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16. Abstract

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 how to choose a method for measuring road roughness in consonance with the objectives of the program, and includes step-by-step instructions for making the measurements, calibrating the equipment, and periodically checking the equipment.

The procedures presented in this document are primarily applicable to roughness measurements of two types: (1) Direct measurement of roughness on a standard scale, derived from a rod and level survey of the profile; and (2) Estimation of the standard roughness measure, using calibrated response-type road roughness measurement systems (RTRRMSs).

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1.0 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:

- How to choose a method for measuring road roughness in consonance with the objectives of the program

- How the measurement equipment should be calibrated to a standard roughness scale

- The procedures that should be observed to ensure reliable measurements in routine daily use

The planning suggestions and measuring procedures presented here are intended to guide the practitioner in acquisition of 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 paved, surface treatment, gravel and earth roads.

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 a rod and level survey of the profile

- Estimation of the standard roughness measure, using calibrated Response-Type Road Roughness Measurement Systems (RTRRMSs)

Other methods, involving procedures tailored to specific instruments, alternate profile measurement systems, and procedures that are still under development, are beyond the scope of this document.

2.0 TERMINOLOGY

Terms that are used in these Guidelines that have specific meanings when used in the context of road roughness measurement are defined below.

Accuracy - The root-mean-square value of the error for a particular measurement method relative to a reference method.

APL Trailer - A Profilometer developed and operated by the French LCPC. The APL Trailer uses a tuned mechanical system to measure the surface profile of a single travelled wheeltrack at highway speeds, over a waveband determined by its response range and the travel speed.

ARS_V - Average Rectified Slope measured directly by a RTRRMS at speed V. ARS_V is the total RTRRMS suspension displacement (in both directions), divided by the distance travelled during the roughness measurement.

$CARS_{50}$ - Estimate of $RARS_{50}$ from an ARS value obtained with a Calibrated RTRRMS. (Calibrated ARS)

GMR-Type Profilometer - An instrumented van developed by General Motors Research and sold commercially by K.J.Law, Inc. in the United States for measurement of road profiles. Early GMR Profilometers used a combination of accelerometer, instrumented follower wheel, and analog signal processing to measure surface profile at highway speeds, over a waveband determined by the instrumentation quality and the travel speed. More recent models have replaced the follower wheel with non-contacting height sensors, and use digital processing rather than analog.

IRI - International Roughness Index. $RARS_{50}$ computed from the profile of a single wheeltrack is the standard IRI.

IRRE - International Road Roughness Experiment, held in Brasilia in 1982.

PCA Meter - An instrument similar to a roadmeter in which discrete levels of suspension displacement are weighted before summing. Most PCA meters can also be used as simple roadmeters.

Profilometer - An instrument that transduces the longitudinal profile of a wheeltrack over a waveband. Depending on the instrument, the profile can be either stored or processed to yield summary numerics during measurement.

$RARS_{50}$ - Reference Average Rectified Slope at 50 km/h. The $RARS_{50}$ measure, obtained from an idealized Reference RTRRMS, is computed mathematically from the measured longitudinal profile of a travelled wheeltrack. $RARS_{50}$ is defined mathematically in Reference [1].

Repeatability - The expected standard deviation of measures obtained in repeat tests, using the same instrument on a 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 an instrument, due to its design.

Roadmeter - An instrument that is installed in a vehicle to transduce and accumulate the suspension stroking that occurs when the vehicle traverses a road. The resultant measure is proportional to the total accumulated 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 $RARS_{50}$.

RTRRMS - Response-Type Road Roughness Measuring System. These systems consist of 1) a passenger car or a towed trailer having either one or two wheels, plus 2) 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.

TRRL Beam - A portable instrument developed by TRRL for static measurement of road profile over the length of the instrument, nominally 3 m.

TRRL Laser Profilometer - A profilometer developed and operated by TRRL. This profilometer uses several non-contacting laser height sensors, spaced over the length of a trailer, to compute surface profile as the trailer is towed at highway speeds. The profile is valid over a waveband determined by the instrumentation quality and the travel speed.

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

VTI Laser Profilometer - Profilometer van developed and operated by the Swedish VTI. This profilometer uses a combination of accelerometer, non-contacting height sensors, and digital computation to measure surface profiles in several wheeltracks at highway speeds. The profile is valid over a waveband determined by its instrumentation quality and the travel speed.

Waveband - A range of spatial frequencies (wavenumber = 1/wavelength). Wavenumbers that lie outside this range are not included in the waveband.

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 follow a straight line.

3.0 GUIDELINES FOR 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 carefully design the program. The design itself is a synthesis process taking into account the project goals, the resources available, and the environment of the project. This chapter defines the alternative methods that can be used to measure roughness, and discusses the accuracy requirements that might be adopted for different objectives, along with the accuracy levels that can be obtained in practice.

3.1 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 $RARS_{50}$ (the standard roughness definition), and the calibration requirements associated with their use.

3.1.1 Class 1: Direct measurement of $RARS_{50}$. The road roughness is determined in two stages: First, accurate and closely-spaced (0.25 m or closer) elevation points are measured along the travelled wheelpath. Second, the measured profile is processed mathematically to yield the $RARS_{50}$ numeric. Although high-speed profilometers offer a potential means for measuring $RARS_{50}$ quickly, the profilometer must be validated against an established procedure such as rod and level to prove its accuracy in this application. At the present time, only rod and level and the TRRL Beam methods have been demonstrated to be valid "Class 1" methods for determining $RARS_{50}$ over a broad range of roughness levels and road types.

The accuracy of a Class 1 method is limited solely by the repeatability associated with the measurement of profile. Repeatability is limited by random error associated with selecting a wheeltrack location, and with obtaining repeated measures in the same wheeltrack when the profile is sampled at finite intervals. Using the guidelines for a Class 1 measurement in Section 4.1, the accuracy that is obtained with this class of measurement is about 0.3 m/km on paved road sections 320 m long, and about 0.7 m/km for all other road types. The accuracy is generally improved for longer sections, as described in Section 3.2.1.1.

The accuracy obtained using a Class 1 method generally exceeds the requirements of even the most demanding applications for roughness data. The primary disadvantage is the great deal of labor involved in making the many elevation measurements and then entering them into a calculator or computer. Approximately 8 man-days of labor are required for each kilometer of roadway lane measured in both wheeltracks. Thus the method is viewed as having primary utility in calibration of roughness measurement systems, or when special high-accuracy data are required.

3.1.2 Class 2: Estimation of $RARS_{50}$ using an independently calibrated instrument. Methods in this class generally involve a measurement of the profile (using hardware that can be functionally verified by an independent calibration process), though with lesser accuracy or bandwidth than the Class 1 method described previously. Consequently, the $RARS_{50}$ value computed from a Class 2 profile measurement may not be accurate, but nevertheless is closely correlated to the true $RARS_{50}$ value over some range of conditions. This class presently includes $RARS_{50}$ values computed from profilometers, $RARS_{50}$ values computed from static measures that do not satisfy the precision and/or measurement interval requirements specified in 4.1, and estimates of $RARS_{50}$ computed from certain other measurements with the use of regression equations.

At the present time, the APL Trailer is the only dynamic profilometer that can be independently calibrated so as to be valid over the range of roughness covered in the IRRE. The GMR-type Inertial Profilometer with follower wheels is limited to roads with roughness levels less than an $RARS_{50}$ value of 3.6 m/km. (On rougher roads the follower wheels bounce, a phenomenon which is not accounted for by the calibration of the instrument.) Other profilometers have not been tested for their ability to measure $RARS_{50}$ against rod and level, including the TRRL Laser Profilometer, the VTI Laser Profilometer, and the newer versions of the GMR Profilometer that use non-contacting height sensors to replace the earlier follower wheels. 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 background. Yet, they offer a great advantage in being able to obtain measurements rapidly, without great effort spent in maintaining calibration.

Detailed procedures for operating a profilometer to obtain estimates of $RARS_{50}$ (or to measure it directly if the profilometer can be proved to qualify as a Class 1 method) are highly specific to the design of the profilometer, and are beyond the scope of these Guidelines.

The accuracy associated with a Class 2 method is also highly specific to the instruments and procedures. During the IRRE, estimates of $RARS_{50}$ computed from rod and level measures spaced at 500 mm intervals, rather than the 250 mm interval recommended in these guidelines, are estimated to have shown the same accuracy as would have been obtained using a Class 1 method on the Brazilian roads included in the IRRE. Measures obtained from the APL Trailer had an accuracy of approximately 1.3 m/km over the 320 m sections. Improved accuracy from the APL Trailer could possibly be demonstrated (qualifying it as either a more accurate Class 2 system, or even a Class 1 system) by using longer section lengths or repeated runs on short sections (see Section 3.2.1).

3.1.3 Class 3: Estimation of $RARS_{50}$ from measures calibrated through correlation. By far, the majority of road roughness data that is collected throughout the world today is obtained with RTRRMSs. Road roughness can be measured at normal highway speeds, thus RTRRMS measurement can be quite rapid. The roadmeter instrumentation is usually simple and inexpensive. A RTRRMS system is normally operated with a driver and an instrumentation operator, with the operator needing little training in instrumentation, electronics, or engineering. Because of all the variables in the operation of RTRRMS, very rigorous maintenance and operating procedures must be employed, control testing must be made a routine part of normal operations, and the system must be calibrated at frequent intervals. Using the calibration methods described in Section 4.2.4, an accuracy of 1.0 m/km can be obtained over all types of roads for sections 320 m long, with some improvement in accuracy possible by using longer sections (see Sections 3.2.1 and 3.2.2).

In addition to RTRRMSs, this class also includes other roughness measurement methods that are not stable with time, such as subjective panel ratings. Within this class, RTRRMSs are the recommended means for obtaining roughness data.

3.1.4 **Class 4: Roughness measures that have no verifiable link to $RARS_{50}$.** 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 standard RARS scale. In those cases, a subjective evaluation, involving either a ride experience on the road, a visual inspection, or a measurement from an uncalibrated instrument could be used. The roughness data would then be converted to the $RARS_{50}$ scale on the basis of subjective judgement. In those cases, the approximate equivalence is best established by comparison to verbal and pictorial descriptions of roads identified with their associated $RARS_{50}$ values. At this time, such methods have not been sufficiently developed to justify inclusion in these Guidelines.

3.2 Defining Accuracy Requirements

The end use of the roughness data has a direct impact on the accuracy that will be necessary in the measurement procedures, while the accuracy that is required will, in turn, determine how much effort must be devoted to obtaining good data.

3.2.1 Sources of error and their control. The road roughness data base that will be acquired in the project may be used for different purposes, each of which may have peculiar sensitivity to different error sources. It is helpful to realize that inaccuracy in roughness measurements result from three types of error sources.

3.2.1.1 **Repeatability.** When repeated measurements are made with an instrument, exact agreement generally 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 repeatabilty should be assumed to be no better than at least half the quantization size. For example, a roadmeter that produces counts has a repeatability no better then the level associated with 1/2 count.

Errors caused by repeatability limitations are generally random in nature, and can thus be controlled by repeating the measuring process and using the average value of the measures as the "true" measure that would have been obtained if repeatability were perfect. As a rule of thumb, five tests are recommended for a section length of 320 m to obtain an average value reasonably free of this error.

Alternatively, the test section length can be increased to reduce repeatability errors. For sections 1.6 km long, a single measure can be adequate if the instrumentation is known to be reliable. When the roughness qualities of a road are homogeneous over a long length, a longer test length results in more averaging and thus better repeatability. The repeatability error is inversely proportional to the square root of the total length covered ($s \sim \sqrt{1/L}$). The total length can be increased either by using longer test sites, or by making repeated measurements on short test sites.

Another means for increasing the averaging is to use a lower RTRRMS speed for a given length of test site. Since changing the speed changes the meaning of the roughness measure, this approach is not recommended.

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 partly-random selection of the lateral position of a travelled wheeltrack, and 3) the random locations of the specific points where the elevation measures are taken. These errors are reduced by specifying higher quality profile measurements, in the way of more accurate elevation measurements and more closely spaced elevation measurements. When these error sources are controlled, as suggested in 4.1, then 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 part-random position of the RTRRMS (laterally) 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.

3.2.1.2 **Calibration error.** Systematic errors exist between instruments which cause their measurements to differ on all roads (of a given type), and can therefore be corrected using a calibration equation. In order to compare results from different instruments, it is therefore necessary to relate the measures to a reference through a calibration. If the calibration does not cover all of the variables that affect the measurement, then a calibration error exists.

Calibration error is reduced using direct profile measurements, because the instruments that measure the profile (rod and level) are calibrated at the factory and the calibration does not change given reasonable care. Nonetheless, systematic errors can appear in profile-based measures when: 1) the profile elevation measures contain errors (making the profile seem rougher than it is), 2) when profile measures are spaced too far apart and miss roughness features, and 3) when profile measures are subjected to a smoothing or a waveband limitation (as occurs with a profilometer) that makes the profile seem smoother. The recommended procedures in 4.1 were designed to hold these effects to negligible levels.

Calibration by correlation with a reference (described in Section 4.2.4) is required for a RTRRMS because:

1) The overall dynamic response of that particular RTRRMS vehicle differs from that of the reference. This effect can cause the ARS_{50} measure from the RTRRMS to be significantly higher or lower than corresponding $RARS_{50}$ values, depending on whether the RTRRMS is more or less responsive than the reference.

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

3) The RTRRMS suspension motions result 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, and temperature. The only way they can be taken into account is through correlation with measures of $RARS_{50}$ obtained with a reference method (Class 1 or 2), as described in Section 4.2.4. This operation is essentially a "calibration by correlation." Following the procedure in Section 4.2.4 should result in a negligible calibration error for RTRRMS measurements.

3.2.1.3 **Reproducibility.** 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 profile measurement (Class 1), reproducibility error is evident only because of the repeatability limits. Repeatability controls can be used to improve the overall accuracy.

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. 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 operating a RTRRMS in Section 4.2 attempt to do this.

Another step that can be taken is to measure roughness for longer road sites. Since the reproducibility error is random with road selection, 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.

3.2.2 Significance of Error. Roughness data are normally utilized in analyses representing two extremes - statistical analyses involving roughness measurements on a major segment of road network, and individual studies related to roughness at specific road sites. An example of the first 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 purpose of the study is to determine trends, using regression methods. Errors that are random with individual measurements or site selection, caused by poor precision or a peculiar road characteristic, will to some extent average out if the study includes a large number of road sites. On the other hand, a systematic bias error resulting from poor calibration practices in a project will influence the resulting equations, precluding the direct comparison of results with other similar studies, or the application (transportation) of the results in other countries.

Studies that involve monitoring roadway deterioration or the effects of maintenance are examples of the second type of study. 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 can obliterate the trends of interest. Thus for measurements to be used for these applications, the practitioner should employ procedures that will minimize the random errors in measurement. This normally translates into using the same equipment and personnel for regular monitoring of a road site, and utilizing repeat tests to reduce repeatability errors.

4.0 SELECTING MEASUREMENT PROCEDURES

The execution of a high-quality road-roughness measuring program is critically dependent on establishing well thought out procedures that are strictly adhered to in a consistent fashion throughout the project. This section includes guidelines for measuring road roughness using 1) rod and level (Class 1), and 2) RTRRMSs (Class 3) methods. Measures involving other instruments will require guidance from the manufacturer, although some of the methods described here may also apply in part. It is expected that in the majority of projects, the Class 3 RTRRMS method will be selected for routine roughness monitoring, whereas the Class 1 rod and level method will be used for calibrating the RTRRMS.

4.1 Direct Measurement of $RARS_{50}$ Using Rod and Level

4.1.1 Marking the wheeltrack. For the calibration of a RTRRMS, the wheeltracks(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 travelled by the RTRRMS need 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 15 m preceding the wheeltrack, as they will affect the measure of the RTRRMS, but will not be reflected in the $RARS_{50}$ 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.

4.1.2 Measurement of profile. A survey crew using rod and level obtains the profile of the marked wheeltrack by measuring elevation at 0.25 meter intervals along the wheeltrack. The 0.25 m interval is valid for all road surface types except those that have isolated "bumps" that contribute to the roughness as measured with a RTRRMS that would be missed using the 0.25 m interval. (Examples would be tar strips or patches on an otherwise smooth surface. If such a road is measured, a smaller measurement interval is needed, and the corresponding alternative $RARS_{50}$ computation from the attached appendix should be used.) The required precision in the elevation measurement depends on the roughness of the road. The required precisions for four ranges of roughness are as follows:

precision $\leq$ 0.5 mm : smooth paved roads ($RARS_{50}$ < 3.0 m/km)

precision $\leq$ 1.0 mm: moderate and rough paved roads, smooth unpaved roads, (RARS < 8 m/km)

precision $\leq$ 2.5 mm: moderate and rough unpaved roads ($RARS_{50}$ < 12 m/km)

precision $\leq$ 5.0 mm: very rough roads ($RARS_{50}$ > 15 m/km)

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. Nonetheless, in order to reduce the potential of error in recording data, it is essential to employ a well-organized procedure and to have either a portable microcomputer for entering data in the field, or special pre-printed data forms for recording data by hand. Recent improvements in procedure developed by the Brazilians in obtaining rod and level profiles may prove helpful, and are suggested here.

In Brazil, the survey crew consists of three persons: a rod man, an instrument man, and a note-taker. When available, a fourth member is added to act as relief, so that the four can rotate positions to reduce fatigue. A metal tape is laid down in the marked wheel track as a reference for the rod man. (It is helpful to mark the 0.25 m measurement intervals on the tape with paint to reduce the chance of error on the part of the rod man.) When the level is set up, the rod man starts at one end of the tape, placing the rod on the tape itself. The instrument man reads the rod measurement out loud to the note-taker, who records the number and verbally acknowledges that he has heard the number correctly. The instrument man then waves to the rod man, who proceeds to the next mark on the tape. With practice, only a few seconds are needed for each measurement. When the rod man reaches the end of the tape, the tape is moved laterally in order to do the next wheeltrack (when both wheeltracks in a lane are being measured). Once the survey crew has some experience in "profiling," human error on the part of the rod man 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 (320 lane-meters = 2560 elevation measurement points/day).

Obtaining the measurements is about half of the effort. All of the numbers must then be typed into a computer. In Brazil, the numbers are written by the note-taker on special field forms, that have the longitudinal position (distance travelled) prerecorded to reduce the chances of missing or repeating a measurement. The numbers are later inspected by an engineer for obvious mistakes, then given directly to keypunch operators at the computer facility for entry. After the data are entered onto the computer, a program is run to detect differences in adjacent elevation values exceeding a level that would indicate erroneous data. In some cases, the profiles are also plotted to expose any elevation values that are obviously incorrect.

During the IRRE, field data were entered directly into a microcomputer, which can "check" the data as it is being entered and warn the typist of possible errors. The microcomputer was programmed to use an input display format compatible with the paper tape output of the TRRL Beam, so that typists unfamiliar with the meaning of the data could enter the data. This approach avoids the delays and increased complexity involved in having the data manually checked and then entered into a large computer facility. Typing data from the paper tape output of the TRRL Beam, a typist was able to enter about 8000 elevation measures/day.

Because of recent increases in performance and decreases in cost, the use of hand-held microcomputers should be considered as a replacement for the traditional notepad in the field. By typing the field measurements directly into an inexpensive hand-held microcomputer with a paper-tape printer and cassette data storage, the effort needed to obtain good profile measures should be a mere fraction of that needed in the past. The program should "echo" entries on printed tape, so that a printed copy is created as the data are entered, creating a back-up in the event that the microcomputer fails.

Another approach for reducing human error that has been used in Bolivia is to use two instrument men and note-takers, taking readings from the same rod man. 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.

4.1.3 Computation of $RARS_{50}$. The calculation of $RARS_{50}$ is accomplished by computing the response of four variables to the measured profile. The equations for the four variables are solved for each measured elevation point except the first. To handle the first interval, between points 1 and 2, the variables are first initialized by assigning the following values:

$$Z_1' = Z_3' = (Y_{29} - Y_1)/7 \qquad (1)$$

$$Z_2' = Z_4' = 0 \qquad (2)$$

where Y_i represents the "i^{th}" profile elevation point. The use of the 29^{th} data point in the first equation establishes initial values equivalent to a RTRRMS approaching the test section on a smooth surface that matches the slope of the actual test site averaged over the first 7 m.

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

$$Z_1 = .99204\ Z_1' + .01719\ Z_2' - .01242\ Z_3' + .00071\ Z_4' + .02038\ Y' \qquad (3)$$

$$Z_2 = -.78943\ Z_1' + .91721\ Z_2' - 2.2951\ Z_3' + .06241\ Z_4' + 3.0845\ Y' \qquad (4)$$

$$Z_3 = .04653\ Z_1' + .00047\ Z_2' + .45311\ Z_3' + .00995\ Z_4' + .50036\ Y' \qquad (5)$$

$$Z_4 = 3.8985\ Z_1' + .41605\ Z_2' - 47.199\ Z_3' + .08359\ Z_4' + 43.301\ Y' \qquad (6)$$

where

$$Y' = (Y_i - Y_{i-1}) / 0.25 = \text{slope input} \qquad (7)$$

and

$$Z_j' = Z_j \text{ from previous position, } j=1,4 \qquad (8)$$

Thus, eqs. 3 - 7 are solved for each position along the wheeltrack, at intervals of 0.25 m. After they are solved for one position, eq. 8 is used to reset the values of Z_1', Z_2', Z_3', and Z_4' for the next position. For each position, the Rectified Slope of the profile is computed as:

$$RS_i = |Z_3 - Z_1| \qquad (9)$$

The $RARS_{50}$ statistic is the average of the RS variable:

$$RARS_{50} = 1/(n - 1) \sum_{i=2}^{n} RS_i \qquad (10)$$

The above equations are formulated for the elevation measurement interval of 0.25 m. Thus computed $RARS_{50}$ will have the units: elevation/m. For example, if elevation is measured as mm, $RARS_{50}$ will have the units mm/m = m/km = slope x 10^3.

A demonstration computer program for performing the above calculations is presented in Figure 1, which can be executed on nearly any microcomputer that uses the BASIC language. For practical use, the program should be upgraded to read profile elevation values from a file (disk or cassette tape) compatible with the particular microcomputer being used.

4.2 Estimation of $RARS_{50}$ Using a Calibrated RTRRMS

By far, most of the roughness data that is collected throughout the world is obtained with RTRRMSs. The reference definition of roughness, $RARS_{50}$, was designed to represent the response of a standardized "ideal" RTRRMS.

4.2.1 Description of equipment. An RTRRMS consists of 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.

4.2.1.1 **The Roadmeter.** Roadmeters are also known by many other names: ride meters, Maysmeters (Rainhart Company, USA), Bump Integrators

Figure 1. Demonstration Computer Program to calculate $RARS_{50}$ from Profile.

```
100  REM      This program is a demonstration of the RQCS. Simulation
110  REM      speed is 50 km/h and the measurement interval is 0.25 m.
120  REM      The profile elevations should have units: mm.  For other
125  REM      simulation speeds (V) or measurement interval (DX) refer
126  REM      to Appendix F in Reference [1].
130  REM
140  DIM Y(1281),Z(4),Z1(4),ST(4,4),PR(4)
150  READ V,DX
160  FOR I = 1 TO 4
170  FOR J = 1 TO 4
180  READ ST(I,J)
190  NEXT J
200  READ PR(I)
210  NEXT I
220  INPUT "NUMBER OF PROFILE ELEVATION POINTS = ";N
230  FOR I = 1 TO N
240  PRINT "POINT #";I;
250  INPUT " ELEVATION = ";Y(I)
260  NEXT I
310  REM
320  REM      Initialize RQCS.
330  REM
340 Z1(1) = (Y(N1 + 1) - Y(1)) / 7
350 Z1(2) = 0
360 Z1(3) = Z1(1)
370 Z1(4) = 0
380 RS = 0
390  REM      Calculate Roughness RS
400  REM
410  FOR I = 2 TO N
420 YP = (Y(I) - Y(I - 1)) / DX
430  FOR J = 1 TO 4
440 Z(J) = PR(J) * YP
450  FOR JJ = 1 TO 4
460 Z(J) = Z(J) + ST(J,JJ) * Z1(JJ)
470  NEXT JJ
480  NEXT J
490  FOR J = 1 TO 4
500 Z1(J) = Z(J)
510  NEXT J
520 RS = RS +  ABS (Z(1) - Z(3))
530  NEXT I
540  PRINT "RARS = ";RS / (N - 1)
550  END
560  DATA     50,.25
570  REM
580  DATA  .992040026, .0171948155, -.0124196184, 7.08544757E-04, .0203795897
590  DATA  -.789425935, .917212924, -2.29510558, .0624074845, 3.0845315
600  DATA  .0465278304, 4.72363171E-03, .453113538, 9.9465964E-03, .500358633
610  DATA  3.89845779, .416049897, -47.1993075, .0835914715, 43.3008497
```

(TRRL, UK), NAASRA meters (AARB, 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, they are functionally equivalent when operating within their design range.

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 measure of ARS for that road/RTRRMS/speed combination.

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 are acceptable for use in World Bank projects due to 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, and may be wired so as to prevent all counts from registering. If not all counts register, then the relative precision of the RTRRMS is 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 (AARB), and the modified Maysmeter (GEIPOT). The commercial Maysmeter (Rainhart, USA) cannot always provide valid measures on rougher roads ($RARS_{50}$ > 4 m/km).

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. Hence, the manual should be used mainly to understand the operational principles of the instrumentation, while these Guidelines should be used to understand its use.

4.2.1.2 **The Vehicle.** Three types of vehicles can be used together 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. A rear-drive vehicle is recommended.

2) A two-wheeled trailer towed by **one** vehicle that is always available for that task. The trailer should have a solid axle. The actual configuration of the towing vehicle is not important, but the same towing vehicle must be used between calibrations, since 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.

4.2.1.3 **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.

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.

4.2.2 Method of measurement with a RTRRMS. The vehicle is run at a constant speed of 50 km/h over the section of road being measured. The vehicle should be brought to speed at least several seconds before the start of the section, to ensure that the resulting measure is not influenced by a speed transition. The roadmeter is turned on at the start of the section, and the number of counts accumulated at the end of the section is recorded. Adjacent sections can be measured in one pass by noting the accumulated counts at the boundary between sections, without resetting the display.

The number from the roadmeter should be converted to a form of ARS_{50} that is convenient for that particular roadmeter, such as "counts/km," "in/mi," or "mm/km." ARS_{50} is computed by dividing the counts accumulated by the roadmeter while on that section by the length of each section. (Thus, if adjacent sections of road are measured, and accumulated counts are noted between sections, the ARS_{50} numeric should be computed from the net change in the accumulated counts that occurred on each section.)

The uncalibrated ARS_{50} numeric is converted to an estimate of $RARS_{50}$ called $CARS_{50}$ using the current calibration equation.

4.2.3 Sources of error and their control. In order for the results obtained from a RTRRMS to be consistent and useful, the mechanical properties of the vehicle (and roadmeter) must be kept constant through good maintenance and operating practices, to prevent variations in the vehicle that 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 following sensitivities [2].

4.2.3.1. **Operating speed.** The standard speed of 50 km/h was selected because most RTRRMSs can operate on even the roughest roads at this speed. The $RARS_{50}$ 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 50 km/h is not safe, for reasons of traffic, pedestrians, restrictive geometry, etc.

2) The roadmeter produces erroneous and inconstant measures at 50 km/h on the rougher roads.

3) 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.

4) The project will mainly cover short test sections, and accuracy on 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.

The recommended solution for problems caused by the mechanics of the RTRRMS is to replace the vehicle and/or roadmeter if possible with something more rugged. If any of these conditions are unavoidable, a lower standard RTRRMS speed of 32 km/h should be adopted for all RTRRMS measurements. The calibration reference is still $RARS_{50}$ thus the calibration method described in Section 4.2.4 should be followed, with the difference that the RTRRMS is operated at the speed of 32 km/h.

When only a few sections need to be measured at a lower speed, then the speed corrections methods described in Section 4.2.7 can be used.

4.2.3.2. **Shock absorber selection.** The single most important vehicle component in terms of sensitivity of the RTRRMS 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 or favoring models that are in wide supply. 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 comparing the absolute magnitude of the ARS values measured by the RTRRMS to the RARS values for the surfaces during calibration. If the measures from the vehicle are more than 20% greater on the average than the RARS on moderately rough roads, more effective damping on the vehicle suspension is recommended.

4.2.3.3. **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 gasoline. The vehicle should not contain extra cargo or occupants during testing.

4.2.3.4. **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 a value selected as being appropriate for the vehicle.

4.2.3.5. **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.

4.2.3.6. **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, and thus ARS. 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.

4.2.3.7. **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 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 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. 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 4.2.6. 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.

4.2.3.8. **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 RARS roughness scale.

4.2.4 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. Calibration is achieved by obtaining "raw" measures of roughness (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 $RARS_{50}$ roughness values as determined with a Class 1 method (rod and level or equivalent). The RTRRMS is periodically run over the calibration sites at the standard speed after suitable warm-up. The "raw" roughness values from the RTRRMS are plotted against the $RARS_{50}$ values, with the RTRRMS values on the x-axis and the $RARS_{50}$ values on the y-axis, as illustrated in Figure 2. A line is fit to the data points and used to estimate $RARS_{50}$ from RTRRMS measurements taken in the field. For a single speed, one relationship will often be obtained even for different surface types when the "raw" measure is plotted directly against $RARS_{50}$ as shown in the figure. When it is necessary, for whatever reason, to conduct tests at any other than the standard speed, this relationship does not apply. Separate relationships between the "raw" measure and the $RARS_{50}$ must be developed for each of the other speeds, as described in the Section on Speed Compensation.

Depending on the required accuracy of the calibrated roughness data and the local roadbuilding practices, separate calibration relationships may be warranted for different surface types (paved and unpaved, for example). This

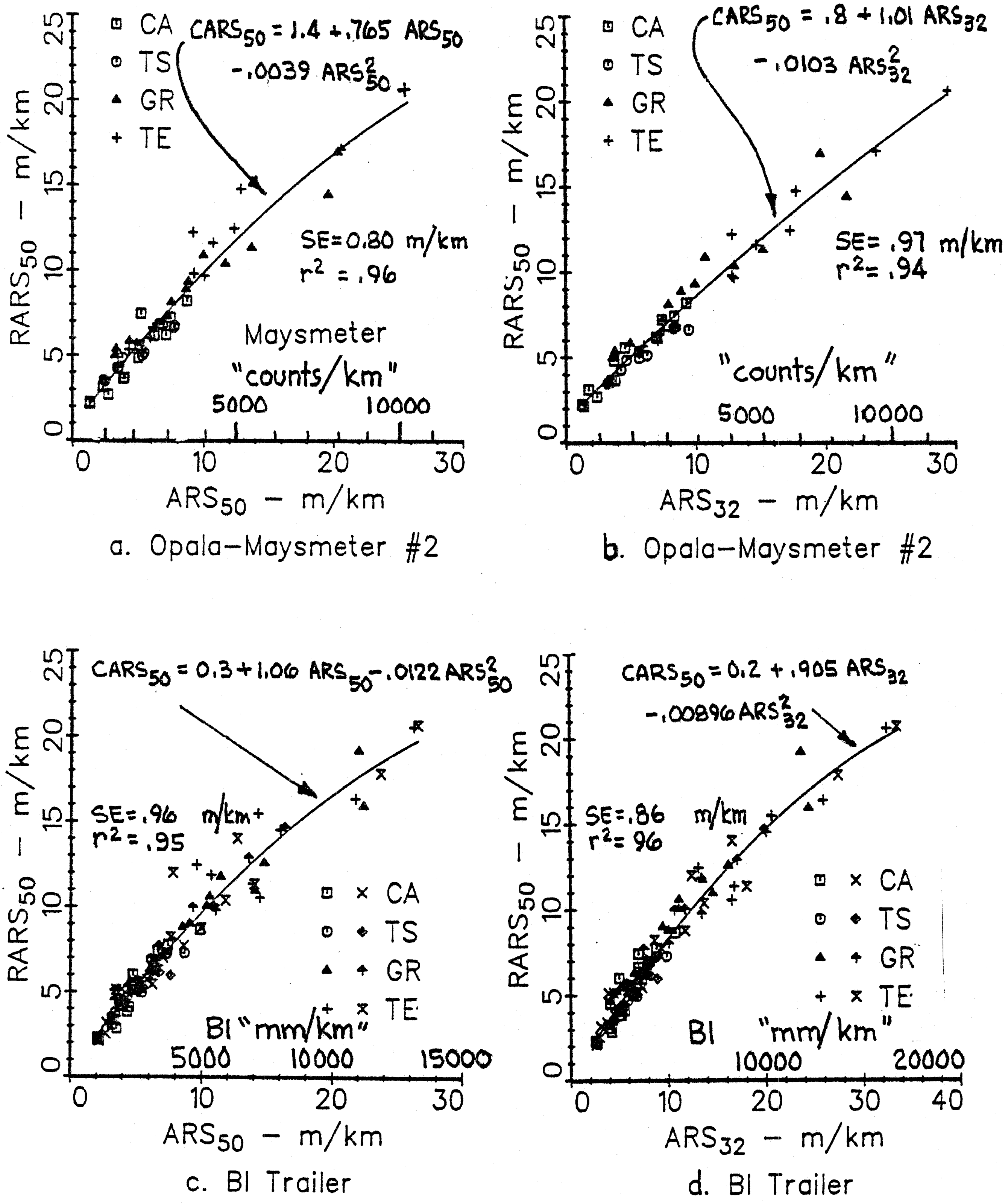

Figure 2. Example plots of calibration curves and the measurements used to compute the curves. Separate calibrations are shown for speeds of 32 and 50 km/h.

section presents guidelines for calibration on a **single** road surface type. Past experience has indicated that a single calibration is adequate for asphaltic concrete, PCC concrete, double surface treatment, and Brazilian earth and gravel roads. It may be expected that a common calibration relationship will be obtained for many other road surface types; however, roads that have potholes, corrugations, or are constructed with methods not common in the United States and Brazil may require separate calibrations.

4.2.4.1 **Considerations in site selection.** For the resulting calibration to be valid, the calibration sites must be representative of the roads being surveyed in the project. It is thus essential that the sections be "naturally rough," exhibiting roughness resulting from normal construction/maintenance/use histories. 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 then the smoothest calibration site and 30% rougher than the roughest) is not recommended. If the additional range is needed, then appropriate calibration sites must be found.

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.

Remember that RTRRMSs always respond to the road **after** they have passed over it. Therefore, avoid sites that have a distinctly different roughness character immediately prior to the start of the site.

Calibration sites should always be on tangent sections of road. 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.

In addition to the above concerns, a valid calibration must meet certain requirements related to the number of sites, their minimum lengths, and the roughness range covered. These requirements are summarized in Table 1. Table 2 is also included to help determine approximate roughness ranges prior to the calibration, by describing six broad ranges of roughness. Note that it is impossible to design a valid calibration that is "minimal" in every respect (just barely meets each requirement). For example, if the project covers all six roughness levels, then a minimum of 12 sites are required (two per roughness level). And if only 12 sections are used, they must be at least 250 m long (3000 m/12 site = 250 m/site). Alternatively, 20 sections, each 150 m long, could be used. When more than two sites of each roughness level are used, the additional sites should be selected to maintain uniform distribution among the roughness levels. At no time should the number of sites for the "most represented" and "least represented" roughness levels differ by more than one.

To obtain a calibration that results in better accuracy, the total overall length should be increased, either by using longer sites, or using more sites. 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 negligible calibration error.

A constant test site length is needed during a calibration, but this restriction does not apply to the routine measurement of road roughness. When calibration sites are measured with a rod and level Class 1 method, 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.

4.2.4.2 **Data processing.** The data from the calibration sites are used to regress $RARS_{50}$ against the "raw" RTRRMS measurements using a quadratic model, and minimization of the squared error. ("Error" is the difference between the "true" $RARS_{50}$ from the Class 1 measurement, and the estimate of it from the RTRRMS measurement.) 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 $RARS_{50}$ is measured for both of the wheeltracks travelled by the tires of the RTRRMS, and the two numbers are averaged. The average is then used as a single measurement of $RARS_{50}$ for that lane, and regressed against the single measure obtained from the two-track RTRRMS.

Table 1. Summary of RTRRMS Calibration Site Requirements.

	RTRRMS Type	
	Two-Track	Single-Track
Minimum Number of Sites	8	12
Minimum Number of Sites for for Each Roughness Level (See Table 2 for roughness descriptions.)	2	3
Maximum Variation in the Number of Sites Per Roughness Level (i.e., sites should be distributed uniformly among different roughness levels)	1	1
Minimum Site Length	150 m	150 m
Maximum Variation in Site Length (i.e., all sites should have the same length)	0	0
Minimum Total Length (site length x number of sites)	3 km	4.5 km
Minimum "Lead-In" Distance for RTRRMS (RTRRMS must be brough to speed **before** entering "Lead-in" area)	30 m	30 m
Minimum Number of Repeated RTRRMS Measures Per Site	3	3

Note: Contiguous calibration sites are permitted.

Table 2 Descriptions of Six Categories of Roughness

$RARS_{50}$ (m/km)	Description of Roughness Category
0 - 2	Extremely high quality new asphalt concrete pavement; for high-speed motorways and airport runways. Uncommonly smooth for highways.
2 - 3	Typical high-quality asphaltic concrete pavement; very good surface treatment construction. No potholes or corrugation.
3 - 5	Paved roads showing early stages of deterioration; good quality unpaved roads. Occasional potholes (1-3 per 50 m) and despression (20-40 mm/5m or 10-20 mm/3m). Travel speeds < 100 km/h.
5 - 8	Severely distressed pavements; deep and uneven depressions (720 mm/3m); frequent potholes (5-10 per 50 m); moderately maintained gravel; shallow/moderate corrugation (6-20 mm depth, 0.7-1.5 m spacing). Speeds < 80 km/h.
8 - 13	Unpaved roads. Frequent transverse despressions. Occasional deep depressions. Strong corrugations (720 mm) frequent shallow potholes. Speed usually < 60 km/h
13 - 18	Unpaved roads. Frequent deep depressions, potholes. Some very deep potholes. Frequent transverse and longitudinal erosion gulleys, speed generally < 50 km/h

Subsequent estimates of $RARS_{50}$ made from the RTRRMS using the calibration equation are in fact the calibrated roughness measurements from the RTRRMS, and are called $CARS_{50}$ for Calibrated ARS_{50}. The mathematical details needed to compute the calibration equation are summarized in Table 3. The accuracy associated with the RTRRMS can also be calculated, and is quantified by the Standard Error (SE) of the $CARS_{50}$ estimate, using the equation given in the Table.

Each RTRRMS requires a separate calibration equation, based on the ARS measures that it produced on the calibration sites.

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), since 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 ARS and RARS measures.

4.2.4.3 **Determining calibration site $RARS_{50}$ values** - The Class 1 measurement of $RARS_{50}$ on paved calibration surfaces (see Section 4.1) needs to be repeated periodically. For unpaved roads, roughness is sensitive to so many environmental conditions that the $RARS_{50}$ measurement remains valid for 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 Class 1 method. Naturally, when calibration sites are exposed to any maintenance the $RARS_{50}$ values are affected, and earlier measurements are no longer valid for future calibration.

When the $RARS_{50}$ roughness value for a road site has changed, that site cannot be used for future calibrations until the new $RARS_{50}$ is established.

Table 3. Computation of the Calibration Equation

The calibration equation for a RTRRMS is:

$$CARS_{50} = A + B \cdot ARS + C \cdot ARS^2$$

ARS is the "raw" measure with units: counts/km or an equivalent (in/mile, mm/km, etc.), and $CARS_{50}$ is the "Calibrated ARS," having the same units used for $RARS_{50}$ (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 = $RARS_{50}$ roughness of i^{th} site (computed from a measured profile). The accuracy of $CARS_{50}$ measures is the Standard Error (SE), which should also be calculated as indicated below.

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

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

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

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

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

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

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

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

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

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 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 the same roughness, routine calibration of a RTRRMS can continue. Whenever a $RARS_{50}$ 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 Control tests for RTRRMS time stability. While the previously described calibration is needed to convert RTRRMS measures to $CARS_{50}$ (estimate of $RARS_{50}$), a simpler test can be used to determine whether or not the response of the RTRRMS has changed on a day-to-day basis. Change will always occur, thus several "control" sites of road should be selected in locations close to the base of operations of the RTRRMS for periodic check tests. Since the purpose of a control test is to determine whether the RTRRMS has changed, the $RARS_{50}$ value for a control test site need not be measured with a Class 1 method. The recommended length for a control site is a minimum of 1.6 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. They should be portions of paved roads that are lightly travelled and are not scheduled for any maintenance over the course of the project. As control sites, their roughness is assumed to be constant with time, and care should be taken to ensure that this assumption is reasonable.

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 (constant speed, RTRRMS "warmed-up"). The measurements should be recorded for future reference. 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, as described in Section 4.2.3. 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. By locating the sites between the storage location of the RTRRMS and the roads being measured as part of the project, the RTRRMS can be checked daily with little time or effort.

On a daily basis, the control site measures should always fall within an acceptable range, where that range is determined by prior experience with the unit. 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. On control sections 320 m long, normal variations can be ±5%, and changes of ±10% indicate that the RTRRMS has changed. On sections 1.6 km long, normal variations should be within ±2%, allowing detection of smaller changes on the order of ±5% in the RTRRMS. If measurements on the control sections do not fall within the control limits, then the RTRRMS should be checked for defects. A new calibration is required unless a simple reason for the change can be found and corrected. When a problem is found, all data gathered by that RTRRMS since the last control check should be discarded.

When an 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.

In addition to quickly recognizing damage, malfunctions, or changing properties of the RTRRMS, daily (or otherwise periodic) control tests can be used to evaluate the sensitivity of the RTRRMS to environmental changes.

The control procedures described in Reference [3] are suggested as a good reference for developing practices. Control tables and charts illustrated in Figures 3 and 4 were maintained to record the mean and range to help indicate when detailed inspection of the RTRRMS was warranted.

4.2.6 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

WORK SHEET FOR MRM
CONTROL RUN

State DF MRM No. 6-001

Date 03/05/79 Operator CL Driver: S. H. M

Section	M-05	M-06	M-07	M-08	M-22
X̄ Initial	326.2	231.4	583.8	407.8	381.0
Run	**Reading**	**Reading**	**Reading**	**Reading**	**Reading**
1	330	231	572	400	391
2	324	219	587	403	384
3	327	228	581	407	386
4	319	225	588	404	379
5	331	233	585	404	388
Sum =	1631	1136	2913	2018	1928
X̄ Current =	326.2	227.2	582.6	403.6	385.6
Δ MRM =	12	14	16	7	12
Δ X̄ =	0	4.2	1.2	4.2	-4.6

$$\bar{X}\text{ Current} = \frac{\text{Sum of readings}}{5}$$

Δ MRM = MRM MAX − MRM MIN Enter on range control chart

$\Delta \bar{X} = \bar{X}$ INITIAL − $\bar{X}$ CURRENT Enter on mean control chart

Figure 3 Typical Worksheet for Maysmeter Control

MT-GEIPOT-PICR

MRM MEAN CONTROL CHART

State DF MRM No. Ø-101 Date 6.7 / 7 / 78

Initial mean

Section	$\overline{X}$
M-01	204
M-02	474
M-03	162
M-04	497
M-05	201
M-06	201
M-07	505
M-08	364
M-09	—
M-10	152
M-11	265
M-12	168
M-13	184
M-14	209
M-15	306
M-17	114
M-18	85
M-19	91
M-20	85
M-22	366
M-23	114

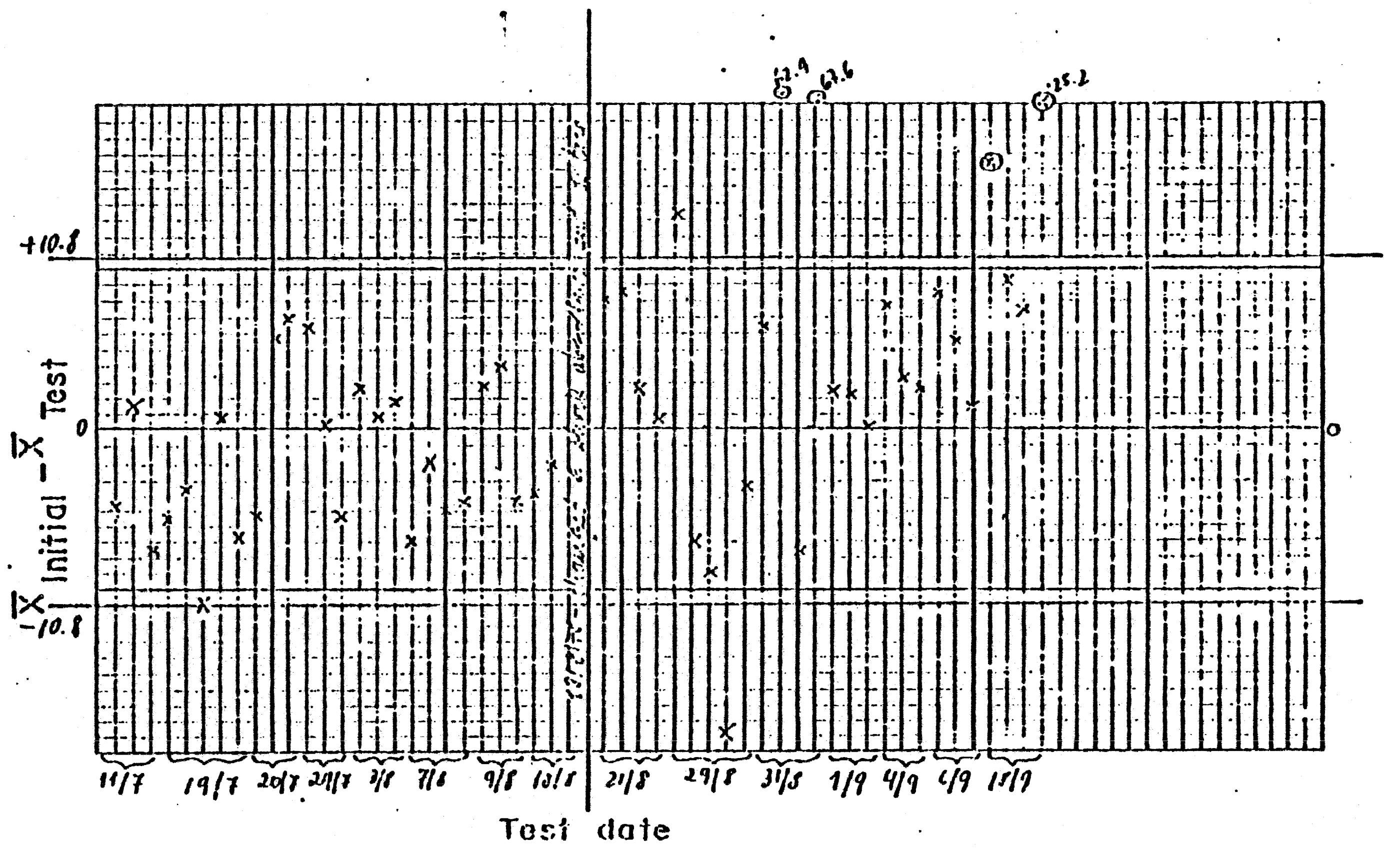

Figure 4 Maysmeter Control Sheet of the Mean

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 1. (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 must be allowed to cool down. Allow one to two hours for the cool-down. 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 RARS 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.

4.2.7. Speed compensation. There may be occasions in a roughness survey project where it is not possible to obtain the roughness measurements at the standard speed of 50 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 32 km/h is recommended. 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 ARS_{32} measurements to $RARS_{50}$. 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 50 km/h necessitate that a different calibration be used. Two basic methods are available for the calibration/conversion process.

4.2.7.1 **Direct calibration for 32 km/h (Preferred method).** The calibration as described in Section 4.2.4 is performed with the RTRRMS operated at 32 km/h, relative to $RARS_{50}$ measures. This is a calibration "across speed." In this case, the $CARS_{50}$ measure obtained from the RTRRMS is the estimate of $RARS_{50}$ based on a measure of ARS_{32}.

When a speed of 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 ARS is measured at 50 km/h, a systematic calibration error can be introduced for some surface types when ARS measures are made at 32 km/h, due to the different wavebands sensed by the RTRRMS at the two speeds.)

4.2.7.2 **Correlation of ARS measures made at different speeds (Alternate method).** When circumstances prevent the direct method described above (4.2.7.1), a two-step conversion should be used. First, the ARS_{32} measure is used to estimate what the ARS_{50} measure would have been if measurement at 50 km/h were possible. Second, the estimated ARS_{50} value is used with the calibration equation for that particular RTRRMS to yield $CARS_{50}$.

To obtain the conversion from ARS_{32} to ARS_{50}, the calibration procedure described in Section 4.2.4 is followed, except that the ARS_{50} measure obtained with the RTRRMS is used as the "reference" measure instead of $RARS_{50}$. Therefore, profile measurement is not required to determine the correlation between ARS_{32} and ARS_{50}.

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 1 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.

5.0 REFERENCES

1. Sayers, M., Gillespie, T.D., and Queiroz, C., "International Experiment to Establish Correlation and Standard Calibration Methods for Road Roughness Measurements," (publication details to be made available).

2. Gillespie, T.D., Sayers, M., and Segel, L., "Calibration of Response-Type Road Roughness Measuring Systems," **NCHRP Report No. 228**, December 1980, 81 pp.

3. Visser, A., and Queiroz, C., "Roughness Measurement Systems," **Working Document No. 10** of the Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization, Brazilian Ministry of Transport, July 1979, 119 pp.

6.0. APPENDIX: GLOSSARY OF OTHER ROAD ROUGHNESS MEASURES

This Appendix provides a short alphabetical listing of the different measures and descriptions of road roughness that are not generally related to the $RARS_{50}$ measure, but which the practitioner may encounter.

APL 72 Waveband Analysis (LCPC) - an analysis applied to the profile signal obtained from the APL Trailer that results in three roughness statistics that together describe the present condition of the roughness of a road. These measures are widely used in France by the Bridge and Pavement Laboratory (LCPC). Each of the measures is the variance of the APL signal filtered to isolate a particular waveband, covering "short-wave," "medium-wave," and "long-wave" roughness properties. The name APL 72 derives from the towing speed of the trailer, which is 72 km/h. Three methods are used to scale the numerics obtained, depending on the application. The APL 72 "Energy" (W) is the mean-square value of the filtered profile. The APL 72 "Equivalent Amplitude" (Y) is the amplitude that would be associated with as sinusoid causing the same Energy (W) numeric. Y is an RMS measure, whereas W is a squared measure. The APL 72 Index is a value indicating the quality of a road for each waveband, relative to the road network in France. 10 is the best, and 1 is the worst. These Numerics are obtained electronically, and methods to compute them with rod and level methods have not been developed. The short-wave numerics are usually correlated with $RARS_{50}$ and RTRRMS measures, while the medium and long-wave numerics cover wavebands that are not "seen" by a RTRRMS. A similar set of three waveband numerics is used in Belgium, based on a moving average numeric called CP. (See CP.)

APL 25 - see CAPL 25

ARV - an abbreviation for Average Rectified Velocity. ARV is a generic name for the vehicle response variable measured by a RTRRMS, and is the average stroking speed of the suspension of the vehicle-part of the RTRRMS. This statistic has units of the form length/time, such as: in/sec, mm/sec, or counts/minute. ARV is the direct measure of vehicle response, such that increased ARV always indicates increased vehicle vibrations, regardless of the measurement speed or source of vibration. ARV = ARS x speed, and is therefore equivalent when a single standard RTRRMS speed is used.

BI - an abbreviation for Bump Integrator, the BI is a Roadmeter used by the British TRRL, based on the rotational clutch concept used with the early BPR Roughometer. Most measurements made with BI Roadmeters are presented with the units: mm/km. The raw measure corresponds to one-half of the total accumulated suspension deflection; thus, BI results should be doubled to obtain the ARS statistic for direct comparison with measures made with other Roadmeters. The BI unit has been used in World Bank projects throughout the world, and has proven to be capable of measuring vehicle response over the entire roughness range that can be expected to be encountered. The BI unit is not trouble-free, but its simple design and construction facilitate maintenance and repair in developing countries. As with any Roadmeter, the roughness measures obtained with the BI depend on the Vehicle portion of the RTRRMS and the operating procedures as much as on the road roughness.

BI Trailer - a RTRRMS consisting of a special single-wheeled trailer that is towed, and instrumented with a BI Roadmeter. The BI Trailer has been developed by the British TRRL, based on the design of the earlier BPR Roughometer. By using a special trailer dedicated to measurement of road roughness, the variation between individual RTRRMSs is reduced, although not eliminated. Compared to other RTRRMSs, the BI trailer has the advantage of having been used a great deal in recent World Bank projects, so that the user can have an idea about what to expect in terms of the measurement magnitudes and repeatability. In the past, the BI Trailer has been used only at the speed of 32 km/h; however, the results of the IRRE demonstrate that it can successfully be used at other speeds for compatibility with other RTRRMSs. The measurements obtained with the BI Trailer are typically reported with the units: mm/km and should be doubled to yield ARS.

In past World Bank projects, roughness data have been obtained with BI Trailers that have not been calibrated against a profile-based roughness numeric. While TRRL has attempted to maintain individual BI Trailers so that they are functionally interchangable, there is ample evidence that each BI Trailer responds slightly differently to road roughness than another BI Trailer, and that a calibration by correlation should be performed. Note that Figure 2.d can be used to approximately obtain the "mm/km" from the $RARS_{50}$ standard.

BPR Roughometer - an early RTRRMS used by the Bureau of Public Roads. The BPR Roughometer is a single-wheeled towed trailer equipped with a mechanical Roadmeter that employs a one-way clutch. The BPR Roughometer has historically been operated at 32 km/h, but can be used at other speeds for compatibility with other RTRRMSs. The BPR Roughometer is conceptually the same as the BI Trailer, but is typically not as rugged or as standardized [1, 2].

CAPL 25 - A numeric obtained with an analysis/test procedure associated with the APL Trailer used widely in France to evaluate newly constructed roads over sections 25 m long. The CAPL 25 numeric can be measured only with the APL Trailer at this time [1].

Counts/km, Counts/Mile - names that have been used in the past to refer to the ARS statistic. These names have also been used to refer to the PCA-Sum-of-squares statistic, which is quite different from ARS.

CP - Coefficient of Eveness, used by the Belgian Road Research Center (CRR) as a roughness numeric. CP is the average rectified value of a profile that has been filtered with a moving average, and has the units: 50 CP = 1 mm. The CP numerics are typically computed from APL 25 and APL 72 profiles, using moving average baselengths of 2.5, 10, and 40 m for the APL 72 signals, and baselengths of 2.5 and 15 m for the APL 25. The CP(2.5) and CP(10) numerics can also be obtained using other profile measurement methods such as rod and level, provided that a small enough sample interval is used. The CP(2.5) numeric is highly correlated with $RARS_{50}$ and RTRRMS measures, while the CP numerics computed for longer baselengths correspond to wavebands not "seen" by a RTRRMS. The CP numerics serve the same purpose in Belgium as the APL 72 numerics computed by LCPC in France, and cover approximately the same wavebands.

Golden Car - a name that has been used for the particular set of parameters used to define the $RARS_{50}$ numeric. The set of parameters is also used for a Half-Car Simulation that processes two wheeltracks simultaneously, rather than singly as described in the Guidelines.

"Inches/Mile" - one of the names that has been used to refer to the ARS measure.

Maysmeter - a commercial Roadmeter made by the Rainhart company in the USA. The transducer employs an optical encoder to produce electronic pulses that are mechanically accumulated by a one-way stepper motor connected to a paper strip-chart recorder. When operated within its allowable roughness range, the Maysmeter measures the ARS statistic with the units Inches/Mile, although some agencies use the length of the paper advanced during the test instead of the actual accumulated suspension. (The two measures differ by a factor of 6.4.) The Maysmeter is one of the most popular Roadmeters used in the United States. Although the transducer portion is generally acceptable for use everywhere, the stepper motor has response limits that make the Maysmeter unsuitable in its factory form for higher roughness levels. The factory version is described in the Mays Ride Meter Booklet, 3rd Ed., Rainhart Co., Austin Texas, 1973.

Maysmeter Simulation - a commercial computer program offered with the digital GMR-type Profilometer (model 690D) by the K.J. Law Engineering Co., Farmington, Michigan. This program uses the Golden Car parameters with a Half Car Simulation, rather than the Quarter Car Simulation used in the Guidelines to define $RARS_{50}$.

"mm/km" - one of the names that has been used to describe the ARS measure. "mm/km" is also the name used to refer to roughness data measured with the BI Trailer in several World Bank projects.

Moving Average - A method of analysis used to obtain roughness numerics from profile. A new, smoothed profile is defined, point-by-point, where each point corresponds to an average taken for the original profile over a specified baselength distance. The smoothed profile, is subtracted from the original to cancel the long wavelength geometry, leaving shorter wavelengths. The resulting filtered profile is summarized by an average rectified value, or by an RMS value. When baselengths ranging from 1.5 - 3 meters are used, high correlations exist with RTRRMSs that are generally unaffected by surface type. Moving average numerics can be measured directly using either a profilometer or static method (rod and level, TRRL Beam), providing that sample interval is sufficiently small.

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 Meter has been found capable of measuring the ARS and ARV statistics over the full range of vehicle excitation (as defined by ARV). The NAASRA RTRRMS is "calibrated" by holding one RTRRMS in storage as a reference, and correlating the other RTRRMSs with it. More recently, a calibration method based on a drum roller having artificial roughness and using ARV measures has been reported. (L. J. Little, "A New Method of Calibrating NAASRA Roughness Meters." ARRB Internal Report, AIR 354-1, 1980.

Profilometer - a mobile instrument used for analyzing the longitudinal profile of roads that does not include uncontrolled dynamic responses in the measurement. A Profilometer must have a means for calibration, other than the empirical regression methods needed for RTRRMSs. The signal produced by a Profilometer is not the "true" profile that would be sampled with the rod and level survey method, but is valid over a certain range of wavelengths. (Most Profilometers cannot sense a steady uphill grade, for example, but instead respond to changes in grade.)

QI - this is the original road roughness statistic adopted for use as a calibration standard in the Brazilian ICR Project when it started in 1975. Since the start of the project, three alternative definitions of QI have also been used, which are designated QI^*, QI_r, and QI_w^*. The original QI was based on the readings taken from a praticular 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 [1].

QI_r - this is a profile-based roughness statistic developed by Queiroz and other Brazilian researchers to replace the QI calibration scale. (C. Queiroz, "A Procedure for Obtaining a Stable Roughness Scale from Rod and Level Profiles." Working Document 22, Research on the Interrelationships between Costs of Highway Construction, Maintenance and Utilization, Empresa Brasileira de Planejamento de Transportes (GEIPOT), Brazil, Sept. 1981.) 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 for baselengths of 1.0 and 2.5 m:

$$QI_r = -8.54 + 6.17 \times RMSVA(1.0) + 19.38 \times RMSVA(2.5)$$

The above equation requires the RMSVA measures to have the units 1/km (.001/m, 10-6/mm), as obtained when profile elevation is measured in mm. The above equation can only be applied when profiles are measured statically, as with a rod and level. When a profilometer is used, a different equation is needed in order to prevent serious bias errors [1]. Correlations between QI_r and $RARS_{50}$ have been found to be excellent for three of the four types of road construction present in the IRRE; however, the correlation varies with surface type. In comparison with RTRRMSs, QI_r numerics tend to be high on asphaltic concrete roads and low on surface treatment roads.

On asphaltic concrete roads, QI_r is functionally equivalent to the original QI, and is by definition equivalent to QI^*. On other types of roads, the QI_r and QI^* roughness scales are not equivalent (see QI^*). (The original QI was never measured on unpaved roads, so there can be no relationship between QI_r and QI on these roads.)

QI^* - The road roughness statistic used for all of the data measured in the ICR Project, as reported and stored in the Brazilian computer data files. QI^* has been shown to depend on the response of the vehicle used in the RTRRMS, and therefore it cannot be replicated except on asphaltic concrete roads. Assuming that the RTRRMS vehicles had not change substantially between the ICR project and the IRRE, QI^* numerics are larger than corresponding QI_r measures on unpaved roads, and substantially higher (sometimes 100%) on surface treatment roads. By definition, QI^* is equivalent to QI_r on asphaltic concrete roads.

QI_w^* - Engineering consultants to the World Bank have been re-processing much of the roughness data obtained during the ICR project. The resulting cost equations, when published, will differ from the original ones, as they are based on yet another variation of QI. The difference between QI^* and QI_w^* applies when the RTRRMS was operated at speeds lower than 80 km/h, and ranges from -20% to +40%. The intent of the modifications is to bring the QI_w^* statistic closer to the QI_r statistic.

QCS - see Quarter-Car Simulation.

Quarter-Car Simulation (QCS) - a mathematical transform that can be applied to a road profile, to yield the "simulated" response of a vehicle. The $RARS_{50}$ numeric is computed using a QCS. More details are provided in Appendix F of Reference [1].

RARV - an abbreviation for Reference ARV. RARV = ARS from a QCS multiplied by the simulation speed.

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 - an abbreviation for Root Mean Square Vertical Acceleration, this roughness statistic has been proposed by McKenzie and Srinarawat ("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) 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:

$$VA_b = [Y(x + b) + Y(x - b) - 2 Y(x)] b^{-2}$$

where Y(x) is the signal amplitude (profile elevation) at position x, and B is the baselength parameter. As defined by the above equation, RMSVA has no relation to profile vertical acceleration, being instead simply a measure of Mid-Chord Deviation with a scale factor of $2b^{-2}$.

The RMSVA statistic was used to define the QI_r calibration standard in the ICR project, and has also been used to define a RTRRMS calibration standard for use in Texas. RMSVA measures obtained with a profilometer will generally be in error due to waveband limitations, and therefore regression equations must be derived to compare RMSVA measures obtained with different profilometry methods.

Slope Variance (SV) - a measure of road roughness that is the variance of a signal produced by the early AASHTO Profilometer and CHLOE Profilometer. The true variance of the slope of a road profile is infinite, since the true profile includes texture effects. As used to describe roughness, Slope Variance (SV) refers to the variance of a signal or "profile" obtained by a specific method. The SV is actually more sensitive to the choice of profile measurement method than to roughness, and does not describe a standard roughness measure. 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 the 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.