this is done, the instrument-reader will need to constantly re-aim the instrument between sightings.

Unless the rod is held perfectly upright, there will be an error in the reading equal to the product of the rod reading and the cosine of the angle the rod makes with true vertical. This error is reduced by attaching a bubble level to the rod, to provide a reference for the rod-holder. The error is also reduced if the levelling instrument is low to the ground, minimizing the lateral displacement of a slightly tilted rod at the height of the level. Tilting of the rod is not a problem likely to go undetected, since it is very noticeable through the level and makes the job of the instrument-reader more difficult.

When the level is set up, the rod-holder starts at one end of the tape, placing the rod on the tape itself. The instrument-reader reads the rod measurement aloud to the note-taker, who records the number and verbally acknowledges to the rod-holder that the measurement has been obtained. The rod-holder then proceeds to the next mark on the tape. With practice, the instrument-reader can refocus the levelling instrument while the rod-holder moves to the next position, so that only a few seconds are needed for each measurement.

Once the survey crew has some experience in "profiling," human error on the part of the rod-holder is nearly eliminated, and the potential problems are limited to the reading and recording of the numerical data. A team of three can measure profile at 0.25 m intervals at the rate of 640 wheeltrack-meters per day, recording elevation with a resolution of 0.1 mm (320 lane-meters = 2560 elevation measurement points/day).

An approach for reducing human error in the field that has been used in Bolivia is to use two instrument-readers and note-takers, taking readings from the same rod-holder. Since the two leveling instruments are not at the same elevation, the rod readings are not identical, but should consistently differ by a constant amount. This method allows a convenient check to quickly discover any errors in recording data, and lends itself to automatic error detection by computer once the data have been entered.

c) Data recording. Due to the large number of measurements (hundreds or thousands per test site), it is critical to eliminate as many sources of human error as possible. Standardized field forms that have the tape distances preprinted are helpful in reducing errors when recording the data. Figure 2 shows portions of two pages of pre-printed field forms that were used in measuring profile with rod and level. At the top of the figure is the bottom of a page that includes all of the rod measurements between 400 and 500 ft. The next page begins at 500, continuing where the provious page ended with an overlap of the first point (500 + 0 = 400 + 100).

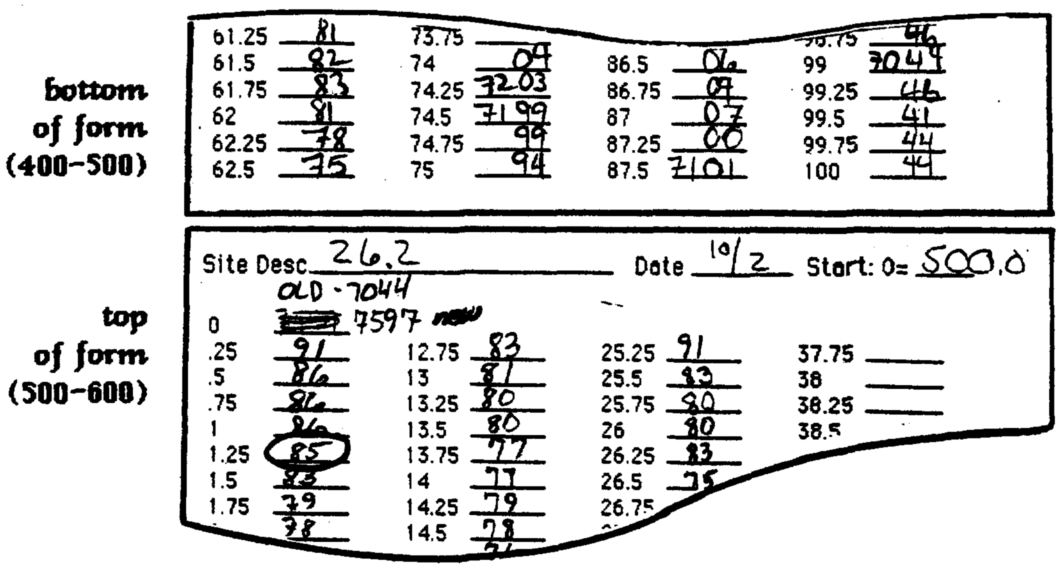
d) Computation of profile elevation. The optics of the levelling instrument limit the range of sight distance that can be used. When the distance to the rod reaches the limits of that range, the level must be moved to a new location. On roads that are sloped, the level may also have to be moved more frequently to keep the level within the vertical range of the rod. It is usually convenient to move the instrument at the same time the tape is moved, so that all of the readings from one tape setup are based on the same instrument height. In order to establish the new instrument height, the last point measured with the old setup should be re-measured in the new setup. The new instrument height is then:

$$Inst_{new} = Inst_{old} + Rod_{new} - Rod_{old}$$

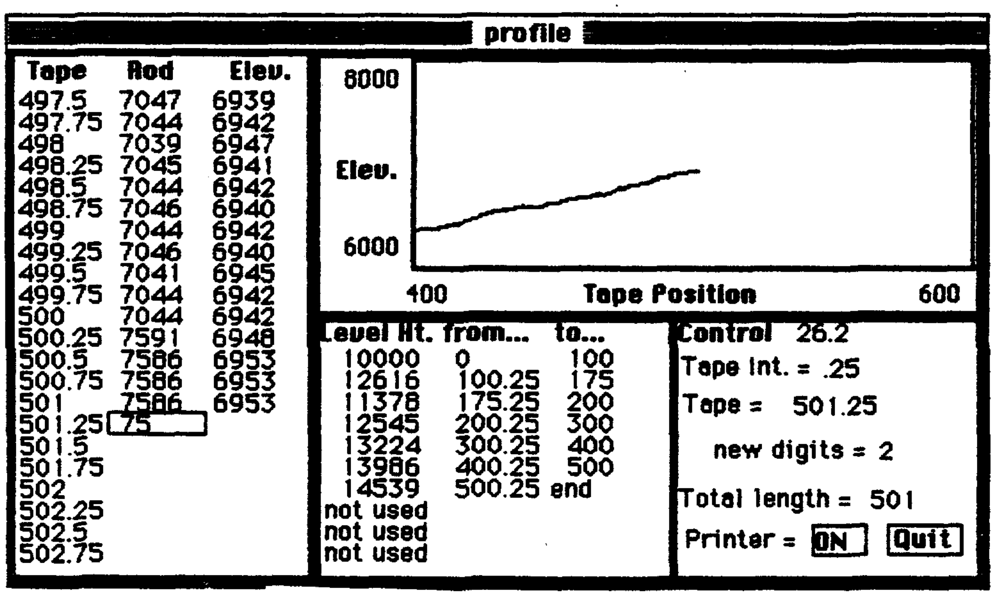
In the example of Figure 2, the instrument was moved along with the tape. The final rod reading on the bottom of the first (400) page was 7044, at tape position 400 + 100. The first reading for the next tape and instrument setup, shown at the top of the next page, was 7597. Therefore, the new instrument height has increased by (7597 - 7044) = 553.

In conventional land survey work, the elevation of the level instrument is carefully established so that the absolute elevation of the road surface is determined. For roughness measurements, it is only necessary to adjust all of the measures to the same relative reference. Therefore, the height of the level can be assumed to equal any convenient arbitrary elevation at the first setup (e.g., 10 m).

e) Computer entry. Obtaining the measurements is not all of the effort. The numbers must then be typed into a computer in order to compute IRI. As noted above, it is critical to eliminate all steps that could introduce error in the IRI measure eventually obtained. In typical elevation survey work, the rod readings are subtracted from the instrument height on the field notes to yield elevation data. However, given that the data are eventually going into a computer, all intermediate steps of copying data, re-scaling data, and converting rod



a) Pre-printed field forms for recording rod readings.



b) Display of the microcomputer screen when typing data into the computer from the field form.

Fig. 2. Example of field forms and special computer program used to record and enter data from rod and level.

readings to elevation values should be deferred. Instead, these tasks can all be performed by the computer after the rod readings are entered.

If possible, the computer program should present a display to the person entering data that approximately matches the field form, to allow the quick detection of any typing errors. To help detect errors, the computer can be programmed to check for differences in adjacent elevation values exceeding a level that would indicate erroneous data. An even better check is to plot the elevation profile at a scale that will reveal any obviously erroneous data values. Figure 2b shows the display of a data entry program that was used together with the field form shown in Figure 2a [3]. This is, in fact, an exact replica of the screen of the Apple Macintosh microcomputer when running this particular program, when the typist has finished entering the rod reading at tape position 501 and is about to enter the reading for 501.25. The screen is shown to indicate how the data entry task has been been streamlined in one project.

In this example, the tape distance is shown in the left-most column on the computer screen. The numbers match those of the field forms, allowing the typist to easily see the correspondence between the position on the computer screen and the field form. As each rod reading is entered, it is shown in the second column on the left. The elevation is computed and shown in the third column. At the same time, the elevation is added to the plot shown in the upper-right hand corner of the screen. Any erroneous data points can be seen as "glitches" in the plot, so errors are easily detected and corrected. (The two boxes in the lower right corner were used to store the changes in the levelling instrument height and to control the flow of the program.)

Using microcomputers with "user-friendly" programs written specifically for entering rod and level data, a typist can enter about 1000 measures per hour (including checking for errors).

f) Computer selection. The computer selected to process the rod and level data should ideally have the ability to store the profile data permanently on tape or disk, the ability to plot profile, and the ability to transmit files to other computers. An often overlooked consideration that should receive high priority is the availability of the computer for the project. A $500 "home" computer that is available 100% of the time can be much more useful than a $100,000 main-frame computer shared by a large group that is neither readily available nor easily programmed.

3.3.2 TRRL Beam Static Profilometer. An automated beam profilometer such as the TRRL Beam can reduce the survey effort required for profile measurement considerably. A two-man crew can measure elevations at 100 mm intervals in two wheeltracks 320 m long in approximately two hours (about 25000 elevation points in an eight-hour day). This instrument was designed with developing country environments in mind, so emphasis was placed on making it portable, rugged, and self-contained.

The instrument consists of an aluminum beam 3 m in length, supported at each end by adjustable tripods used for levelling. A sliding carriage on the beam contacts the ground through a follower wheel that is 250 mm in diameter, while traversing the length of the beam. Instrumentation in the carriage detects the vertical displacement, digitizes it with 1 mm resolution, and records the numerical values at constant intervals, currently 100 mm. The sliding carriage is manually moved from one end of the beam to the other at walking speed to "profile" the segment. To obtain the continuous profile of a wheeltrack, the beam is successively relocated at consecutive 3 meter segments. The instrument contains a battery-powered microcomputer that stores the data on magnetic cassette tape and automatically computes a roughness index. The microcomputer has also been used to compute calibration equations that are later used to re-scale data from a RTRRMS to the profile-based index.

When programmed to compute IRI, the TRRL Beam qualifies as a Class 1 system (in accordance with Table 1) for all but the smoothest road surfaces. However, by resetting the gain in the electronics to allow a finer digitizing resolution (0.25 mm), the instrument would qualify as a Class 1 measuring method for even the smoothest of roads.

If the microcomputer does not compute IRI directly, then IRI must be estimated using an experimentally determined regression equation with a subsequent reduction in accuracy. In this context, the Beam would be considered a Class 3 method. (Unlike the RTRRMS, the Beam is time-stable, and thus the "calibration by correlation" would not need to be repeated periodically as is the case for the RTRRMS.)

Details for obtaining and operating the TRRL Beam can be obtained from the Overseas Unit of TRRL.

3.3.3 APL Inertial Profilometer. The LCPC Longitudinal Profile Analyzer (APL) is designed for continuous high-speed evaluation of 100 to 300 km of road per day. The APL consists of a special towed trailer that has one bicycle-type wheel, a chassis with ballast, and a special low-frequency inertial pendulum that serves as a pseudo-horizontal reference. The trailer is designed to be insensitive to movements of the towing vehicle, sensing only the profile of the travelled wheeltrack over the frequency band of 0.5 - 20 Hz. When towed at any constant speed between 50 and 100 km/h, it senses roughness in the full wavelength range that is required for the IRI. The actual band of wavelengths sensed by the APL depends on the towing speed: it senses wavelengths as long as 100 m when towed at 150 km/h, or as short as 0.3 m when towed at 21.6 km/h.

The APL Trailer is the only high-speed profilometer that has been proven to measure IRI over a full range of roughness, including rough unpaved roads.

Although the APL Trailer can be used to measure IRI, it was developed for other purposes by LCPC, and is routinely used in Europe for other applications. It is normally packaged with special instrumentation in one of two configurations: APL 72 for routine survey work; and APL 25 for precision work involving quality control and acceptance, project evaluation, and research.

a) APL 72. The APL 72 system employs a powerful modern station wagon as towing vehicle (sustaining 100,000 km per year for testing and transfers) [4]. Single-wheeltrack systems are the norm, although dual-track systems (two APL Trailers, one towed in each of the travelled wheelpaths) have been used. In normal survey usage in Europe the wheel travels between the wheeltracks. The profile signal from the trailer, the speed, distance travelled, and manually entered event comments are all recorded on magnetic tape in the towing vehicle. Data processing is performed later in the laboratory. Traditional processing methods classify the roughness on a ten-point scale of signal energy in three wavelength ranges, i.e., 1 - 3.3 m/cycle, 3.3 - 13 m/cycle, and 13 - 40 m/cycle.

Site lengths need to be selected in multiples of 100 m, generally with a minimum of 200 m and normal length for APL 72 of 1000 m. Adequate allowance of approach length is necessary for the faster test speed.

The APL 72 system can be easily adapted to measure IRI, by processing the recorded data differently in the laboratory. The manufacturer's instructions should be followed for details of test operation. In the laboratory, the analog signals stored on the tape recorder should be digitized using standard microcomputer hardware (also available as part of the APL 72 system, or available in different forms from various commercial sources). Once the profile signal is digitized and stored on a microcomputer, it can then be processed as any other profile data, as described in Section 3.4. When this is done, the APL 72 can be considered to be a Class 2 method for measuring IRI.

b) APL 25. The APL 25 system consists of a towing vehicle and only one trailer, and is used at a slower speed of 21.6 km/h [5]. A different instrumentation system is used. It digitizes the profile signal and stores the numerical values on digital cassette tape along with a single summary roughness index called CAPL 25, calculated for every 25 m of wheeltrack that is covered.

Because of the relatively low towing speed used with the APL 25, it does not sense the longer wavelengths to which to the IRI numeric is sensitive. Thus, the APL 25 cannot be used to directly measure IRI without introducing bias. It can, however, be used to estimate IRI through the use of experimentally derived regression equations that relate IRI to other numerics that can be measured by the APL 25. This approach would qualify as a Class 3 method. It should not be expected to be as accurate as the direct measurement that can be made with the APL 72 or with other systems using the APL Trailer at higher speeds, however. Therefore, the APL 25 data collection system is not the system of choice for measuring IRI with the APL Trailer.

3.3.4 K. J. Law Inertial Profilometers. These profilometers, manufactured by K. J. Law Engineers, Inc. in the United States, are modern versions of the original GMR-type inertial profilometer, developed in the 1960's [6]. The profilometer is an instrumented van that measures profile in both wheeltracks as it is driven along the road. Vertical accelerometers provide the inertial reference. The distance to the road surface is sensed, originally by mechanical follower wheels, but more recently with non-contacting sensors (optical or acoustic, depending on the model). The accelerometer signals are double-integrated to determine the position of the profilometer body. When this position is added to the road-follower position signal, the profile is obtained.

The original profilometers used analog electronics to perform the double-integration and other processing, and the operator was required to maintain a constant travel speed during measurement. In the late 1970's, the design was upgraded to replace the analog processing with digital methods. With the conversion to digital methods, a new computation procedure was developed to make the profile measurement independent of speed. This allows the profilometer to be operated with greater ease in traffic.

In addition to measuring the road profile, these profilometers routinely calculate summary statistics associated with quarter-car simulations. Originally, the BPR Roughometer simulation was used. In 1979, the QCS model used for the IRI was added to these profilometers, and has been in use since that time. Thus, both models have the IRI measuring capability built in and automated, and can be considered as Class 2 methods at this time. Neither model has been validated against rod and level yet, although validation for a wide variety of paved road types is underway [3].

Two versions of a profilometer are currently available:

a) Model 690DNC Road Profilometer. This version is the more expensive and offers the greater capability. It includes a van, the full instrumentation needed to measure profiles in both wheeltracks, an on-board minicomputer, a 9-track digital tape system, and various software options for computing numerous profile numerics (including IRI). The road-following height is detected by a noncontacting sensor using a visible light beam, replacing the mechanical follower wheels used in earlier versions.

The software that calculates the IRI type of roughness was developed during the NCHRP 1-18 project [2], and is called the Maysmeter simulation. It differs from the IRI in that it is computed from both wheeltracks (emulating a passenger car with an installed roadmeter) rather than the single-track IRI. Some of these profilometers can measure the roughness of the wheeltracks separately as required for the IRI; if not, the software can be enhanced readily by the manufacturer. When obtained from the Maysmeter simulation, the IRI is reported with units of inches/mile, rather than m/km (1 m/km = 63.36 in/mi).

The performance of the Model 690DNC has not yet been validated against a static method for measurement of the IRI. The earlier designs with mechanical follower wheels were validated up to roughness levels of about 3 m/km on the IRI scale in NCHRP Report 228 [2]. With the noncontacting sensors, operation to higher roughness levels should be possible. Three Model 690DNC systems participated in the 1984 Road Profilometer Meeting in Ann Arbor, and validation of the profilometer will be provided from that study [3]. The Model 690DNC has not been tested on unpaved roads, and is not likely to be tested soon, since there is little interest in measuring the roughness of unpaved roads at the present time in the United States.

b) Model 8300 Roughness Surveyor. The Model 8300 is a single-track profilometric instrument designed specifically to measure IRI. In order to minimize its cost, the instrumentation is used to provide an internal profile signal only as input to the IRI calculations, thereby eliminating the need for many of the expensive computer and recording components included in the Model 690DNC. Although the system provides IRI roughness as the default, other roughness indices can be obtained as options from the manufacturer.

The Model 8300 utilizes a bumper-mounted instrumentation package containing an ultrasonic road-follower system and a vertical accelerometer. The system can be mounted on most passenger cars. It has not yet been validated for measurement of the IRI, but did participate in the 1984 Road Profilometer Meeting; hence, information on its validity (on paved roads) is expected from that study [3].

3.3.5 Other Profilometers. Other profilometry methods not specifically covered in these guidelines are likely to fall in the Class 2 category. Within the general provisions of these guidelines, such methods may be used in accordance with the manufacturer's instructions to obtain profile data for computing IRI as described in Section 3.4. Some instruments called profilometers (for example, rolling straightedges) may not be capable of providing a profile signal with sufficient waveband and accuracy as needed for the IRI computation, however. Even if they are stable with time, they can only qualify as Class 3 methods if they cannot be used to measure profile for IRI computation.

3.4 Computation of IRI

3.4.1 Equations. The calculation of IRI is accomplished by computing four variables as functions of the measured profile. (These four variables simulate the dynamic response of a reference vehicle travelling over the measured profile.) The equations for the four variables are solved for each measured elevation point, except for the first point. The average slope over the first 11 m (0.5 sec at 80 km/h) is used for initializing the variables by assigning the following values:

$$Z_1' = Z_3' = (Y_a - Y_1) / 11 \tag{1}$$

$$Z_2' = Z_4' = 0 \tag{2}$$

$$a = 11 / dx + 1 \tag{3}$$

where Y_a represents the "a^{th}" profile elevation point, Y_1 is the first point, and dx is the sample interval. (Thus, for a sample interval of dx = 0.25 m, Equation 1 would use the difference between the 45^{th} elevation point and the first elevation point to establish an initial slope for the IRI computation.)

The following four recursive equations are then solved for each elevation point, from 2 to n (n = number of elevation measurements).

$$Z_1 = s_{11} * Z_1' + s_{12} * Z_2' + s_{13} * Z_3' + s_{14} * Z_4' + p_1 * Y' \tag{4}$$

$$Z_2 = s_{21} * Z_1' + s_{22} * Z_2' + s_{23} * Z_3' + s_{24} * Z_4' + p_2 * Y' \tag{5}$$

$$Z_3 = s_{31} * Z_1' + s_{32} * Z_2' + s_{33} * Z_3' + s_{34} * Z_4' + p_3 * Y' \tag{6}$$

$$Z_4 = s_{41} * Z_1' + s_{42} * Z_2' + s_{43} * Z_3' + s_{44} * Z_4' + p_4 * Y' \tag{7}$$

where

$$Y' = (Y_i - Y_{i-1}) \ / \ dx = \text{slope input} \tag{8}$$

and

$$Z_j' = Z_j \text{ from previous position, } j=1,4 \tag{9}$$

and s_{ij} and p_j are coefficients that are fixed for a given sample interval, dx. Thus, Equations 4 - 7 are solved for each position along the wheeltrack. After they are solved for one position, Eqn. 9 is used to reset the values of Z_1', Z_2', Z_3', and Z_4' for the next position. Also for each position, the rectified slope (RS) of the filtered profile is computed as:

$$RS_i = |Z_3 - Z_1| \tag{10}$$

The IRI statistic is the average of the RS variable over the length of the site. Thus after the above equations have been solved for all profile points, the IRI is calculated as:

$$IRI = \frac{1}{(n-1)} \sum_{i=2}^{n} RS_i \tag{11}$$

The above procedure is valid for any sample interval between dx=.25 m and dx=.61 m (2.0 ft). For shorter sample intervals, the additional step of smoothing the profile with an average value is recommended to better represent the way in which the tire of a vehicle envelops the ground. The baselength for averaging is 0.25 m long. The IRI can then be calculated in either of two ways:

1) The elevation points falling within each .25 m of length may be averaged to obtain an equivalent profile point for the .25 m interval. Then the IRI is calculated from the above equations based on a .25 m interval using the coefficients for the .25 m interval.

2) A "moving average" is obtained as the average of all points falling within a .25 m interval centered on the profile elevation point. Then the IRI is calculated by solving the equations for each averaged point using coefficients in the equations appropriate for the smaller interval.

The algorithm used in the example computer program listed in Figure 3 in Section 3.4.2 is valid for any baselength over the range 10 - 610 mm. When dx is less then 0.25 m, it applies the proper moving average to the input.

The computed IRI will have units consistent with those used for the elevation measures and for the sample interval. For example, if elevation is measured as mm, and dx has units of m, then IRI will have the preferred units: mm/m = m/km = slope x 10^3.

3.4.2 Example program for computing IRI. A demonstration computer program for performing IRI calculations by the above method is listed in Figure 3. The program is written in the BASIC language, and can be executed on nearly any microcomputer. However, specific commands in the BASIC language vary slightly for different computers, and it may be necessary to modify some statements slightly for operation on some computers. (The program has been run without modification on the Apple II family, the IBM PC, and the Apple Macintosh.) The algorithm used in the program includes smoothing for short sample intervals, and is valid for any sample interval between 10 and 610 mm.

The BASIC language was chosen because it is the most widely available on small computers, and because it can be understood by persons with little or no programming background. It is not very fast or efficient for computation of IRI, however. Thus, it might be worth translating into a more efficient language (FORTRAN is well suited) if a great deal of time will be spent computing IRI. In the listing, BASIC commands are shown in bold print: other names shown in normal print are variables and constants.

The program begins by setting values of constants, in lines 1040 - 1140. DX is the sample interval and must have units of meters. The ST array is the state transition matrix containing the s_{ij} coefficients from Eqs. 4 - 7, and PR contains the p_j coefficients used in those equations. The values for DX and the 20 ST and PR coefficients are contained in the **DATA** statements at the end of the program, in lines 1510 - 1550. K is the number of profile points used to compute a slope input, and BL is the baselength. When DX is larger than 0.25 m, then only 2 elevation points are used to compute the slope (Eq. 8), and the baselength is necessarily equal to DX. For smaller values of DX, K may be greater than 2, and the moving average smoothing is incorporated into the slope calculation. If a different sample interval is used, then lines 1510 - 1550 should be replaced with the correct sample interval and the corresponding coefficients. (The coefficients can be copied from Table 2 or computed with the computer program listed in Figure 4.)

The variables used in the program are the four vehicle variables stored in the Z array (Z_1, Z_2, Z_3, and Z_4 in Eqs. 1 - 7), the previous values stored in the Z1 array (Z_1', Z_2', Z_3', and Z_4' in Eqs. 1 - 7), the accumulated slope RS, and counters IX and I. When DX is greater than 0.25 m, then IX and I are equal, and are proportional to distance travelled.

```
1000 REM    This program demonstrates the IRI computation.
1010 REM    A number of recommended modifications are described in
1020 REM    the accompanying text.
1030 REM ---------------------------------------- Initialize constants
1040     DIM Y(26),Z(4),Z1(4),ST(4,4),PR(4)
1050     READ DX
1060     K = INT (.25 / DX + .5) + 1
1070     IF K < 2 THEN K = 2
1080     BL = (K - 1) * DX
1090     FOR I = 1 TO 4
1100         FOR J = 1 TO 4
1110             READ ST(I,J)
1120         NEXT J
1130         READ PR(I)
1140     NEXT I
1150 REM --------------------------------------- Initialize variables.
1160     INPUT "profile elevation 11 m from start:", Y(K)
1170     INPUT "X = 0. Elevation = ",Y(1)
1180     Z1(1) = (Y(K) - Y(1)) / 11
1190     Z1(2) = 0
1200     Z1(3) = Z1(1)
1210     Z1(4) = 0
1220     RS = 0
1230     IX = 1
1240     I = 0
1250 REM -------------- Loop to input profile and Calculate Roughness
1260     I = I + 1
1270     PRINT "X = ";IX * DX,
1280     IX = IX + 1
1290     INPUT "Elev. = "; Y(K)
1300 REM ------------------------------------------ Compute slope input
1310     IF IX < K THEN Y(IX) = Y(K)
1320     IF IX < K THEN GOTO 1270
1330         YP = (Y(K) - Y(1)) / BL
1340         FOR J = 2 TO K
1350             Y(J-1) = Y(J)
1360         NEXT J
1370 REM ------------------------------------ Simulate vehicle response
1380     FOR J = 1 TO 4
1390         Z(J) = PR(J) * YP
1400         FOR JJ = 1 TO 4
1410             Z(J) = Z(J) + ST(J,JJ) * Z1(JJ)
1420         NEXT JJ
1430     NEXT J
1440     FOR J = 1 TO 4
1450         Z1(J) = Z(J)
1460     NEXT J
1470     RS = RS +  ABS (Z(1) - Z(3))
1480     PRINT "disp = ";RS * DX, "IRI = ";RS / I
1490     GOTO 1260
1500 END
1510 DATA .25
1520 DATA .9966071 , .01091514,-.002083274 , .0003190145 , .005476107
1530 DATA -.5563044 , .9438768 ,-.8324718 , .05064701 , 1.388776
1540 DATA .02153176 , .002126763 , .7508714 , .008221888 , .2275968
1550 DATA 3.335013 , .3376467 ,-39.12762 , .4347564 , 35.79262
```

Figure 3. Demonstration program for computing IRI with a microcomputer

Lines 1260 - 1360 compute the slope input from the entered elevation points. The Y array is a buffer used for temporary storage of up to 26 profile points. Only the first K elements are ever used, however. Thus, when DX is 0.25 m or greater, which will be the case for most applications where profile is measured manually, K=2 and only the first two elements in the Y array are needed. For very short sample intervals, however, the Y buffer is needed for the moving average. When DX = .01 m, then all 26 elements in the Y buffer are used.

Lines 1380 - 1490 are straightforward translations of Eqs. 4 - 10.

A major change that is recommended to make the program more practical is to provide for reading the measured profile from disk or tape. Since file structures are specific to different machines, the example program does not do this, but instead requires that the user enter each profile elevation in sequence. Lines 1160, 1170, 1280, and 1290 can be replaced with equivalents that read data from stored files.

Details concerning the characteristics of the reference and this particular computation method are readily available [1, 2].

3.4.3 Tables of coefficients for the IRI equations. The coefficients to be used in Eqns. 4 - 7 and in the example IRI computation program depend on the interval at which the elevation measurements are obtained. Table 2 provides the coefficient values for the commonly-used intervals that are convenient for manual measurement of profile. When an interval is used that is not covered in the table, then the coefficients can be computed using the algorithm listed in Figure 4 in Section 3.4.4.

3.4.4 Program for computing coefficients for the IRI equations. Coefficients for use in Eqns. 4 - 7 can be determined for any profile interval by using the computer program listed in Figure 4. The language is BASIC, which was discussed in Section 3.4.2. The details of the vehicle simulation are covered elsewhere [1], so only the actual equations used in the program are included here.

The coefficients used in Eqs. 4 - 7 are derived from the dynamic properties of the reference vehicle model. These dynamic properties are described by four differential equations, which have the matrix form:

$$dz(t)/dt = \underline{A} * z(t) + \mathbf{B} * y(t) \qquad (12)$$

where z is a vector containing the four Z variables of Eqs. 1 - 7; $\underline{\mathbf{A}}$ is a 4 x 4 matrix that describes the dynamics of the model; **B** is a 4 x 1 vector that describes how the profile interacts with the vehicle; and y(t) is the profile input, as perceived by a moving vehicle. These matrices are defined as:

Table 2. Coefficients for the IRI Equations.

dx = 50 mm, dt = .00225 sec

	.9998452	2.235208E-03	1.062545E-04	1.476399E-05		4.858894E-05
ST =	-.1352583	.9870245	7.098568E-02	1.292695E-02	**PR** =	6.427258E-02
	1.030173E-03	9.842664E-05	.9882941	2.143501E-03		1.067582E-02
	.8983268	8.617964E-02	-10.2297	.9031446		9.331372

dx = 100 mm, dt = .0045 sec

	.9994014	4.442351E-03	2.188854E-04	5.72179E-05		3.793992E-04
ST =	-.2570548	.975036	7.966216E-03	2.458427E-02	**PR** =	.2490886
	3.960378E-03	3.814527E-04	.9548048	4.055587E-03		4.123478E-02
	1.687312	.1638951	-19.34264	.7948701		17.65532

dx = 152.4 mm (0.50 ft), dt = .006858 sec

	.9986576	6.727609E-03	3.30789E-05	1.281116E-04		1.309621E-03
ST =	-.3717946	.9634164	-.1859178	3.527427E-02	**PR** =	.5577123
	8.791381E-03	8.540772E-04	.8992078	5.787373E-03		9.200091E-02
	2.388208	.2351618	-27.58257	.6728373		25.19436

dx = 166.7 mm, dt = .0075015 sec

	.9984089	7.346592E-03	-1.096989E-04	1.516632E-04		1.70055E-03
ST =	-.4010374	.9603959	-.2592032	3.790333E-02	**PR** =	.6602406
	1.038282E-02	1.011088E-03	.8808076	6.209313E-03		.1088096
	2.556328	.2526888	-29.58754	.6385015		27.03121

dx = 200 mm, dt = .009 sec

	.9977588	8.780606E-03	-6.436089E-04	2.127641E-04		2.885245E-03
ST =	-.4660258	.9535856	-.4602074	4.352945E-02	**PR** =	.9262331
	1.448438E-02	1.418428E-03	.8332105	7.105564E-03		.1523053
	2.908761	.2901964	-33.84164	.5574984		30.93289

dx = 250 mm, dt = .01125 sec

	.9966071	1.091514E-02	-2.083274E-03	3.190145E-04		5.476107E-03
ST =	-.5563044	.9438768	-.8324718	5.064701E-02	**PR** =	1.388776
	2.153176E-02	2.126763E-03	.7508714	8.221888E-03		.2275968
	3.335013	.3376467	-39.12762	.4347564		35.79262

dx = 304.8 mm (1.00 ft), dt = .013716 sec

	.9951219	1.323022E-02	-4.721649E-03	4.516408E-04		9.599989E-03
ST =	-.6468806	.9338062	-1.319262	5.659404E-02	**PR** =	1.966143
	3.018876E-02	3.010939E-03	.6487856	9.129263E-03		.3210257
	3.661957	.3772937	-43.40468	.3016807		39.74273

dx = 333.3 mm, dt = .0149985 sec

	.9942636	1.442457E-02	-6.590556E-03	5.25773E-04		1.232715E-02
ST =	-.6911992	.9287472	-1.597666	5.892596E-02	**PR** =	2.288865
	3.496214E-02	3.505154E-03	.5920432	9.472713E-03		.3729946
	3.775608	.3928397	-45.01348	.2341656		41.23787

dx = 500 mm, dt = .0225 sec

	.9881727	2.128394E-02	-2.520931E-02	9.923165E-04		3.703847E-02
ST =	-.928516	.9001616	-3.391369	6.280167E-02	**PR** =	4.319885
	6.386326E-02	6.615445E-03	.2402896	9.862685E-03		.6958473
	3.743294	.4186779	-46.67883	-.1145251		42.93555

dx = 609.6 mm (2.00 ft), dt = .027432 sec

	.9832207	2.567633E-02	-.0448194	1.291335E-03		6.159972E-02
ST =	-1.080368	.8808161	-4.541246	5.758515E-02	**PR** =	5.621614
	8.111078E-02	8.608906E-03	2.055522E-02	8.861093E-03		.898334
	3.194438	.3839011	-41.76972	-.2822351		38.57529

```
1000  REM   This program calculates the coefficients needed to simulate
1010  REM   the reference vehicle that is the basis of the IRI.
1020  REM
1030  REM   Initialize vehicle constants (spring rates, masses, damper)
1040  REM
1050     N = 4
1060     K1 = 653
1070     K2 = 63.3
1080     MU = .15
1090     C = 6
1100    DIM A(4,4), ST(4,4), PR(4), A1(4,4), A2(4,4), IC(4), JC(4), Y(4)
1110  REM
1120  REM    Get sample interval and convert to time step at 80 km/h
1130  REM
1140     PRINT
1150     INPUT "Sample interval (mm) = ";MM
1160         V = 80
1170         T = MM / V * 0.0036
1180     PRINT
1190     PRINT "*** Time step = ";T;" sec"
1200  REM
1210  REM   Build the 'A' matrix from the vehicle parameters and
1215  REM   initialize the 'ST' matrix.
1220  REM
1230      FOR I = 1 TO 4
1240          FOR J = 1 TO 4
1250             A(J,I) = 0
1260             A1(J,I) = 0
1270             ST(I,J) = 0
1280          NEXT J
1290         A1(I,I) = 1
1300         ST(I,I) = 1
1310     NEXT I
1320     A(1,2) = 1
1330     A(3,4) = 1
1340     A(2,1) =  - K2
1350     A(2,2) =  - C
1360     A(2,3) = K2
1370     A(2,4) = C
1380     A(4,1) = K2 / MU
1390     A(4,2) = C / MU
1400     A(4,3) =  - (K1 + K2) / MU
1410     A(4,4) = - C / MU
1420  REM
1430  REM   Compute the state transition matrix 'ST' using a Taylor
1440  REM   series expansion.  The variable 'IT' counts iterations in
1450  REM   the series.  The variable 'IS' is used to indicate when the
1460  REM   series has converged.  (IS=1 means that no changes in 'ST'
1470  REM   occurred in the current iteration.)
1475  REM
```

Figure 4. Program to compute coefficients for IRI equations with a microcomputer

```
1480      IT = 0
1490      IT = IT + 1
1500      IS = 1
1510      FOR J = 1 TO N
1520          FOR I = 1 TO N
1530              A2(I,J) = 0
1540              FOR K = 1 TO N
1550                  A2(I,J) = A2(I,J) + A1(I,K) * A(K,J)
1560               NEXT K
1570          NEXT I
1580       NEXT J
1590       FOR J = 1 TO N
1600          FOR I = 1 TO N
1610              A1(I,J) = A2(I,J) * T / IT
1620              IF ST(I,J) = ST(I,J) + A1(I,J) THEN  GOTO 1650
1630              ST(I,J) = ST(I,J) + A1(I,J)
1640              IS = 0
1650           NEXT I
1660       NEXT J
1670       IF IS = 0 THEN  GOTO 1490
1680       PRINT
1690       PRINT "STATE TRANSITION MATRIX:"
1700       PRINT
1710       FOR J = 1 TO N
1720           FOR I = 1 TO N
1730               PRINT ST(J,I),
1740           NEXT I
1750           PRINT
1760       NEXT J
1770   REM
1780   REM    The following code is a matrix inversion routine.  ER is an
1790   REM    error threshold that can be used to indicate singularity.
1800   REM
1810       ER = 0
1820       FOR KK = 1 TO N
1830           KD = KK - 1
1840           PV = 0
1850           FOR I = 1 TO N
1860               FOR J = 1 TO N
1870                   IF KK = 1 THEN 1930
1880                   FOR II = 1 TO KD
1890                       FOR JJ = 1 TO KD
1900                          IF I = IC(II) OR J = JC(JJ) THEN GOTO 1970
1910                       NEXT JJ
1920                  NEXT II
1930                  IF  ABS (A(I,J)) <  =  ABS (PV) THEN  GOTO 1970
1940                  PV = A(I,J)
1950                  IC(KK) = I
1960                  JC(KK) = J
1970               NEXT J
```

Figure 4 (continued)

```
1980          NEXT I
1990          IF  ABS (PV) > ER THEN  2020
2000              PRINT "PIVOT < ";ER
2010              STOP
2020          II = IC(KK)
2030          JJ = JC(KK)
2040          FOR J = 1 TO N
2050              A(II,J) = A(II,J) / PV
2060          NEXT J
2070          A(II,JJ) = 1 / PV
2080           FOR I = 1 TO N
2090              AA = A(I,JJ)
2100              IF I = II THEN 2150
2110                  A(I,JJ) =  - AA / PV
2120                  FOR J = 1 TO N
2130                     IF J <  > JJ THEN A(I,J) = A(I,J) - AA * A(II,J)
2140                  NEXT J
2150           NEXT I
2160       NEXT KK
2170       FOR J = 1 TO N
2180           FOR I = 1 TO N
2190               Y(JC(I)) = A(IC(I),J)
2200           NEXT I
2210           FOR I = 1 TO N
2220               A(I,J) = Y(I)
2230           NEXT I
2240       NEXT J
2250       FOR I = 1 TO N
2260           FOR J = 1 TO N
2270               Y(IC(J)) = A(I,JC(J))
2280           NEXT J
2290           FOR J = 1 TO N
2300               A(I,J) = Y(J)
2310           NEXT J
2320       NEXT I
2330   REM
2340   REM    Calculate the Particular Response matrix.
2350   REM
2360       PRINT
2370       PRINT "PR MATRIX:"
2380       PRINT
2390       FOR I = 1 TO N
2400           PR(I) =  - A(I,4)
2410           FOR J = 1 TO N
2420               PR(I) = PR(I) + A(I,J) * ST(J,4)
2430           NEXT J
2440           PR(I) = PR(I) * K1 / MU
2450           PRINT PR(I)
2460       NEXT I
2470   END
```

Figure 4 (continued)

$$\underline{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -K_2 & -C & K_2 & C \\ 0 & 0 & 0 & 1 \\ K_2 / u & C / u & -(K_1 + K_2)/u & -C/u \end{bmatrix} \qquad B = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ K_1/u \end{Bmatrix} \tag{13}$$

The four constants K1, K2, C, and u are vehicle parameters with values of K1=653., K2=63.3, C=6., and u=0.15. The s coefficients from Eqs. 4 - 7 constitute a state transition matrix, which is computed from the $\underline{A}$ matrix as:

$$\underline{ST} = e^{\underline{A} * dt} \tag{14}$$

The program in Figure 4 solves for the s matrix (called ST in the program) by using a Taylor series expansion of Eq. 13:

$$\underline{ST} = \underline{I} + \underline{A} * dt + \underline{A} * \underline{A} * dt^2 / 2! + \underline{A}^3 * dt^3 / 3! + ... \tag{15}$$

The program keeps adding terms from Eq. 15 until all of the 16 elements in the ST matrix are precise to the limits of the computer.

The remaining four p coefficients constitute the partial response matrix, which is defined as:

$$PR = \underline{A}^{-1} (\underline{ST} - \underline{I}) * B \tag{16}$$

The computer program uses the Gauss elimination method to invert the $\underline{A}$ matrix in solving Eq. 16 for the four elements of the PR matrix.

3.4.5 Test input for checking computation. In order to check that a method for computing IRI from profile is valid, the simple profile shown in Figure 5 should be used as input. The input is a single triangular pulse. It starts at x = 1 m, rises to a value of 2 at x = 3 m, then decreases back to 0 a x = 5 m. The output of the IRI computation is also shown. Because the IRI is the result of averaging, its value will decrease when there is no continuing roughness input, as shown. (Note that the scale on the left of the figure is used for the two plots of displacement, whereas the IRI uses the scale on the right-hand side for slope.) Also shown is the accumulated deflection, which is also printed by the example IRI program listed in Figure 3. This displacement eventually reaches a constant value as indicated. The output data shown in the figure are also listed in Table 3 for intervals of 0.25 m. (The table was generated using the example IRI program from Figure 3 with a sample interval of 25 mm.)

This check can only be used to confirm that the computation method is valid. It is in no way a "calibration." That is, if the results from some computation method are 10% high, they cannot be corrected to

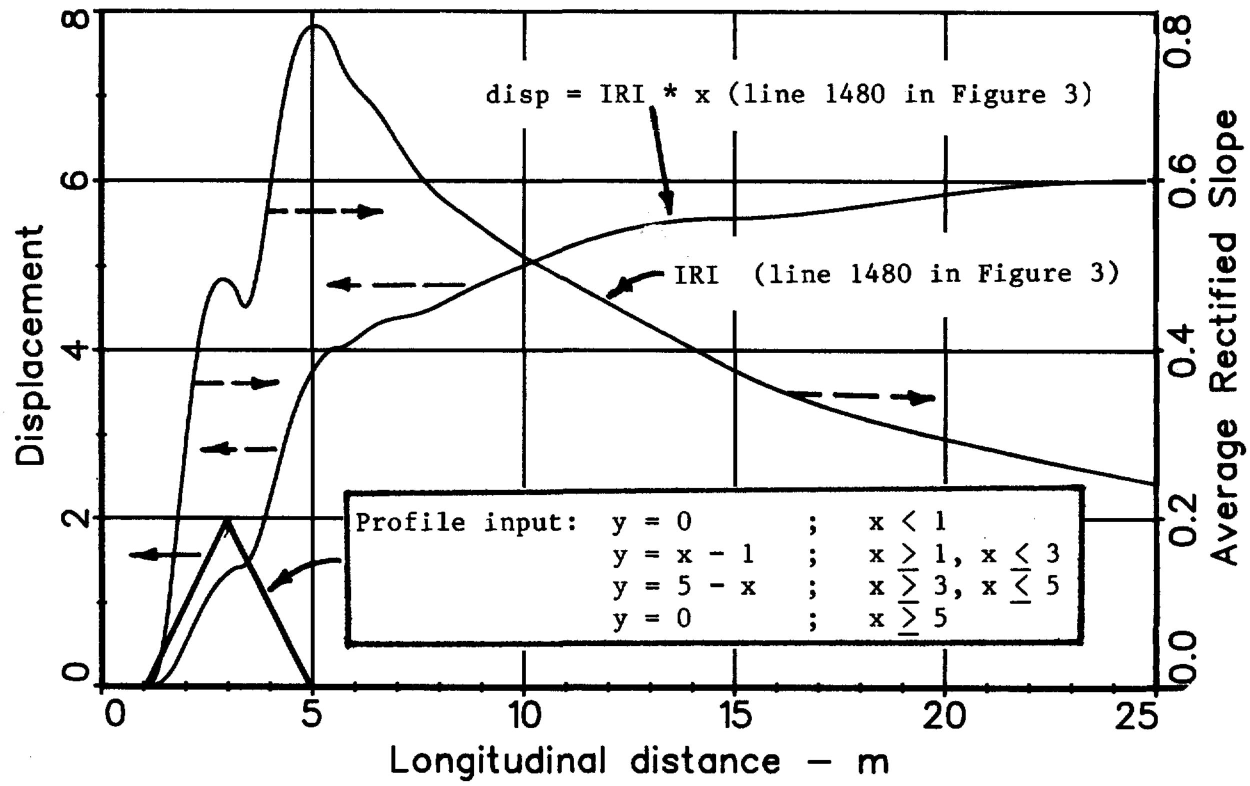


Figure 5. Special profile input used to check IRI computation program.

Table 3. Response of IRI computation algorithm for check input shown in Figure 5

dx = 0.25 m
x = longitudinal distance (m), disp = IRI * x

x	disp	IRI	x	disp	IRI	x	disp	IRI
0.25	0.00000	0.00000	10.25	5.14023	5.01486	20.25	5.91848	2.92270
0.50	0.00000	0.00000	10.50	5.19121	4.94401	20.50	5.93316	2.89423
0.75	0.00000	0.00000	10.75	5.23892	4.87342	20.75	5.94686	2.86596
1.00	0.00000	0.00000	11.00	5.28312	4.80283	21.00	5.95951	2.83786
1.25	0.05553	0.44424	11.25	5.32388	4.73234	21.25	5.97110	2.80993
1.50	0.22023	1.46822	11.50	5.36141	4.66210	21.50	5.98158	2.78213
1.75	0.47306	2.70319	11.75	5.39585	4.59221	21.75	5.99095	2.75446
2.00	0.75476	3.77380	12.00	5.42720	4.52266	22.00	5.99920	2.72691
2.25	1.00790	4.47956	12.25	5.45534	4.45334	22.25	6.00633	2.69948
2.50	1.20138	4.80554	12.50	5.48014	4.38411	22.50	6.01236	2.67216
2.75	1.33439	4.85232	12.75	5.50150	4.31490	22.75	6.01729	2.64496
3.00	1.42554	4.75180	13.00	5.51941	4.24570	23.00	6.02116	2.61790
3.25	1.46459	4.50642	13.25	5.53394	4.17656	23.25	6.02400	2.59097
3.50	1.72578	4.93081	13.50	5.54521	4.10756	23.50	6.02584	2.56419
3.75	2.16300	5.76800	13.75	5.55336	4.03881	23.75	6.02673	2.53757
4.00	2.66248	6.65620	14.00	5.55853	3.97038	24.00	6.02674	2.51114
4.25	3.11728	7.33478	14.25	5.56086	3.90236	24.25	6.02762	2.48561
4.50	3.47144	7.71431	14.50	5.56124	3.83534	24.50	6.02929	2.46093
4.75	3.72540	7.84294	14.75	5.56420	3.77234	24.75	6.03170	2.43705
5.00	3.91465	7.82931	15.00	5.56956	3.71304	25.00	6.03479	2.41392
5.25	4.02533	7.66730	15.25	5.57717	3.65716	25.25	6.03851	2.39149
5.50	4.03072	7.32857	15.50	5.58683	3.60441	25.50	6.04278	2.36972
5.75	4.10399	7.13737	15.75	5.59836	3.55451	25.75	6.04755	2.34856
6.00	4.20709	7.01181	16.00	5.61155	3.50722	26.00	6.05274	2.32798
6.25	4.29849	6.87758	16.25	5.62622	3.46229	26.25	6.05831	2.30793
6.50	4.35937	6.70672	16.50	5.64216	3.41949	26.50	6.06418	2.28837
6.75	4.39329	6.50858	16.75	5.65920	3.37863	26.75	6.07030	2.26927
7.00	4.41616	6.30880	17.00	5.67714	3.33949	27.00	6.07660	2.25059
7.25	4.44437	6.13016	17.25	5.69580	3.30192	27.25	6.08303	2.23231
7.50	4.48715	5.98287	17.50	5.71501	3.26572	27.50	6.08954	2.21438
7.75	4.54489	5.86438	17.75	5.73459	3.23075	27.75	6.09606	2.19678
8.00	4.61197	5.76496	18.00	5.75437	3.19687	28.00	6.10256	2.17949
8.25	4.68122	5.67420	18.25	5.77419	3.16394	28.25	6.10898	2.16247
8.50	4.74746	5.58524	18.50	5.79391	3.13184	28.50	6.11529	2.14572
8.75	4.80882	5.49579	18.75	5.81338	3.10047	28.75	6.12144	2.12920
9.00	4.86616	5.40684	19.00	5.83247	3.06972	29.00	6.12739	2.11289
9.25	4.92149	5.32053	19.25	5.85107	3.03952	29.25	6.13311	2.09679
9.50	4.97650	5.23842	19.50	5.86907	3.00978	29.50	6.13858	2.08087
9.75	5.03175	5.16077	19.75	5.88635	2.98043	29.75	6.14376	2.06513
10.00	5.08670	5.08670	20.00	5.90285	2.95143	30.00	6.14864	2.04955

yield IRI. Instead, the error in the computation must be found and corrected.

Although the IRI computation method used in the example computer program is relatively insensitive to the choice of sample interval, small differences do exist and exact agreement with the values shown in Table 3 should not be expected unless the same sample interval of 0.25 m is used. Differences should be relatively small, however (less than 1%).

CHAPTER 4

ESTIMATION OF IRI USING A CALIBRATED RTRRMS (CLASS 3)

By far, most of the roughness data that is collected throughout the world is obtained with RTRRMSs. The RTRRMS is suited to the rapid and inexpensive collection of roughness data on roads, covering 200 to 300 km per day on continuous surveys. The reference definition of roughness, IRI, was designed to functionally duplicate the response of a standardized "ideal" RTRRMS.

In order for the performance obtained from a RTRRMS to be consistent, the mechanical properties of the vehicle (and roadmeter) must be kept constant through good maintenance and operating practices. Variations in the vehicle will cause corresponding variations in the roughness measures. In selecting and maintaining the vehicle for use in a RTRRMS, the practitioner should be aware of the many variables affecting performance, listed in Section 4.1.

A potential problem with RTRRMSs is that no two are alike in their response to road roughness. Thus, it is necessary to transform the measures to a standard scale (IRI) using relationships established in a calibration, as described in Section 4.2.

In order to ensure that measures made from day-to-day maintain the same meaning, control procedures must be specified in order to limit the changes in the RTRRMS performance. Section 4.3 describes the control test methods and procedures that should be used to ensure that roughness measurements are obtained that will have the same meaning in the future as they had during measurement.

4.1 Selection and Maintenance of a RTRRMS

An RTRRMS consists of three components: a vehicle, a transducer that detects relative movement of the suspension, and a display that is connected electrically to the transducer. The transducer and display together are called a roadmeter, and are purchased as one item. The measurement obtained from the roadmeter is actually the response of the vehicle to the road surface as it is travelled at some speed. Thus, the measure is the result of the roadmeter, the operating procedure, and the vehicle and all of the variables affecting its response.

4.1.1 The roadmeter. Roadmeters are known by many names: ride meters, Mays Meters (Rainhart Company, USA), Bump Integrators (TRRL, UK), NAASRA Meters (ARRB, Australia), Cox Meters (James Cox Company, USA) PCA Meters, and others. Although the many meters have different names, and come with incompatible instructions and recommendations for use, most are functionally equivalent when operating within their design range [1, 2].

A roadmeter provides a number of counts for a test, with each count corresponding to a certain amount of suspension movement. By summing the counts--a task that may or may not be performed by the instrument--a number is obtained that is proportional to the total accumulated suspension travel that occurred during a test. When divided by the length of the test section, the result is a ratio with units of slope that is called average rectified slope (ARS).

When selecting the roadmeter, consider its ruggedness, simplicity of use, and range of roughness measurement, in addition to cost and availability. Although most are functionally equivalent within their operating ranges, not all roadmeters may be acceptable under specific terms of reference due to the outmoded designs of some systems. Also, note that many roadmeters are designed with the evaluation of new paved roads in mind, and may not be able to cope with medium and high roughness levels. In general, electro-mechanical components (mechanical counters, stepper motors) should be avoided because they are unable to keep up with the high stroking rates of the vehicle suspension that occur on rougher roads. Also, their performance can depend on the supply voltage, which may vary during use, thus adding to the errors in measurement. Some roadmeters, such as the PCA Meter, have been used to compute a "weighted" sum of counts. Most PCA meters can be used to measure ARS by simply summing counts; however, some may be wired so as to prevent all counts from registering. If not all counts register, then the linearity and relative precision of the RTRRMS are degraded, with a result of less accuracy.

The only roadmeter designs that have been validated for use over the full range of roughness covered in the IRRE have been developed by highway research agencies for their own use: the BI unit (TRRL), the NAASRA unit (ARRB), and the modified Mays Meter[1] (GEIPOT).

Every roadmeter design is somewhat different, so the instruction manual should always be studied to understand the principles of its operation. Be aware that the instructions are seldom sufficient to explain how to obtain calibrated roughness measurements, and that some of the suggested procedures may be outdated or nonstandard. Hence, the manual should be used mainly to understand the operational principles of the instrumentation, while these Guidelines should be used to understand the proper use.

[1]The commercial Mays Meter (Rainhart, USA) cannot always provide valid measures on rougher roads (IRI > 4 m/km).

4.1.2 The vehicle. Three types of vehicle can be used in conjunction with a roadmeter to constitute a RTRRMS:

1) A passenger car or light truck with a solid rear axle. A vehicle with independent rear suspension should not be used because roll motions of the vehicle will be sensed as roughness. A rear-drive vehicle is recommended because the mass of the axle more closely matches the standard. Coil springs are preferred to leaf springs because they have less Coulomb friction.

2) A towed two-wheeled trailer. The trailer should have a solid axle. The actual configuration of the towing vehicle is not critical, but the same towing vehicle should always be used between calibrations, because its characteristics will influence the ARS measures. If a towing vehicle is replaced, the RTRRMS must be re-calibrated.

3) A towed one-wheeled trailer. As with a two-wheeled trailer, recalibration is needed if the towing vehicle is changed. The hitch arrangement must have provision to hold the trailer upright during use.

4.1.3 Installation of the roadmeter in the vehicle. In a two-track vehicle, the roadmeter transducer should be mounted vertically (within 5 degrees of true vertical) between the body (or frame) and the center of the axle. Care should be taken to ensure that the transducer is located correctly to prevent the roadmeter from registering extra counts caused by vehicle braking, accelerating, and cornering (all of which should be kept to a minimum during testing).

In a single-track trailer, the roadmeter is usually an integral part of the trailer. If replaced, the new roadmeter should be installed in the same location as the original unit, in a vertical orientation.

4.1.4 Operating speed. The standard IRI speed is 80 km/h. The IRI numeric is designed to match typical operation of a RTRRMS when operated at this speed; thus, the reproducibility associated with a RTRRMS is generally best when this speed is used. The ARS measures obtained by a RTRRMS are speed dependent, and therefore the operators of the instruments must appreciate the importance of making all measurements at the same speed. There are situations, however, when a lower speed may be needed. These include cases where:

1) A speed of 80 km/h is not safe, for reasons of traffic, pedestrians, restrictive geometry, etc.

2) The roadmeter produces erroneous and inconsistent measures at 80 km/h on the rougher roads.

3) The project will mainly cover short test sections, and repeatability for individual sites has a high priority. The shortness of the site is to some extent compensated by the longer time needed to cover the site at a reduced speed.

4) The vehicle and/or roadmeter portion of the RTRRMS are too fragile for continued operation at that speed, and must be operated slower if they are to be operated at all.

The recommended solution for problems associated with fragile or inconsistant mechanisms is to replace the vehicle and/or roadmeter with something more rugged. If any of these conditions are unavoidable for more than a few sites, then a lower standard RTRRMS speed should be adopted for all RTRRMS measurements (50 or 32 km/h are recommended when lower speeds are needed). The calibration reference is still IRI, thus the calibration method described in Section 4.2 should be followed, with the difference that the RTRRMS is operated at the selected speed.

When only a few sections need to be measured at a lower speed, then the speed correction methods described in Section 4.2 can be used.

4.1.5 Shock absorber selection. The single most important vehicle component affecting the RTRRMS response to roughness is the shock absorber. In order to obtain the best reproducibility (and thus, overall accuracy), the vehicle should be equipped with very "stiff" shock absorbers. When "softer" shock absorbers are used (often selected by the vehicle manufacturer for improved ride quality), a particular RTRRMS can "tune in" on certain roughness conditions that do not affect other RTRRMSs or the standard reference, leading to "outlier" data points. The use of "stiff" shock absorbers also has an advantage in that the effects of other sources of error are reduced, and therefore, less effort is needed to maintain the RTRRMS in calibration.

The shock absorbers are such a critical element of the RTRRMS performance that a new calibration is required whenever they are replaced, even if the replacement shock absorbers are of the same make and model as the previous ones. Since recalibration is always required, there is no advantage in selecting replacements made by the same manufacturer, unless their performance has been quite satisfactory. The primary characteristics to look for are ruggedness, insensitivity to temperature, and high damping (the shocks should be "stiff"). Whether the installed shock absorbers provide sufficient damping can be judged by direct comparison of the ARS values (in m/km) from the RTRRMS to the IRI values on the calibration surfaces. If the measures from the vehicle are more than 20% greater on the average than the IRI on moderately rough sites, more effective damping on the vehicle suspension is recommended.

4.1.6 Vehicle loading. The weight of the vehicle body affects the roughness measures, such that increasing the weight usually increases the measured ARS. This effect is nearly eliminated when the roadmeter is mounted in a trailer. But when the roadmeter is mounted in a car or truck, care must be taken to always maintain the same vehicle loading during roughness measurement and calibration, although some variation is inevitable due to the consumption of fuel. The vehicle should not contain extra cargo or occupants during testing.

4.1.7 Tire pressure. Measures of roughness increase with tire pressure (for both passenger car- and trailer-based RTRRMSs). Therefore, pressure should be checked every morning before the vehicle has been started and set to some value selected as being appropriate for the vehicle.

4.1.8 Mechanical linkages in the roadmeter. The roadmeter transducer is connected to the axle of the vehicle by some type of linkage. If the roadmeter transducer is spring loaded, it can sometimes oscillate independently if the spring is not stiff enough, resulting in increased counts. If the linkages between axle, transducer, and vehicle body (or trailer frame) are at all loose, counts will be lost. Pulleys on shafts can slip, also resulting in lost counts. Frequent inspection and maintenance of this linkage must be included in the operating procedures established.

4.1.9 Tire imbalance and out-of-roundness. The rotating tire/wheel assemblies on the axle instrumented with the roadmeter will oscillate as a result of imbalance and/or runout, causing an increase in roadmeter counts. The increase in counts due to the extra vibrations for the tire/wheel assemblies is most important on smoother roads, where the road-induced vibrations are smaller. This effect can be reduced by using premium tires, mounted on the wheels with attention given to obtaining uniform bead seating. Damaged wheels or tires should be replaced, as should tires that have been "flat spotted" by the skidding that occurs during emergency braking. The tire/wheel assemblies on the instrumented axle should be statically balanced (dynamic balancing has not been shown to help), to within 8 gram-meters (1.0 ft-oz) for routine use. Calibration checks should be performed any time one of these components is changed.

4.1.10 Temperature effects. The most critical mechanical behavior of the RTRRMS vehicle is its ability to damp suspension vibrations. Low damping results in many counts, while high damping results in few counts. The damping derives from the mechanical properties of the shock absorbers, the tires, and the linkages in the suspension. Unfortunately, the damping changes significantly with the temperatures of the various components that contribute to the overall damping. If the air temperature is greater than 0 deg C, changes in damping due to changes in air temperature are not significant over a range of 10 deg or less. (For example, variations between 20-30 deg C should not have a noticeable effect on roughness measurements.) Greater variations generally do have a noticeable effect, with the higher temperatures resulting in an increase in counts. When the temperature drops to 0 deg C and lower, the RTRRMS measurements become much more sensitive to air temperature.

Under most operating conditions, the far greater influence on component temperature is roughness itself: the vehicle shock absorbers heat up much more on rougher roads than on smooth ones [8]. For this reason, special attention should be given to ensuring adequate "warm-up" prior to recording roughness data, in routine survey work and during calibration. The amount of time needed for warm-up depends on the vehicle and the roughness level. Typical times needed are 10-30 minutes, and should be determined experimentally for each RTRRMS as described in Section 4.3.3. The warm-up time should be spent operating the RTRRMS at the test speed on roads having approximately the same roughness level as the one being measured (within 20%). Therefore, if the RTRRMS must travel to a test site over good roads, and the test site itself is a rough road, additional warm-up time will be needed at the test site.

4.1.11 Water and moisture effects. The mechanical properties of the vehicle part of the RTRRMS are not normally influenced directly by the presence of water. Indirectly, however, rain and surface water can affect roughness measurements by cooling components to lower-than-normal temperatures, with the result that fewer counts are accumulated. The common problem is water splashing on the tires and shock absorbers, cooling them in the process. If the climate is so wet that rainy days are the norm rather than the exception, a "wet calibration" should be performed to convert raw measures taken on wet days to the IRI roughness scale.

Another problem related to water is the accumulation of mud, snow, and ice in the wheels, causing imbalance of the tire/wheel assemblies (Section 4.1.9). Ice on the vehicle body can change its overall weight, thereby affecting the roadmeter readings (Section 4.1.6).

4.2 Calibration of a RTRRMS

Because the response behavior of a particular RTRRMS is unique and variable with time, the system must be calibrated when it is initially put into service, and periodically throughout its use when its response falls outside the control limits (see Section 4.3.4).

4.2.1 Calibration method. Calibration is achieved by obtaining "raw" measures of ARS (the "counts/km" or other similar number produced as output by the instrument) on special calibration sites. These sites are sections of road that have known IRI roughness values as determined with a Class 1 or 2 method (rod and level, or profilometer). The RTRRMS is periodically run over the calibration sites 3 - 5 times at the standard speed after suitable warm-up. (Longer calibration sites can be used to reduce the need for repeated measurement, as described in Section 2.3.1.) The "raw" ARS values from the RTRRMS are plotted against the IRI values, with the RTRRMS values on the x-axis and the IRI values on the y-axis, as illustrated for four examples in Figure 6. A line is fitted to the data points and used to estimate IRI from RTRRMS measurements taken in the field. The accuracy of the calibrated measures can be seen approximately as the scatter of the points about the fitted line: the smaller the scatter, the better the accuracy.

a) Calibration for a fleet of vehicles. Each RTRRMS requires its own calibration. Even when two RTRRMSs use the same model of vehicle and roadmeter, their responses can differ by over 25% when new. Much larger differences can exist after they have experienced wear and tear. Thus, a "fleet calibration" should not be attempted.

b) Calibration for different speeds. When it is necessary, for whatever reason, to conduct tests at any other than the standard speed, the routine calibration equation does not apply. Separate relationships between the "raw" measure and the IRI must be developed for each of the other speeds, as described in Section 4.2.5.

c) Calibration for different surface types. Depending on the required accuracy of the calibrated roughness data and the local road-building practices, separate calibration relationships may be warranted for different surface types (paved and unpaved, for example). This section presents guidelines for a single calibration for all road surface types to be covered in the project. Past experience has indicated that this is adequate for asphaltic concrete, PCC concrete, surface treatment (chip seal), and Brazilian earth and gravel roads.

The calibration data can be examined to determine whether an unacceptable bias exists that can be attributed to surface type. If such a bias exits, then separate calibrations can be performed for subsets of surface types. For example, the plot shown in Figure 6a includes data from four surface types. The points for asphaltic concrete, gravel, and earth appear to be fairly evenly distributed. However, there are four "outlier" points taken on slightly corrugated surface treatment sites, which have higher ARS values than would be expected from a single calibration line (because the vehicle tuned-in to the corrugation wavelength). In the worst case, an error of nearly 4 m/km exists between the IRI as estimated from the calibration line and

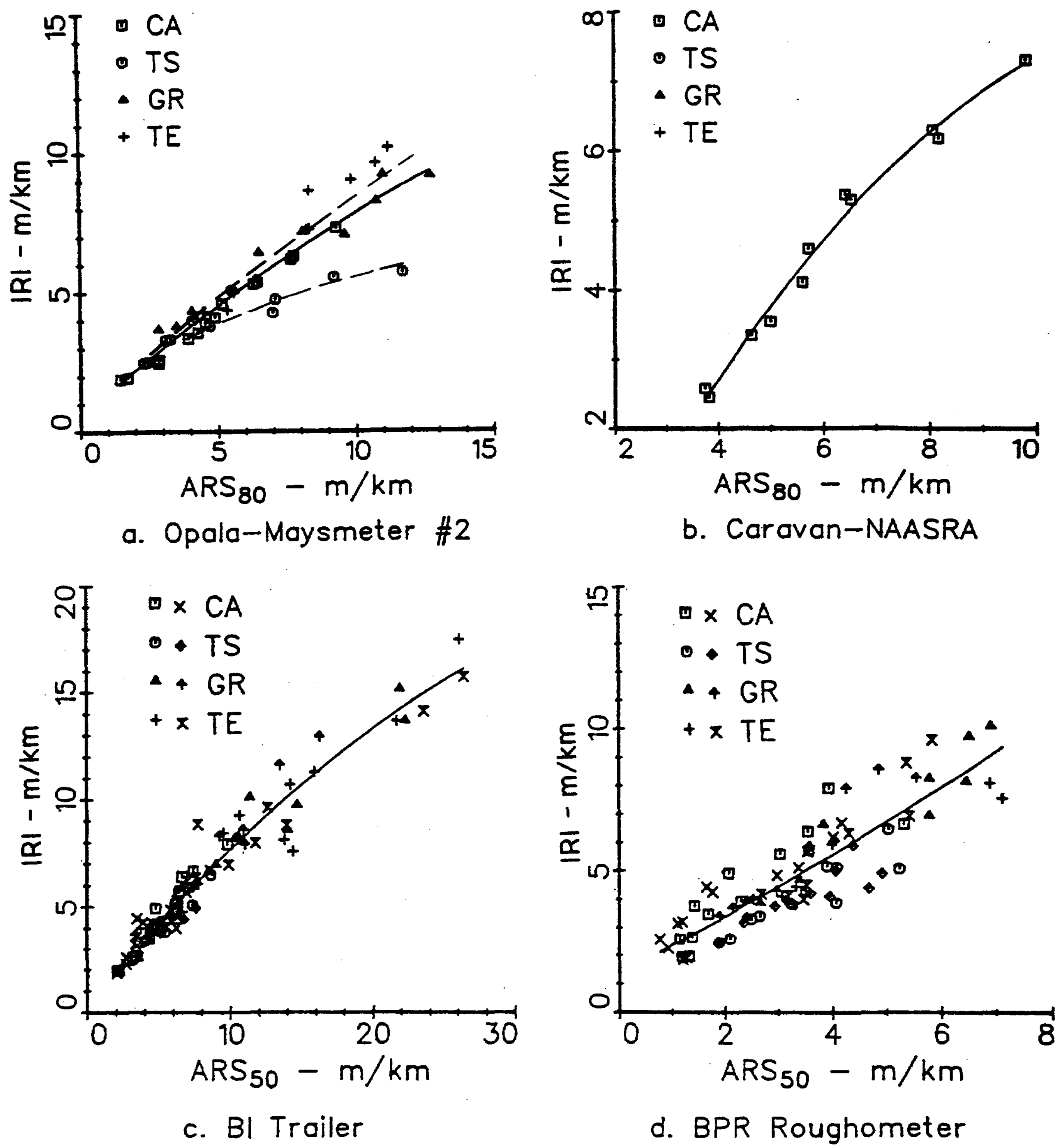


Fig. 6. Example calibration plots.

the true IRI. Better accuracy could be obtained if a separate calibration were performed for the surface treatment sites. When this is done, then two calibration equations are obtained, as indicated by the dotted lines. By using separate calibrations, the maximum error is reduced by half. A second example is the plot shown in Figure 6c. In this case, there is no obvious bias due to surface type. The worst error that would be obtained is about 3 m/km, although the typical error can be seenh to be much smaller: about 1 m/km. Thus, the single calibration equation appears equally representative for all four of the surface types.

4.2.2 Calibration equation. The data from the calibration sites are used to regress IRI against the "raw" RTRRMS measurements, by minimizing the squared error between the reference IRI values and the values estimated from the RTRRMS using a quadratic equation. When a single-track RTRRMS is used, the regression is computed on the basis of individual wheeltrack measurements. When a two-track RTRRMS is used, the IRI is measured for both of the wheeltracks traveled by the tires of the RTRRMS, and the two numbers are averaged. The average is then used as a single measurement of IRI for that lane, and regressed against the single measure obtained from the two-track RTRRMS.

Subsequent estimates of IRI made from the RTRRMS using the calibration equation are in fact the calibrated roughness measurements from the RTRRMS, and are designated in this section as E[IRI]. The mathematical details needed to compute the calibration equation are summarized in Figure 7. The accuracy associated with the RTRRMS can also be calculated, and is quantified by the Standard Error (SE) of the IRI estimate, using the equation given in the figure.

It should be mentioned here that the calibration equation and Standard Error are computed in a convention opposite to that normally used for statistical analysis (that is, the definitions of x and y are reversed from what they would be in a classical analysis of variations), because the calibration serves a different purpose. Rather than describing the statistics of the raw ARS measurement, the practitioner is concerned with the accuracy of the final roughness measure. Therefore, care should be taken in using statistical analysis packages, to ensure that the x and y variables are associated correctly with the RTRRMS and IRI measures.

4.2.3 Selection of calibration sites. For a calibration to be valid, the calibration sites must be representative of the roads being surveyed in the project. When possible, the sites should be located on tangent or low-curvature roads, and they should have roughness properties that are uniform over the length of the site, including a 50 m lead-in. When used for long-term projects, the calibration sites

The calibration equation for a RTRRMS is:

$$E[IRI] = A + B \cdot ARS + C \cdot ARS^2$$

ARS is the "raw" measure with units: counts/km or an equivalent (in/mile, mm/km, etc.), and E[IRI] is the estimate of IRI, having the same units used for $RARS_{80}$ (m/km is recommended). The coefficients A, B, and C are calculated as indicated below, where N = number of calibration sites, x_i = ARS measurement on i^{th} site, and y_i = $RARS_{80}$ roughness of i^{th} site (computed from a measured profile). The accuracy of E[IRI] measures is the Standard Error (SE), which should also be calculated as indicated below.

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i = (x_1+x_2+\ldots x_N)/N \qquad \overline{x^4} = \frac{1}{N}\sum_{i=1}^{N} x_i^4 = (x_1^4+x_2^4+\ldots x_N^4)/N$$

$$\overline{x^2} = \frac{1}{N}\sum_{i=1}^{N} x_i^2 = (x_1^2+x_2^2+\ldots x_N^2)/N \qquad \overline{y} = \frac{1}{N}\sum_{i=1}^{N} y_i = (y_1+y_2+\ldots y_N)/N$$

$$\overline{x^3} = \frac{1}{N}\sum_{i=1}^{N} x_i^3 = (x_1^3+x_2^3+\ldots x_N^3)/N \qquad \overline{y^2} = \frac{1}{N}\sum_{i=1}^{N} y_i^2 = (y_1^2+y_2^2+\ldots y_N^2)/N$$

$$\overline{xy} = \frac{1}{N}\sum_{i=1}^{N} x_i \cdot y_i = (x_1 \cdot y_1+x_2 \cdot y_2+\ldots x_N \cdot y_N)/N$$

$$\overline{x^2y} = \frac{1}{N}\sum_{i=1}^{N} x_i^2 \cdot y_i = (x_1^2 \cdot y_1+x_2^2 \cdot y_2+\ldots x_N^2 \cdot y_N)/N$$

$$C = \frac{(\overline{x^2y} - \overline{x^2} \cdot \overline{y}) \cdot (\overline{x^2} - \overline{x} \cdot \overline{x}) + (\overline{x} \cdot \overline{x^2} - \overline{x^3}) \cdot (\overline{xy} - \overline{x} \cdot \overline{y})}{(\overline{x^4} - \overline{x^2} \cdot \overline{x^2}) \cdot (\overline{x^2} - \overline{x} \cdot \overline{x}) - (\overline{x^3} - \overline{x} \cdot \overline{x^2})^2}$$

$$B = \frac{[\overline{xy} - \overline{x} \cdot \overline{y} + C \cdot (\overline{x} \cdot \overline{x^2} - \overline{x^3})]}{\overline{x^2} - \overline{x} \cdot \overline{x}}$$

$$A = \overline{y} - B \cdot \overline{x} - C \cdot \overline{x^2}$$

$$SE = \overline{y^2} + A^2 + (B^2 + 2 \cdot A \cdot C) \cdot \overline{x^2} + C^2 \cdot \overline{x^4}$$
$$- 2 \cdot A \cdot \overline{y} - 2 \cdot B \cdot \overline{xy} - 2 \cdot C \cdot \overline{x^2y}$$
$$+ 2 \cdot A \cdot B \cdot \overline{x} + 2 \cdot C \cdot \overline{x^3}$$

Fig. 7. Computation of the calibration equation.

should be located on little-used roads whose roughness properties will not change rapidly with time.

a) roughness range. It is essential that the sections be "naturally rough," exhibiting roughness resulting from normal construction/maintenance/use histories. (Artifically induced roughness on calibration sites will not calibrate the RTRRMS for real-world roads.) The calibration is technically valid only over the range of roughness covered by the calibration sites; hence, extrapolation should be avoided if at all possible. In any case, extrapolation beyond the calibration range by more than 30% in each direction (30% less than the smoothest calibration site and 30% rougher than the roughest) should not be considered. If the additional range is needed, then appropriate calibration sites must be found.

b) Uniformity. The calibration sites should be uniformly rough over their lengths, such that the rate at which counts accumulate on the roadmeter of the RTRRMS is fairly constant while traversing the section. A RTRRMS responds differently to a road with uniform and moderate roughness than to a road that is smooth over half its length and rough over the other half. If a two-track RTRRMS is being calibrated, then the roughness should also be reasonably uniform across the wheeltracks.

c. Approach. Remember that vehicles always respond to the road after they have passed over it, and that the measurement on a site is partly the result of the surface immediately preceding the site. Therefore, avoid sites that have a distinctly different roughness character in the 50 m approach to the site.

d. Geometry. Calibration sites should preferably be on tangent sections of road. Only in exceptional circumstances should even a slight curvature be accepted. The road need not be level, but there should be no noticeable change in grade on or immediately before the site, as the transition in grade can affect the measurement of a RTRRMS. Gentle grades also facilitate the maintenance of constant test speed, and reduce the effort needed to manually measure profile with rod and level equipment.

e. Distribution of roughness among sites. In order to minimize calibration error (Section 2.3.2), each roughness level of interest should be represented approximately equally in the calibration. Table 1, which listed accuracy requirements in Section 3, lists seven ranges of roughness. Each of these ranges should be equally represented by the calibration sites if they are to be included in the project. Table 4 lists the requirements for distribution of roughness: a minimum of two sites for each range that will be covered in the project. When more than two sites of each roughness level are used, the additional sites should be selected to maintain uniform distribution among the roughness

Table 4. Summary of Requirements for RTRRMS calibration sites

	RTRRMS Type Two-track	RTRRMS Type Single-track
Minimum number of sites...........................	8	12
Recommended number of sites for each roughness level covered by the calibration. (See Table 1 for definitions of the seven roughness levels)	2	3
Maximum variation in the number of sites.......... representing each roughness level. (i.e., sites should be distributed uniformly among different roughness levels.	1	1
Minimum site length*	200 m	200 m
Allowable variation in site length*................ (all sites should have the same length)	0	0
Recommended total length .... (site length x number of sites)	4.5 km	6.0 km
Recommended number of repeat RTRRMS................ measures per site (L = length in meters)	1000 / L	1000 / L
Minimum approach distance for site................. (RTRRMS must be brought to speed **before** entering approach area.)	50 m	50 m

* In practice, it can sometimes be difficult to find long homogeneous sites on very rough unpaved roads. It is better to include shorter homogeneous sites than to omit high roughness sites from the calibration.

levels. At no time should the number of sites for the "most represented" and "least represented" roughness levels differ by more than one.

Figure 1 (in Section 2) and Figures 12 and 13 (and the accompanying text in Section 5) may be of help in determining approximate roughness ranges prior to the calibration. Note that the seven levels of roughness from Table 1 cover an extremely broad range of road quality. The smoothest applies only to very high-quality highway and airport runway surfaces, while the roughest two categories only apply to the rougher unpaved roads.

f. Number of sites and site length. In order for the calibration equation to be representative, it must be based on a sufficient amount of test data. Table 4 also lists minimal requirements concerning the number of sites and their lengths.

Note that it is impossible to design a valid calibration that is "minimal" in every respect covered by the table (just barely meets each requirement). For example, if the project covers six of the seven roughness levels, then a minimum of 12 sites are required (two per roughness level). And if only 12 sites are used, they must be at least 375 m long (4500 m/12 sites ≃ 320 m/site). Alternatively, 23 sections, each 200 m long, could be used.

Better accuracy can be obtained by increasing the overall length over that shown in the table. This can be done either by using longer sites, or using more sites of a given length. At the present time, however, the overall accuracy is largely limited by the reproducibility of the RTRRMS, such that the calibration requirements of the table lead to calibration error that is in most cases negligible. The main advantage of longer sites would be in reducing the need for repeat measurements with the RTRRMS during calibration, as described in Section 2.3.1. This is recommended if a high-speed profilometer is available to establish the reference IRI values.

A constant test site length is needed during a calibration, but this restriction does not apply to the routine measurement of road roughness. When IRI of the calibration site is measured with a rod and level, it is natural to select short sites to minimize the manual effort. The calibration is valid, however, for any length of road having reasonable homogeneity.

g. Identification of wheeltracks. For the calibration of a RTRRMS, the wheeltrack(s) should be identified to ensure that the same lines along the roadway are traversed by the tire(s) of the RTRRMS as are measured by the rod and level. For a single-track RTRRMS, only the wheeltrack traveled by the RTRRMS needs to be marked. For a two-track

RTRRMS, both wheeltracks traveled by the vehicle should be marked, and the space between the marked wheeltracks should match the spacing between the tires on the axle with the roadmeter instrument. A wheeltrack selected for calibration of a RTRRMS should not have any distinguishing roughness features in the 40 m preceding the wheeltrack, as they will affect the measure of the RTRRMS, but will not be reflected in the IRI measure. The starting point, the ending point, and the lateral location of the wheeltrack should be clearly marked to ensure that the survey crew measures the correct profile, and so that the driver of the RTRRMS can orient the RTRRMS correctly.

4.2.4 Determining IRI of calibration sites. The IRI for the calibration sites is determined by obtaining a Class 1 or Class 2 measurement of profile on the sites and computing the values for IRI, as described in Section 3.

a) Frequency of measurement. The measurement of IRI on paved calibration surfaces may need to be repeated periodically, particularly if the project covers a long period of time. The frequency needed for repeat measures with a Class 1 or Class 2 method depends on the local conditions and the accuracy requirements of the project. For paved roads that are not subjected to heavy traffic or harsh seasonal changes, the IRI may change so slowly that measures need only be repeated every year or so. For unpaved roads, roughness is sensitive to so many environmental conditions that the IRI changes in a much shorter time. If there is rain, significant change in humidity or temperature, or traffic on the site, its roughness can change in a matter of weeks, days, or even hours. Therefore, calibrations involving unpaved roads should be planned so that the RTRRMSs can be run over the unpaved sites at approximately the same time they are measured with a profilometric method. Naturally, when calibration sites are exposed to any maintenance, the IRI values are affected, and earlier measurements are no longer valid for future calibration.

b) Replacement of calibration sites. When the IRI roughness value for a road site has changed, that site cannot be used for future calibrations until the new IRI is established. Technically, it does not matter whether the old site is re-measured, or a new site is selected. Given that normal practice is to repair the "worst" roads, it would be expected that road containing some of the "rough" calibration sites would be scheduled for maintenance during the duration of a long study. As long as alternative sites can be found having similar roughness, routine calibration of a RTRRMS can continue. Whenever an IRI measurement must be made of a calibration site, the "best" site (from the standpoint of length, geometry, roughness, location, and likelihood of remaining unchanged for the longest time) should be selected. Unless it is desired to monitor the changes in roughness of a certain calibration site as a part of the project, there is no technical advantage in routinely reselecting the same sites.

4.2.5 Compensation for non-standard speed. There may be occasions in a roughness survey project where it is not possible to obtain the roughness measurements at the standard speed of 80 km/h. A lower speed may be required due to high density of local traffic, restrictive geometry, or high roughness levels that are beyond the operating range of a particular RTRRMS. In those cases, an alternative speed of 50 km/h is recommended. A speed of 32 km/h can also be used, but lower speeds should be avoided because the measured ARS roughness becomes strongly affected by the envelopment properties of the tires used on the RTRRMS.

The practitioner is then faced with the task of developing a speed conversion procedure for translating the RTRRMS measurements made at a lower speed to IRI. Vehicle speed has a complex effect on the observed roughness of a road that very subtly influences how a RTRRMS should be calibrated and used. It may be noted that in the 50-80 km/h speed range, the ARS roughness is sometimes insensitive to speed, which is fortunate in the sense that it minimizes the errors in standard measurements arising from minor speed variations during test. However, roughness measurements made purposely at test speeds different than the standard 80 km/h necessitate that a different calibration be used. Two basic methods are available for the calibration/conversion process.

a) Direct calibration for non-standard speed (32 or 50 km/h). This is the preferred method. The calibration as described earlier is performed, with the only difference in procedure being that the RTRRMS is operated at the non-standard speed on the sites and correlated directly against IRI. This is a calibration "across speed."

When a very low speed such as 32 km/h is used, the reproducibility associated with the RTRRMS may suffer slightly, and the calibration obtained may be specific to surface type. That is, while a single calibration may yield sufficient accuracy over several surface types when measures are made at 80 km/h, a systematic calibration error can be introduced for some surface types when measures are made at reduced speed. This is due to the different wavebands sensed by the RTRRMS at the two speeds.

b) Correlation of ARS measures made at different speeds. This is an alternate method involving a two step conversion. It has more potential for error, and should therefore be used only when the method above is not possible.

First, a correlation relationship between measures from the RTRRMS at the non-standard speed and at 80 km/h is obtained by running tests with the RTRRMS at the two speeds on a number of sites. The calibration sites may be used, although a number of other representative sites should be included. This does not involve a significant amount of additional effort because profile measurement is not required.

Then the measurements at the non-standard speed are used to estimate the value that would have been obtained at 80 km/h. That estimate of the 80 km/h measurement is then used with the calibration equation for that particular RTRRMS to yield IRI.

Note that the roughness range covered by this second method does not need to cover the roughness range of the entire project, but only the roughness range over which speed conversions are needed. The minimum requirements of Table 4 still apply, however, meaning that at least three roughness levels must be included.

This second method is less accurate than the first, and can result in a calibration error due to the combined use of two regression equations.

4.3 Operating and Control Test Procedures

To ensure that meaningful results are obtained, a fixed procedure has to be followed any time a series of measurements are to be taken. The procedure must ensure that a valid calibration is in effect and that proper function can be verified via control tests. Figure 8 diagrams the logic that should be followed in the procedures [9]. As indicated in the figure, normal operation includes more than simply turning the meter on: it includes the operation of the equipment, the calibration of the equipment, and the constant monitoring of the equipment for damage and change. The exact procedures followed in a project sould be formulated with the accuracy and efficiency requirements of the project in mind. This section describes some of the factors to consider in devising the routine procedures.

4.3.1 Vehicle and roadmeter operation. Standard operating procedures need to be followed to obtain reproducible measurements.

a) Personnel. Two operators are recommended. The driver is responsible for maintaining the test speed and the alignment of the vehicle in the wheeltracks. The second operator sets the roadmeter at the beginning of a test section, records the roadmeter readings at the pre-determined intervals, and records location and event markers at the test speed. The combined weight of the two operators should be within 10 kg of those who calibrated the vehicle.

Automated roadmeter systems can allow operation by the driver. However, the recording of data and notes can be difficult while driving.

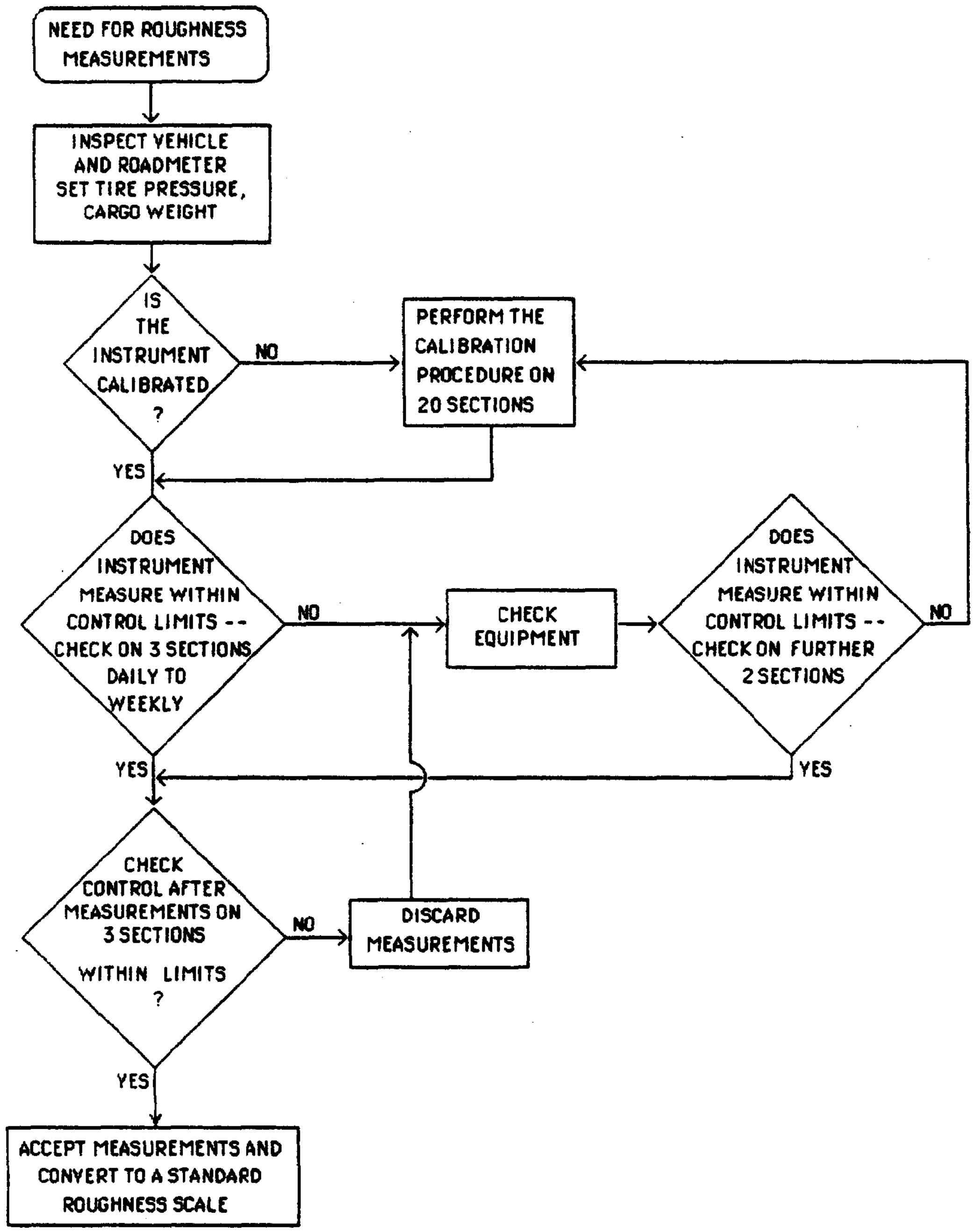


Fig. 8 Logic diagram for RTRRMS operation

A one-person operation is probably best only for projects involving few measurements, where the time lost in stopping the vehicle to record and organize field notes is not a problem.

b) Inspection. Before measurement, the equipment should be visually inspected to ensure that it is functioning correctly. The roadmeter linkages, tire pressures, and cleanliness of the wheels need checking at rest stops or at least daily. During winter, accumulation of ice and snow on the vehicle should be kept in check. When operating in muddy conditions, the accumulation of mud in the wheels can be a problem.

c) Weather. Measurements should not be made during heavy rain or strong or gusty winds. On unpaved roads, measurements should not be made if the surface is very wet or slippery, due to the effect of mud on the wheels and the cooling effect of water on the shock absorbers.

d) Speed control. It is important that the test be run within 5% of a constant speed, since roughness results are speed dependent. The vehicle should be brought to speed at least several seconds (100 m) before the start of the test section. Usually, the standard speed of 80 km/h will be adopted.

e) Lateral positioning. The vehicle should travel consistently in the wheeltracks. As far as practicable, potholes should be avoided since these can damage the roadmeter and invalidate the calibration. When potholes are included in the measurement path, their presence and a brief description should be noted.

f) Warm-up. Rest stops between measurements should be kept to a minimum, and adequate warm-up time of 5 to 10 minutes of the vehicle running at test speed should be allowed prior to test. Longer periods of 15 to 20 minutes are necessary on roughness exceeding 8 m/km or during cold or wet weather. (See Section 4.3.3 for more specific guidelines on selecting an appropriate warm-up time.)

4.3.2 Data processing. The number from the roadmeter should be converted to a form of ARS that is convenient for that particular roadmeter, such as "counts/km," "in/mi," or "mm/km." ARS is computed by dividing the counts accumulated by the roadmeter while on the test section by the length of the section. If the test speed differs from the standard, then it should be noted also. (When data are taken at several speeds, a convenient convention for indicating speed is to add a subscript to ARS, e.g., ARS_{80} 3.2, ARS_{50} = 3.8, etc.)

The calibrated result is obtained by applying ARS in the calibration equation (from Figure 7):

$$E\,[IRI] = A + B * ARS + C * ARS^2 \qquad (16)$$

The value of E [IRI] is the RTRRMS estimate of the IRI on the measured section.

When repeat measurements have been performed, simple averaging of the original ARS measures is recommended, prior to conversion to IRI.

Figure 9 shows a combination field form and work sheet that can be used to help convert the readings from the roadmeter to calibrated roughness measures. In this example, the procedure requires three repeat measurements on each site. The calibration equation, shown at the top of the figure, is also plotted for graphical conversion to IRI.

4.3.3 Temperature sensitivity test. The responsiveness of a RTRRMS to roughness changes as vehicle components "warm up" when traversing rough roads. This test should be conducted for each RTRRMS when it is first used to determine the amount of warm-up time that should be allowed for daily operation, and also to quickly identify vehicles that are unduly sensitive to temperature and thus unsuitable for RTRRMSs.

A section of road should be found that is at the roughest level anticipated in the study. It should have the minimum length required for a calibration site, as defined in Table 4. (The roughest calibration site is, in fact, a good choice of location for this test.) The vehicle should be instrumented with a roadmeter and taken to the selected site, where it is allowed to cool down for a period of one to two hours. The vehicle can be considered "cool" 15 minutes after the shock absorbers and tires no longer feel warm to the touch.

When the vehicle has cooled, "measure" the roughness of the warm-up test site at the constant test speed. Record the time and the roadmeter "measure." Conversion to the IRI scale is not necessary, as the interest here is in the relative change obtained. Immediately repeat the test, again recording the roadmeter reading and the time. Continue until the roadmeter readings reach a constant level for at least five consecutive runs.

The amount of time needed to reach the steady readings should always be used as a minimum warm-up time. If the difference between the initial and final reading is more than 30%, alternative shock absorbers should be considered for the vehicle.

4.3.4 Control tests for RTRRMS time stability. Control sites are sections of road that are measured on a daily or weekly basis to determine wherther the RTRRMS has changed since the last check. They can also be used to determine and/or monitor the repeatability of the RTRRMS, and its sensitivity to environmental conditions. One example of how control testing can be integrated into the operating procedure

RTRRMS unit UM#1 Driver TDG Operator Sayers
Date 3-15-85 Weather Sunny, 60°F ± 5°

Comments:

site #	Description	Speed (km/h)	Length (km) L	Roadmeter - 3 runs (counts) #1	#2	#3	Σ	ARS (counts/km) Σ/3L	IRI (m/km) eq. 1
180a	I94, mi 180	80	.50	6	6	7	19	12.6	2.1
180b			.50	9	8	9	26	17.3	2.7
180c			.5	12	12	15	39	26.0	3.8
180d			.5	10	9	10	29	19.3	3.0
200	Terr+Curtis		1.0	32	33	[illegible]			
"	"		"	"	"	30	95	31.7	4.6

eq. 1: Calibration equation: E [IRI] = .48 + .130 • ARS + .000025 • ARS²

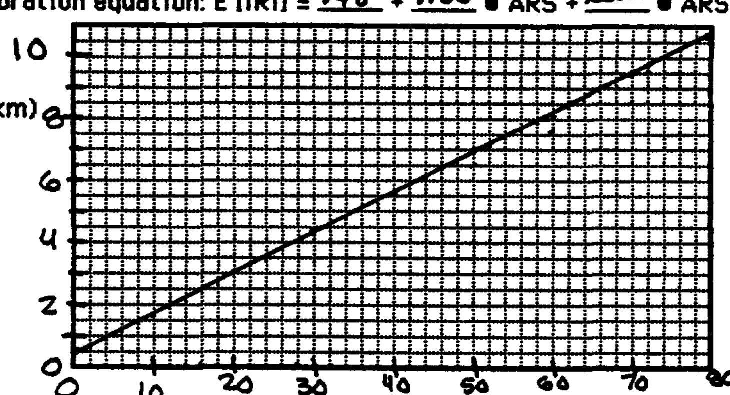


Fig. 9. Examples of pre-printed field form for recording ARS measures and converting to IRI.

established for a project was shown in Figure 8. If measurements on the control sections do not fall within limits established for the project, then the RTRRMS can be checked for defects, and hopefully corrected. A new calibration is required unless a simpple reason for the change can be found and corrected. If it is determined that the vehicle (or roadmeter) has changed, then all data gathered by that RTRRMS since the last control check should be discarded.

a) Objectives of control tests. Control tests have been used mainly for three purposes:

1) to detect gradual changes in the RTRRMS that cause bias in the data.

2) to detect change in the repeatability of the RTRRMS, which results in greater error in individual measurements.

3) to determine whether environmental contditions (rain, temperature, wind, etc.) have an impact on the measurements.

The control tests are much more simple than the calibration testing described in Section 4.2, in order that they can be applied more frequently. They are used solely to determine if the RTRRMS has changed, and should not be used to attempt to compensate or calibrate the RTRRMS. Thus, the reference IRI value for a control test site can be provided from the RTRRMS immediately after a calibration so that profile measurement is not required.

b) Number of sites. At least two control sites should be used in each check, covering a "smooth" site and a "rough" site. This is because some errors affect only rough measurements and others affect only smooth measurements. The RTRRMS can then be periodically checked by comparing measurements to the recorded reference values, and comparison to the variability of measurements obtained in previous checks.

c) Location of sites. By locating the sites between the storage location of othe RTRRMS and the roads being measured as part of the project, the RTRRMS can be checked daily with little time or effort. When a RTRRMS is operated over a wide geographic area, control sections convenient to each area should be identified so that sites are available to check the RTRRMS every day.

As control sites, their roughness is assumed to be constant with time, and care should be taken to ensure that this assumption is reasonable. They should be portions of paved roads that are lightly traveled and are not scheduled for any maintenance over the course of the project.

d) Site length. The length for a the control sites should be consistant with the lengths of road sections normally measured in the project. If the main interest is only the detection of gradual changes in RTRRMS sensitivity, then long control sites are preferable, from 1.5 - 5 km. Shorter sections can be used, but it is more difficult to discern changes in RTRRMS behavior because the RTRRMS repeatability suffers on the shorter sections. On sections 1.6 km long, normal variations should be within $\pm 2\%$, allowing detection of smaller changes on the order of $\pm 5\%$ in the RTRRMS. On control sections 320 m long, normal variations can be $\pm 5\%$, with changes of $\pm 10\%$ indicating that the RTRRMS has changed.

e) Repeat measures. Measurements can be repeated in order to discern smaller changes in RTRRMS performance. This is mainly useful when using shorter control sites (1 km or less in length), and when the repeatability of the RTRRMS is being checked.

f) Site identification. The beginning and end points of each site should be visibly identifiable from landmarks or semi-permanent markings made for that purpose. Immediately after calibration, all of the control sites should be measured, just as any test sections of road would be (i.e., constant speed, RTRRMS "warmed up"). The measurements should be recorded for future reference.

g) Acceptance levels. The control site measures obtained with a RTRRMS should always fall within an acceptable range, where that range is determined by prior experience with the unit and by the project objectives. It should be kept in mind that the control limits tolerated on the control test sections have an impact on the general level of accuracy that can be associated with the RTRRMS system. The acceptable range for a particular RTRRMS should be based on the initial measurements of the control site made with that specific RTRRMS. At least three approaches can be taken for specifiying maximum and minimum levels of ARS that are acceptable for a given RTRRMS. Using the notation that ARS is the current value, and ARS_{init} is the initial value obtained when the control site was first measured, these methods are:

1) Percentage range, e.g., $ARS = ARS_{init} \pm 5\%$

2) decibel range (or log increment), e.g., $ARS = ARS_{init} \pm 1$ dB, or $\log(ARS) = \log(ARS_{init}) \pm 0.05 \log(ARS)$

3) linear ARS range, e.g. $ARS = ARS_{init} \pm 5$ "counts/km"

The first two are roughly equivalent in effect, and are appropriate when the measurement error is roughly proportional to roughness. The third is more appropriate when measurement error is fairly constant for the entire range of roughness covered in the project. When the range of interest covers mainly paved roads, and in particular, smoother paved roads such as major highways, then the third form is recommended. When the range covers unpaved roads, or extremely rough paved roads, then one of the first two forms is recommended.

The exact threshold selected must be determined from experience with the actual RTRRMS. (The 5% figure used in the above example may or may not be appropriate.)

h) Data reporting. As with other areas of data collection, pre-printed field forms can help to reduce human error and to detect trends as they start to occur. Figures 10 and 11 show work sheets that have been used for this purpose [9]. In this example, the control testing covered both changes in the sensitivity of the RTRRMS and in its repeatability. Thus, repeat measures on the control sites are required. Each week, several control sites are measured five times. From the work sheet (Figure 10), the mean value for each site is computed, and the range of measures (an indication of repeatabilty) is noted. The log of the mean value is compared to the log of the original measure, and the change is plotted in the top chart in Figure 11. This visually indicates any trends in the sensitivity of the RTRRMS to roughness. The range is also plotted, in the bottom chart of Figure 11, so that inconstant behavior indicative of damaged components can be detected early.

i) Frequency of testing. There is a trade-off involved in establishing the frequency with which control tests are performed: frrequent control tests take up time that could instead be used obtaining data. Yet, when problems are discovered from a control test, less data is discarded if the previous test was performed recently. Essentially, the control tests should be repeated with sufficient frequency so that if data must be discarded, the loss in time will not be too severe for the project.

WORK SHEET FOR LDI CONTROL RUNS

INSTRUMENT IDENTIFICATION: LDI TP 125-555

TECHNICIANS: Herman & Poppe DATE: 02/18/82

SECTION	22	24	26	32	
$\bar{X}_{initial}$	0.54	0.25	0.43	-0.15	
RUN	LOG_{10} LDI VALUES (m/km)				
1	0.53	0.21	0.44	-0.11	
2	0.53	0.25	0.44	-0.17	
3	0.54	0.25	0.43	-0.17	
4	0.53	0.25	0.42	-0.19	
5	0.54	0.22	0.43	-0.14	
SUM LOG_{10}(LDI)	2.67	1.18	2.16	-0.78	
$\bar{X}_{current}$	0.53	0.24	0.43	-0.16	
DEVIATION	0.01	0.01	0.00	0.01	
RANGE	0.01	0.04	0.02	0.08	

$$\bar{X}_{current} = \frac{\text{SUM } LOG_{10}(LDI)}{5} \qquad RANGE = LDI_{max} - LDI_{min}$$

DEVIATION = $\bar{X}_{initial} - \bar{X}_{current}$

RANGE = ENTER ON RANGE CONTROL CHART

DEVIATION = ENTER ON MEAN CONTROL CHART

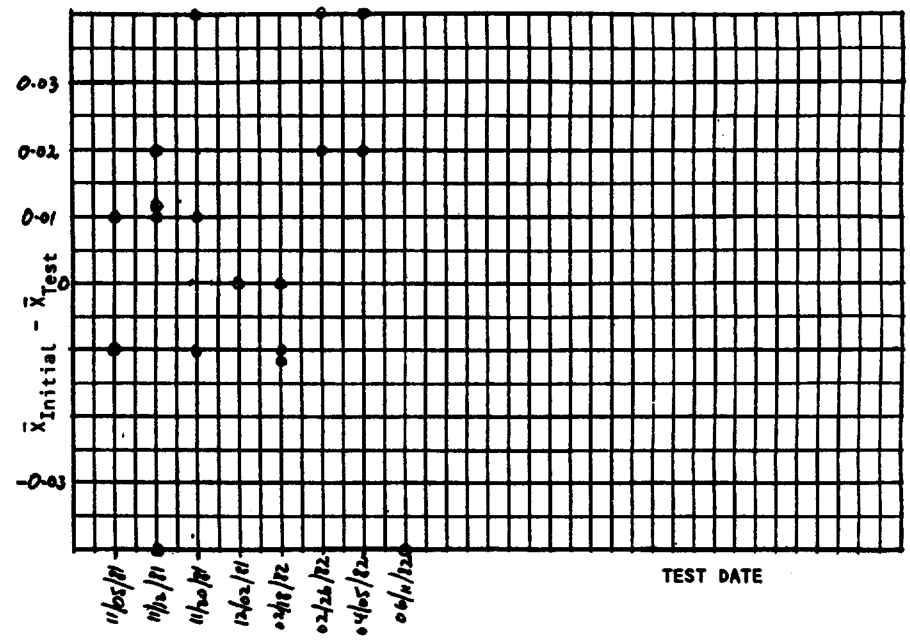
Fig. 10. Example of worksheet used for recording control test data (9)

INITIAL MEAN

SECTION	$\bar{X}$
2	0.30
4	0.23
6	0.32
7	0.18
8	0.15
10	0.07
11	0.04
12	0.05
13	0.44
14	0.38
17	0.45
22	0.54
24	0.25
25	0.13
26	0.43
27	-0.09
30	-0.18
32	-0.15
33	-0.13
34	-0.19

LDI MEAN CONTROL CHART

INSTRUMENT IDENTIFICATION: LDI TP125-555 DATE OF CALIBRATION: 11/05/81



LDI RANGE CONTROL CHART

INSTRUMENT IDENTIFICATION: LDI TP125-555 DATE OF CALIBRATION: 11/05/81

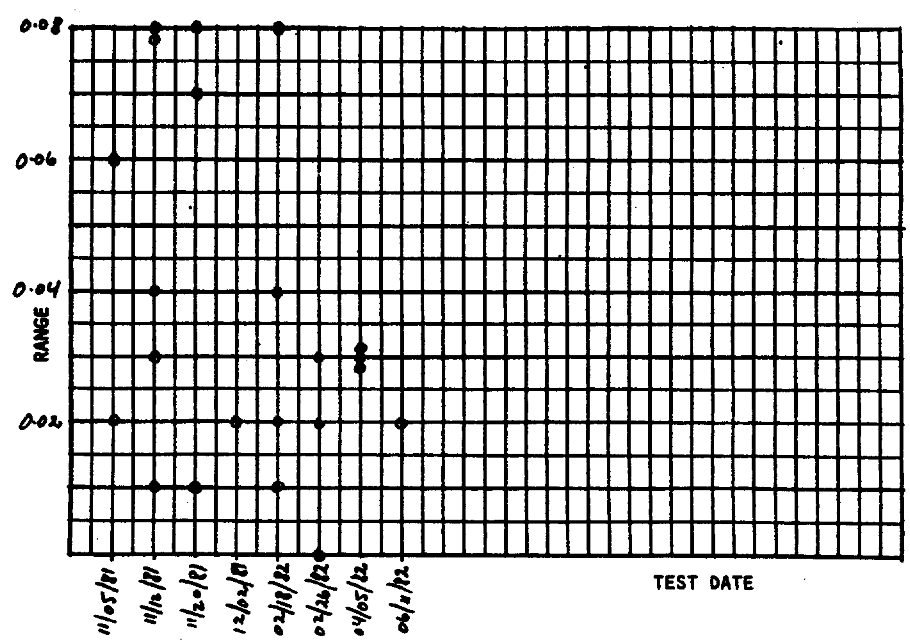


Fig. 11. Example of worksheet for plotting mean and range of RTRRMS control test (9).

CHAPTER 5

ESTIMATION OF IRI BY SUBJECTIVE EVALUATION (CLASS 4)

5.1 Descriptive Evaluation Method

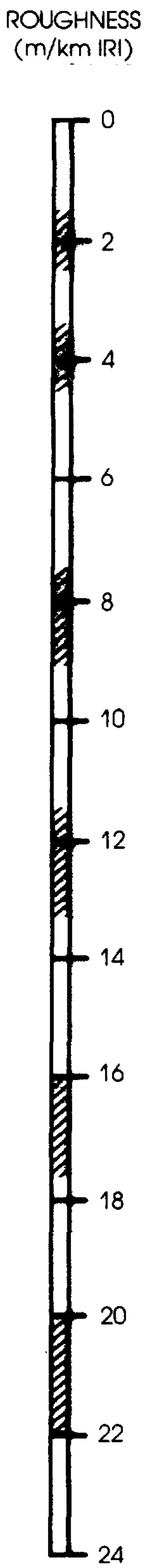
When Class 1, 2, or 3 methods for measuring roughness are not feasible, estimations of the roughness on the IRI scale can be made subjectively. This approach may be used in the initial stages of a project to develop approximate assessments of the roughness, or in situations where an RTRRMS is not available. The descriptions used can also serve to acquaint the practitioner with the IRI scale, helping to visualize the meaning of the IRI values and the road conditions associated with them.

5.1.1 Method. The method provides adjective (and some quantitative) descriptions of the road surface conditions and ride sensations representative for several points on the IRI scale. These descriptions enable an observer traveling in a vehicle, and occasionally stopping to inspect the road, to recognize the conditions and to estimate the roughness. Photographs can be used effectively to support the method, but they can also be misleading because they tend to accentuate visual defects and minimize the shape or profile variations which relate most closely to roughness.

A method of this type has not been rigorously developed and proven, yet the success experienced with subjective ratings in the IRRE suggests that IRI values can be estimated with an accuracy that provides some indication of the road conditions at hand. Therefore, preliminary guidance is provided for this approach.

The accuracy of the method generally varies with the experience of the observer. Experienced observers will usually estimate roughness with an accuracy within 2 to 3 m/km, or about 30%, while new observers may have errors of 2 to 6 m/km, or about 40%. The estimates of IRI are therefore approximate and this method should not be used when mechanical means are available.

5.1.2 Description of the IRI scale. Figures 12 and 13 provide a series of descriptors for selected levels on the roughness scale. Figure 12 applies to surfaces of asphaltic concrete or surface treatment types, whereas Figure 13 applies to gravel and earth surfaces. These describe the typical categories of road, surface shape defects, ride sensation, and typical travelling speed associated with each given roughness level. The observer is expected to use all these to make an objective assessment of the roughness of a road while travelling along it. The most objective description relates to the surface shape defects



Recently bladed surface of fine gravel, or soil surface with excellent longitudinal and transverse profile (usually found only in short lengths).

Ride comfortable up to 80-100 km/h, aware of gentle undulations or swaying. Negligible depressions (e.g. < 5mm/3m) and no potholes.

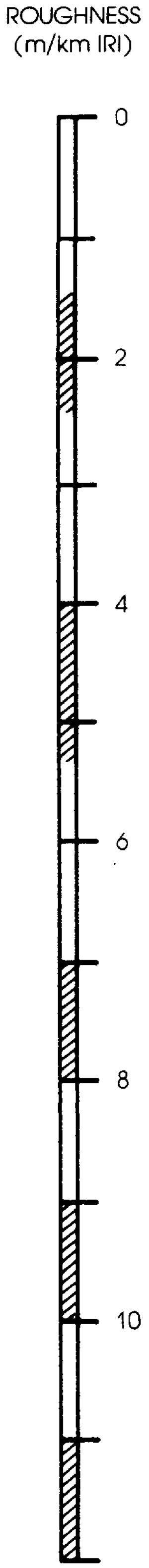
Ride comfortable up to 70-80 km/h but aware of sharp movements and some wheel bounce. Frequent shallow-moderate depressions or shallow potholes(e.g. 6-30mm/3m with frequency 5-10 per 50m). Moderate corrugations (e.g. 6-20mm/0.7-1.5m).

Ride comfortable at 50km/h (or 40-70 km/h on specific sections). Frequent moderate transverse depressions (e.g. 20-40mm/3-5m at frequency 10-20 per 50m) or occasional deep depressions or potholes (e.g. 40-80mm/3m with frequency less than 5 per 50m). Strong corrugations (e.g. > 20mm/0.7-1.5m).

Ride comfortable at 30-40 km/h. Frequent deep transverse depressions and/or potholes (e.g. 40-80mm/1-5m at freq. 5-10 per 50m); or occasional very deep depressions (e.g. 80mm/1-5m with frequency less than 5 per 50m) with other shallow depressions. Not possible to avoid all the depressions except the worst.

Ride comfortable at 20-30 km/h. Speeds higher than 40-50 km/h would cause extreme discomfort, and possible damage to the car. On a good general profile: frequent deep depressions and/or potholes (e.g. 40-80mm/1-5m at frequency 10-15 per 50m) and occasional very deep depressions (e.g. > 80mm/0.6-2m). On a poor general profile: frequent moderate defects and depressions (e.g. poor earth surface).

Fig. 12. Road roughness estimation scale for paved roads with asphaltic concrete or surface treatment (chipseal) surfacings.



Ride comfortable over 120 km/h. Undulation barely perceptible at 80 km/h in range 1.3 to 1.8. No depressions, potholes or corrugations are noticeable; depressions < 2mm/3m. Typical high quality asphalt 1.4 to 2.3, high quality surface treatment 2.0 to 3.0

Ride comfortable up to 100-120 km/h. At 80 km/h, moderately perceptible movements or large undulations may be felt. Defective surface: occasional depressions, patches or potholes (e.g. 5-15mm/3m or 10-20mm/5m with frequency 2-1 per 50m), or many shallow potholes (e.g. on surface treatment showing extensive ravelling). Surface without defects: moderate corrugations or large undulations.

Ride comfortable up to 70-90km/h, strongly perceptible movements and swaying. Usually associated with defects: frequent moderate and uneven depressions or patches (e.g. 15-20mm/3m or 20-40mm/5m with frequency 5-3 per 50m), or occasional potholes (e.g. 3-1 per 50m). Surface without defects: strong undulations or corrugations.

Ride comfortable up to 50-60 km/h, frequent sharp movements or swaying. Associated with severe defects: frequent deep and uneven depressions and patches (e.g. 20-40mm/3m or 40-80mm/5m with frequency 5-3 per 50m), or frequent potholes (e.g. 4-6 per 50m).

Necessary to reduce velocity below 50km/h. Many deep depressions, potholes and severe disintegration (e.g. 40-80 mm deep with frequency 8-16 per 50m).

Fig. 13. Road roughness estimation scale for unpaved roads with gravel or earth surfaces.

which are expressed as a range of tolerances under a 3-m straight-edge; these can only be assessed by pedestrian inspection.

Note that both the descriptions and the associated IRI cover ranges of conditions at each level. This is necessary because the combinations of defects and severities vary widely, and because pavements at the same roughness level can have very different appearances.

The scale in the figures ranges from 0 to 24 m/km IRI, as this is the range that has been covered in the IRRE and in other projects. The actual scale can continue to even higher levels, although roughness is so severe that travelling such roads is almost impossible. In describing benchmark levels of roughness, as done in the two figures, it is helpful to use the following descriptors:

a) **Typical categories of road.** The roads are first divided into the two categories of paved and unpaved because of characteristic differences between the roughness on these two types. The descriptions further refer to the quality of the shape (i.e., longitudinal profile) which can be expected for each type and quality of construction. They include the quality of shape after construction, and the extent and types of deterioration.

b) **Surface shape defects.** It is important to realize that roughness is related only to vertical changes in the level of the road in the wheelpaths of the vehicle, and that the superficial appearance of the surfacing can sometimes be misleading. Patches in the surfacing, or a coarse surface texture which results in loud tire noise may mislead the observer to overestimate roughness. Alternatively, a defect-free surface or a recent reseal may mislead the observer to underestimate the roughness if the road is very uneven. The observer must therefore become attuned to vertical surface irregularities. The characteristics used to describe surface shape are:

1) depressions: dish-shaped hollows in the wheelpaths with the surfacing in-place (by corollary, this includes humps of similar dimensions)

2) corrugations: regularly-spaced transverse depressions usually across the full lane width and with wavelengths in the range of 0.7 to 3.0 m (also termed washboarding)

3) potholes: holes in the surface caused by disintegration and loss of material, with dimensions of more than 250 mm diameter and 50 mm depth.

The size is indicated by the maximum deviation under a 3-m-long straight-edge, e.g., 6-20 mm/3 m, similar to a construction tolerance. The frequency is given by:

"occasional" = 1 to 3 per 50 m in either wheelpath

"moderate" = 3 to 5 per 50 m in either wheelpath

"frequent" = more than 5 per 50 m in either wheelpath

c) Ride sensation. In Figures 12 and 13, the "comfortable" ride is relative to a medium-size sedan car with regular independent shock-absorber suspension. Ride varies from car to car so more detailed descriptions are generally not transportable, but an observer can quickly become "calibrated" for a given vehicle. The ride sensation can be described in simple terms of the undulations and sharp movements experienced by the observer at a speed relevant to the level of roughness being defined. These descriptions can help considerably, but they must be developed for local conditions and vehicle types.

d) Travel speed. This indicates common travelling speeds on dry, straight roads without traffic congestion, with due consideration of care for the vehicle and the comfort of the occupants.

5.1.3 Personnel. The selection of observers should be made from those competent to make consistent, sound estimates of rating; typically, these will include professional engineers, technical personnel, etc. Usually, only one observer is used, but the accuracy of the result can be enhanced by the use of two or three persons.

5.1.4 Calibration. In order to calibrate to the scale, the observer should become thoroughly familiar with the salient features of each set of descriptions above. This could be called a "calibration by description." The final validity of such a calibration depends on how well the descriptions are tied to physical features of the road surface.

When possible, it is a valuable introduction for the observer to be driven over a few sections which cover a wide range of roughness and for which the IRI is known from physical measurements. If the vehicle to be used for the survey is very different in wheelbase or suspension characteristics from a mid-size passenger car sedan, special care should be taken to adjust the ride descriptions used. Preferably, this should be done by "calibration" on a few physically measured sections. Alternatively, it can be done by pedestrian inspections and careful comparison of the shape measures with the descriptors.

5.1.5 Survey. On routes which are to be surveyed, the driver should be instructed to normally travel at 80 km/h on paved roads and 50 km/h on unpaved roads. At times, the observer may wish to vary the speed to test the rideability against the ride sensation descriptions. An estimate of average IRI should be made at 1 km intervals (50 or 70 seconds), although on long, uniform routes, this interval could be extended to 2 km or 5 km depending on the accuracy and detail required of the survey. Occasional stops for spot measurements are useful. The vehicle speed, surface type, and weather conditions should be noted.

5.1.6 Data processing. The estimates for individual sections may be averaged to determine the average roughness of the route. If roughness levels range widely, by 100 percent for example, then the route should be subdivided into nominally homogeneous segments for averaging.

5.2 Panel Rating of Riding Quality

Panel ratings of riding quality have been implemented in many places in the past. Passenger observers rate the riding quality of road sections on an arbitrary scale from excellent to very poor (impassable), often quantified on a scale of 5 to 0. Usually, this is linked to the Serviceability Index (PSI) developed at the AASHO Road Test or a Ride Comfort Index. The PSI scale is limited in that it was developed for roads of relatively high quality, in comparison to some of the poorer roads covered in the IRRE and representative of conditions in less-developed countries. Thus the PSI scale, as classically used in the United States, only covers the low roughness end of the IRI scale.Data relating PSI to IRI and other objective roughness measures are scarce and inconsistent, due in part to the different methods that are used by different agencies for estimatng PSI. Some of the relationships are linear, while others are not [10]. A PSI value of 5 is defined as a perfect surface, and is thus equivalent to a 0 on the IRI scale. As roughness increases, IRI increases, and PSI decreases down to 0 for a completely impassable surface.

Experience has shown that panel raters in different countries or regions attribute widely different ratings to a given roughness, commensurate with their expectations of riding quality. Thus panel rating scales are not comparable unless well anchored, and this approach does not qualify as a Class 4 method unless specific provisions are made to anchor the scale through calibration against the IRI.

The potential advantage of the panel ratings method is that the ratings assigned to the road can be genuinely representative of subjective opinion. For most applications of roughness data, however, this is not the main priority. It is usually more desirable to use a roughness scale that has the same meaning from year to year and from region to region. Although subjective panel ratings can be "anchored" to a time-stable scale such as IRI, the method is expensive and inaccurate in comparison to the other methods available. Thus, panel ratings are not recommended for obtaining IRI measures, nor for any applications other than research projects where local public and/or profesisonal opinion is a variable of interest.

GLOSSARY

Accuracy - The root-mean-square value of the error when comparing measurements from a particular method to those of a reference method.

APL Trailer - A high-speed profilometer developed and operated by the French Laboratoire Central des Ponts et Chaussees. The trailer uses a tuned mechanical system to measure the surface profile of a single wheeltrack over the frequency range of 0.5 to 20 Hz.

APL 72 Waveband Analysis - An analysis applied to the profile signal obtained from the APL Trailer operated at 72 km/h. The profile is filtered into short-, medium-, and long-wave bands. The content may be expressed as:

a) the APL 72 "Energy" (W), which is the mean-square value of the filtered profile in each waveband,

b) the APL 72 "Equivalent Amplitude", which is the amplitude of a sine wave having the same energy (E),

c) the APL 72 Index, which is a value between 1 (worst) and 10 (best) indicating the relative quality of the road.

The short-wave numeric is most closely correlated to the IRI and to RTRRMS measures. A similar set of three waveband numerics (CP) is used by the Centre de Recherches Routieres in Belgium.

APL 25 - See CAPL 25

ARS_V - Average rectified slope measured by a RTRRMS at speed V. The recommended units are m/km, although the units "inches/mile" and "mm/km" are also popular. It is the total RTRRMS suspension displacement (in both directions) divided by the distance travelled during the roughness measurement. Roadmeters based on the BPR Roughometer design produce measures of ARS/2, as they accumulate displacement in only one direction.

ARV_V - Average rectified velocity measured by a RTRRMS. It is the average stroking speed of the vehicle suspension during a roughness measurement. The ARV is a direct measure of vehicle response to roughness, such that increased ARV always indicates increased vehicle vibrations, regardless of the measurement speed or source of vibrations. ARV = ARS x speed, with the speed expressed in appropriate units.

BI - Abbreviation for Bump Integrator, the roadmeter used by the British TRRL, which is a derivative of the rotational clutch system used with the early BPR Roughometer. Measurements are usually expressed in "mm/km". The raw measure corresponds to one-half the total accumulated suspension deflection: thus BI results must be doubled to obtain ARS.

BI Trailer - A RTRRMS consisting of a special single-wheeled trailer instrumented with a BI roadmeter. The trailer has been developed by the TRRL, based on the design of the earlier BPR Roughometer. In the past the BI Trailer has been used only at the speed of 32 km/h; however, results from the IRRE demonstrate that it can be used successfully at higher speeds.

BPR Roughometer - An early RTRRMS developed by the Bureau of Public Roads. It is a single-wheeled trailer equipped with a mechanical roadmeter employing a one-way clutch, and historically has been operated at 32 km/h. The BPR Roughometer is conceptually similar to the BI Trailer, but is typically not as rugged or as standardized.

CAPL 25 - A numeric obtained with an APL Trailer when operated at 21.6 km/h. It includes an analysis/test procedure used widely in France for evaluation of newly constructed roads. The CAPL 25 numeric is computed for each 25 meter length of roadway.

Counts/km, Counts/mile - Names used to refer to the ARS statistic. The "count" normally has associated with it a certain increment of suspension deflection measured by the roadmeter. These names have also been used to refer to the PCA sum-of-squares statistic, which is quite different from the ARS.

CP - Coefficient of Evenness, used by the Centre de Recherches Routieres in Belgium (CRR) as a roughness measure. CP is the average rectified value of a profile that has been filtered with a moving average. It has units of 50 CP = 1 mm. The CP numerics use baselengths of approximately 2.5, 10, and 40 m when calculated from APL 72 profiles, and baselengths of 2.5 and 15 m when calculated from the APL 25 profile. The CP(2.5) and CP(10) numerics can be obtained using other profile measurement methods, provided that a small sample interval is used. The CP(2.5) is highly correlated with the IRI and RTRRMS measures.

GMR-Type Inertial Profilometer - An instrumented van developed by General Motors Research, and sold commercially by K. J. Law Engineers, Inc., for measuring road profiles at highway speeds. The first profilometers used an accelerometer, instrumented road-follower wheel, and analog electronics to measure profile. More recent models use noncontacting road-follower systems and digital signal processing methods. Since 1979, they have been equipped with software to compute IRI at the time of measurement. The computation program is called the Mays Meter Simulation.

Inches/mile - Name used to refer to an ARS measure of roughness. It denotes inches of suspension deflection per mile of distance travelled.
1 m/km = 63.36 in/mi.

IRI - International Roughness Index, equivalent to the ARS computed using a reference mathematical RTRRMS for a standard speed of 80 km/h. It is a mathematical property of the profile of a single wheeltrack. It is based on a calibration reference developed in an NCHRP program [2], which was later found to be the most suitable roughness index for international use in the IRRE.

IRRE - International Road Roughness Experiment held in Brasilia in 1982. The IRRE was conducted by research teams from Brazil, England, France, Belgium, and the United States.

K.J.Law Profilometers - see GMR-type inertial profilometer.

Mays Meter - A commercial roadmeter made by Rainhart Company. The transducer employs an optical encoder to produce electrical pulses that are mechanically accumulated by a one-way stepper motor connected to a strip-chart recorder. The meter measures the accumulation of suspension travel with units of Inches/6.4, indicated by the advancement of paper in the strip-chart recorder. This measure is then converted to inches/mile by most practitioners. Although the transducer works properly on roads of all roughness levels, the stepper motor has response limits that cause it to count improperly at high roughness levels.

Mays Meter Simulation - A commercial computer program offered by K. J. Law Engineers, Inc. with the GMR-type profilometer. In some versions, the program exactly matches the IRI (using units of inches/mile rather than m/km); in others, the program uses the IRI car parameters with a half-car simulation, rather than the quarter-car specified for the IRI.

mm/km - A name used to describe the ARS measure. It is commonly used with the BI Trailer. Measures from the BI roadmeter are generally reported with half the value that would be used for ARS.
Thus, 1 m/km ARS = 500 mm/km BI.

Moving Average - A method of analysis used to compute a roughness index from a measured profile. The analysis smooths the profile by replacing each point with the average of adjacent points over a in 1975[1]. In concept, QI is identical to IRI, and in practice, the two indices are very highly correlated. It is an ARS measure with arbitrary units of "counts"/km, and is based on an early reference simulation of a RTRRMS. The original QI was an abbreviation for Quarter-car Index, and was based on the readings taken from a particular piece of hardware as operated on paved roads in Brazil. Due to a number of equipment defects and errors in calibration methodology, the original QI measure cannot be replicated today using the same method. Since the beginning of the PICR project, there have been three types of QI data:

1) **QI_r** - A profile-based roughness statistic developed by Queiroz and other Brazilian researchers to replace the QI calibration scale. QI_r is computed from a single statically measured profile, typically obtained with the rod and level method, using a weighted sum of two RMSVA statistics calculated from baselengths of 1.0 and 2.5 m:

   $$QI_r = -8.54 + 6.17 \cdot RMSVA_{1.0} + 19.38 \cdot RMSVA_{2.5}$$

   The above equation requires the RMSVA measures to have the units of 1/km (.001/m), as obtained when profile elevation is measured in mm. Designed with rod and level profilometry in mind, QI_r cannot be measured with as many methods as IRI. Also, the correlations with RTRRMSs are not quite as good for some conditions.

2) **QI^*** - The "calibrated" measures from RTRRMSs, used for all of the data measured in the PICR Project, as reported and stored in the Brazilian computer data files. The calibration used was not complete and did not correct the measures to the QI scale for all surface types. On asphaltic concrete roads, QI^* is equivalent to QI_r; however, QI^* numerics are larger than corresponding QI_r measures on unpaved roads, and substantially higher (sometimes by 100%) on surface treatment roads.

3) **QI_w^*** - Engineering consultants to the World Bank have been reprocessing roughness data obtained during the ICR Project. The resulting cost equations, when published, will differ from the original ones, as they have been rescaled to bring the QI_w^* statistic closer to the QI_r statistic on all types of roads.

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[1]Research on the Interrelationships between Costs of Highway Construction, Maintenance, and Utilization. (The Brazilian Transportation Planning Agency - GEIPOT)

specified base length. The smoothed profile is subtracted from the original to cancel the long wavelength geometry. The resulting filtered profile is summmarized by an average rectified value, or by an RMS value. With a proper choice of baselength (1.5 - 3 m), high correlations exist with RTRRMSs. The analysis is mainly used to isolate roughness properties of interest that often cannot be detected with RTRRMSs.

NAASRA Meter - A roadmeter developed and used by the Australian Road Research Board (ARRB), together with a reference vehicle to define a NAASRA RTRRMS. The NAASRA roadmeter was found capable of measuring ARS and ARV statistics over the full roughness range. The NAASRA RTRRMS used in Australia has been "calibrated" by holding one RTRRMS in storage as a reference, and correlating the other RTRRMSs with it.

PCA Meter - An instrument similar to a roadmeter in which discrete levels of suspension displacement are summed independently. Most PCA meters can also be used as simple roadmeters simply by adding the readings from all of the counters together.

PCA sum-of-squares - a measure obtained from a PCA meter, where the readings from the different counters are each weighted before they are added. The resulting measure was intended to be indicative of a mean-square response, but it has been shown the the weighted sum has no relation to any physical variables [2]. The use of this measure is not recommended.

Profilometer - A mobile instrument used for measuring the longitudinal profile of roads. A profilometer has its own means for calibration, other than the empirical regression methods needed for RTRRMS. The profile measured may not be true in the sense that it may not include all wavelengths, yet can be valid for applications in road roughness measurement and calibration. Depending on the instrument, the profile may be stored and/or processed on board the profilometer to yield summary numerics during measurement. **high-speed** profilometers are instruments that can be used at normal road speeds, whereas **static** profilometers are used at walking speeds (or slower).

QCS - Quarter car simulation. A mathematical model of a vehicle that has a body and single tire. It computes the response of a reference vehicle from measured profile input.

QI - The original road roughness statistic adopted for use as a calibration standard in the Brazilian PICR user-cost project begun

QI can be considered as an earlier version of IRI. Although the original definitions of QI are difficult to apply with confidence in many cases, the data from the IRRE indicate that for all practical purposes, QI can be considered to be IRI with different units and an offset. The conversion equation recommended is:

$$E\,[QI]\ \text{"counts/km"} = 14 \bullet IRI\ (m/km) - 10$$

$RARS_{80}$ - Reference average rectified slope at 80 km/h. This is the more technical name for IRI.

RARV - An abbreviation for reference ARV. RARV = ARS x speed, where the ARS is obtained from the QCS of the reference vehicle.

Repeatability - The expected standard deviation of measures obtained in repeat tests, using the same instrument on a single, randomly-selected road.

Reproducibility - The standard deviation of the error included in a single measurement, relative to a reference measure. The reproducibility of an instrument includes errors that are systematic with respect to that instrument, but random with respect to a particular test.

Resolution - The smallest increment that can be measured with a particular instrument, due to its design.

Ridemeter - An instrumentation package that is installed in a vehicle to measure vibrations. Sometimes, the word Ridemeter is used in other documents as a substitute for the word Roadmeter; other times the word Ridemeter is applied to instruments that measure vehicle response to determine ride quality, rather than the roughness of the road.

RMSVA - Abbreviation for the words "Root Mean Square Vertical Acceleration." This measure was proposed by McKenzie and Srinarawat[2] as a profile-based calibration reference. The statistic is a function of a measured profile signal, together with a single baselength parameter. The VA (vertical acceleration) is defined at longitudinal position x as:

$$VA_b = [Y(x + b) + Y(x - b) - 2\,Y(x)]\ /\ b^2$$

[2] "Root Mean Square Vertical Acceleration (RMSVA) as a Basis for Mays Meter Calibration," Brazil Project Memo BR-23, Center for Transportation Research, The University of Texas at Austin, February 1978

where Y(x) is the signal amplitude (profile elevation) at positon x, and b is the baselength parameter. As defined by the above equation, RMSVA has units of vertical acceleration, but has no relationship with the actual spatial acceleration of the profile. Instead, it is simply a measure of mid-chord deviation with a scale factor of $2/b^2$. The RMSVA statistic was used to define the QI_r calibration standard in the PICR Project, and has also been used to define a RTRRMS calibration standard for use in Texas.

Roadmeter - An instrument that is installed in a vehicle to transduce and accumulate the suspension deflections that occur when the vehicle traverses a road. The resultant measure is proportional to the total accmulated suspension deflection that occurred during the test.

Roughness of a road - The variation in surface elevation along a road that causes vibrations in traversing vehicles. The standard summary statistic that quantifies this variation is the IRI.

RTRRMS - Response-type road roughness measuring system. These systems consist of a passenger car or a towed trailer having either one or two wheels, plus a roadmeter installed to measure suspension deflections.

Single-track RTRRMS - A towed trailer supported by a single wheel, instrumented with a roadmeter. The roughness measure obtained applies only for a single wheeltrack.

Slope Variance (SV) - A measure of road roughness that is the variance of a signal produced by the early AASHTO Profilometer and CHLOE Profilometer. As used to describe roughness, Slope Variance refers to the variance of a signal or "profile" obtained by a specific method. The Slope Variance is more sensitive to the choice of profile measurement method than to roughness, and does not describe a standard roughness measure. (The "true" variance of the slope of a road profile is infinite, since the true profile includes texture effects.) Although the simple geometry of the early "profilometers" implies that Slope Variance can readily be computed mathematically from more accurate profile measures, the earlier instrumentation systems had quirks and complexities that have not been well documented, so that estimates of Slope Variance made from measured profiles are not equivalent to outputs of the old instruments. Slope Variance measures have never been found to be very compatible with the ARS and ARV measures obtained with RTRRMSs.

TRRL Beam - A quasi-static profilometer developed by TRRL that measures a profile in 3-m sections (the length of the instrument). The

Beam is designed with developing country environments in mind, and is lightweight, portable, and self-contained. It includes a battery-powered microcomputer that controls the measurement process and can automatically calculate roughness statistics.

TRRL Laser Profilometer - A high-speed profilometer developed and operated by TRRL. The profilometer uses several noncontacting laser height sensors, spaced over the length of a trailer, to compute surface profile as the trailer is towed at highway speeds.

Two-track RTRRMS - A RTRRMS based on a passenger car, light truck, or a towed two-wheel trailer. The measure obtained is a function of the roughness in two wheeltracks.

VTI Laser Profilometer - Profilometer van developed and operated by the Swedish VTI. This profilometer operates at normal highway speeds and uses a combination of accelerometers, noncontacting height sensors, and digital computation to measure a number of parallel longitudinal profiles distributed across the 2.5 to 3.5 m width of the highway lane.

Waveband - A range of spatial frequencies (wavenumber = 1/wavelength). The waveband includes only the wavenumbers that lie inside its range.

Wheeltrack - The path followed by the tire of a vehicle traversing a road. Each lane has two travelled wheeltracks. When measuring roughness, the wheeltrack should parallel the centerline insofar as possible.

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Washington, D.C. 20433, U.S.A.

Telephone: (202) 477-1234
Telex: WUI 64145 WORLDBANK
RCA 248423 WORLDBK
Cable Address: INTBAFRAD
WASHINGTONDC

European Office
66, avenue d'Iéna
75116 Paris, France

Telephone: (1) 47.23.54.21
Telex: 842-620628

Tokyo Office
Kokusai Building
1-1 Marunouchi 3-chome
Chiyoda-ku, Tokyo 100, Japan

Telephone: (03) 214-5001
Telex: 781-26838

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