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16. Abstract

The International Road Roughness Experiment (IRRE) was conducted in Brazil in May-June 1982. The purposes were to examine correlations between various road roughness measuring equipment in use throughout the world, and to identify a standard roughness measure that can be used as an International Roughness Index when exchange of roughness data is desired. The IRRE was a cooperative effort initiated by the World Bank (IBRD), and conducted by researchers from Brazil (GEIPOT and IPR/DNER), England (TRRL), France (LCPC), Belgium (CRR), and the United States (UMTRI). Equipment was provided by these agencies and also COPPE/UFRJ (Brazil) and ARRB (Australia).

The experiment involved measurement of 49 test sites, covering a wide range of roughness over paved and unpaved roads. Each site was measured at several speeds by seven response-type road roughness measuring systems and evaluated subjectively by a rating panel. The longitudinal profiles of the travelled wheeltracks were measured both statically and dynamically with a profilometer. The profiles were processed to obtain spectral density plots and a number of summary numerics that have been used to quantify roughness, including waveband analyses, vehicle simulation, moving average, RMSVA, and others.

The data showed that excellent correlation is seen between any two response-type systems when operated under the same conditions, and that most differences other than durability are cosmetic. A standard speed of 50 km/h is recommended for these systems when exchange of data is desired. A number of the profile-based numerics were investigated as calibration references for the response-type systems. One, the Reference Quarter-Car Simulation, was shown to be compatible with every measurement method included in the IRRE, and it is recomended as the International Roughness Index for direct measurement with profilometric methods and as a calibration reference for response-type systems.

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INTERNATIONAL EXPERIMENT TO ESTABLISH CORRELATION AND STANDARD CALIBRATION METHODS FOR ROAD ROUGHNESS MEASUREMENTS

M. Sayers
T.D. Gillespie
C. Queiroz

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The International Road Roughness Experiment (IRRE) reported here was sponsored by a number of institutions: the Brazilian Transportation Planning Company (GEIPOT), the World Bank (IBRD), the Brazilian Road Research Institute (IPR/DNER), the French Bridge and Pavement Laboratory (LCPC), the British Transport and Road Research Laboratory (TRRL), and the Belgian Road Research Center (CRR). The Australian Road Research Board (ARRB) and the Federal University of Rio de Janeiro (COPPE/UFRJ) provided roughness measuring equipment. The University of Michigan Transportation Research Institute (UMTRI) provided personnel and computer support through contract with the World Bank.

Many individuals contributed towards the completion of the IRRE and the subsequent analyses reported here, and it would be impossible to mention here all of their names. However, the participation of the following people was invaluable for the success of this work: S. W. Abaynayaka, H. Hide, and G. Morosiuk formed the research team from TRRL; M. Boulet, A. Viano, and F. Marc formed the research team from LCPC; M. I. Izabel (GEIPOT) supervised the subjective rating study and aided in the data entry; I. L. Martins (GEIPOT), Z. M. S. Mello (IPR/DNER), and H. Orellana (GEIPOT) aided in the data entry and analysis; L. G. Campos (GEIPOT) was responsible for selection of test sites and, together with O. Viegas (IPR/DNER), provided day-to-day supervision and control of the IRRE; M. Paiva (GEIPOT) repaired and calibrated the GMR Profilometer, and worked together with S. H. Buller (GEIPOT) to provide technical support during the IRRE.

Aid in the planning of the IRRE was provided by an expert working group that included W. R. Hudson, R. Haas, V. Anderson, R. S. Millard, and W. Phang. Help was also provided by A. Visser and W. Paterson.

CHAPTER 1

INTRODUCTION

Background

The "roughness" of a road, defined in this report as "the variation in surface elevation that induces vibrations in traversing vehicles," has long been recognized as an important measure of road performance. By causing vehicle vibrations, roughness has a direct influence on ride comfort, safety, and vehicle wear [1, 2, 3, 4]. In turn, the dynamic wheel loads produced are implicated as causative factors in roadway deterioration [5].

As a consequence, the characterization and measurement of road roughness is a major concern of highway engineering worldwide. As the highway networks in developed countries near completion, the maintenance of acceptable quality at minimum cost gains priority. In sophisticated management systems, roughness measurements are an important factor in making decisions toward spending limited budgets for maintenance and improvements. In developed countries, ride comfort has been emphasized because it is the manifestation of roughness most evident to the public.

In less developed countries, the same concerns face administrators from the very beginning; constrained by limited resources, they must choose between quantity and quality in the development of public road systems. Optimizing road transport efficiency involves trade-offs between the high initial costs of smooth roads and subsequent high maintenance and user operating costs of poor roads. Hence, studies of the road-user cost relationship to roughness are underway in India [6], Brazil [7, 8], Kenya [2], and other locations. User costs are generally quantified in terms of fuel, oil, tires, maintenance parts, maintenance labor, and vehicle depreciation. Other costs (often excluded from these analyses) are less direct but are also a consequence of roughness, such as transport speed limitations, accidents, and cargo damage.

A persistent problem in these studies is characterizing the roughness of a road in a universal, consistent, and relevant manner. The popular methods now in use are based on either profile measurement or measurement of vehicle response to roughness.

When profile is measured, the continuous representation of the road can be inspected to identify local defects, or processed to yield roughness numerics adapted to specific applications. Direct comparison of profiles obtained by different methods is not always possible, since profiles measured with high-speed dynamic profilometers generally do not include the underlying slope of the road, nor variations that occur over very long wavelengths. On the other hand, static measurements obtained with manual methods such as rod and level do include the long wavelengths, but are not practical for covering long distances, due to the required effort.

The second type of measurement is obtained using a vehicle instrumented to produce a numeric proportional to the vehicle response to road roughness, when the road is traversed at a constant speed. These systems have acquired the name response-type road roughness measuring systems (RTRRMSs), and have been developed from a practical approach to the problem, often without a thorough technical understanding of exactly how the measures relate either to road profile geometry or vehicle response. As a result, the relationship between different RTRRMS measurements is sometimes uncertain, as is also the relevancy to ride comfort or road-user costs. Nonetheless, most of the currently popular RTRRMS instrumentation systems share a commonality in configuration and operation, and are in such widespread use that drastic changes in measurement methodology are not imminent.

Early high-speed profilometers were costly, complex, difficult to maintain, and required knowledgeable users to operate them and make good use of the measurements, which is part of the reason that the more simple RTRRMSs have been so popular. More recent profilometers are less complicated, less expensive, and can be used over a wider range of conditions. The natural trend appears to be toward profilometers in the coming years, as their cost and operational efficiency approaches that of RTRRMSs. Already they have advantages in terms of improved accuracy and relatively simple calibration procedures, compared to RTRRMSs. But for the present time, RTRRMS use can be expected to continue, and even grow (as more agencies begin monitoring roughness for the first time), since they are presently more accessible and there is general agreement worldwide that RTRRMSs provide useful and meaningful data.

The users of RTRRMSs recognize that the roughness numeric obtained from one of these systems is the result of many factors, two of which are road roughness and test speed. Other factors, that affect the responsiveness of the vehicle to road excitation at its travelling speed, can be difficult to control. While great effort is spent limiting the variability of these other factors, there is growing recognition that some variation will still persist between RTRRMSs, and that even the most carefully maintained systems should be independently calibrated occasionally. Recent research on the variability of RTRRMSs, funded by the National Cooperative Highway Research Program (NCHRP) has indicated that the only calibration approach that will be valid for any roughness level or surface type is a "calibration by correlation" [9]. The calibration is performed by running the RTRRMS over a number of "control" road sections that have known values of "true" roughness, obtained through concurrent measurement by a reference method. The measures obtained from the RTRRMS, together with the reference roughness numerics, are used to determine a regression equation that is used to convert future RTRRMS measures to estimates of what the reference measure would have been. These estimates are the "calibrated" roughness measures.

The key to this approach is the ability to assign reference roughness levels to the control sections. This requires the ability to accurately transduce the longitudinal profiles of the control sections in the wheeltracks traversed by the RTRRMS. It also requires a method for distilling the information in a profile to a single roughness measure for the correlation.

Although RTRRMS use is popular, there has been no consensus as to how a RTRRMS should be operated, nor agreement as to what reference measure should be used in its calibration by correlation. In response to this need, the World Bank proposed that roughness measurement devices representative of those in use be assembled at a common site for an International Road Roughness Experiment (IRRE) to determine correlations among the instruments and encourage the development and adaptation of an International Roughness Index (IRI) to facilitate the exchange of roughness-related information.

The IRRE was held in Brasilia, Brazil, during May and June of 1982.

Research teams participated from the Brazilian Transportation Planning Company (GEIPOT), the Brazilian Road Research Institute (IPR/DNER), the British Transport and Road Research Laboratory (TRRL), the French Bridge and Pavement Laboratory (LCPC), and the University of Michigan Transportation Research Institute (UMTRI--formerly the Highway Safety Research Institute, HSRI). In addition, the Belgian Road Research Center (CRR) participated in the analyses of the data after the experiment.

The IRRE included the participation of a variety of equipment: seven RTRRMSs (four types), two high-speed dynamic profilometers (only the data from one were processed, however), and two methods for statically measuring profile. Four road surface types were included: asphaltic concrete, surface treatment, gravel, and earth. At the finish of the experiment, all of the sections were evaluated by a panel of raters.

Objectives

Main Objective: Define an International Roughness Index (IRI). The meaningful exchange of road roughness data and findings related to road roughness is presently difficult, and can usually be accomplished only with the use of regression equations that are valid only under limited conditions. By selecting a single standard roughness measurement, information can be compared directly. In order for the IRI to be practical, it must be:

- Stable with time
- Transportable (it can be measured with equipment available in most countries, including developing countries with less technical support)
- Valid (demonstrated to work with various types of equipment from all over the world, on all types of road surfaces without bias)
- Relevant (indicative of road condition as it affects user cost, ride quality, and safety)

Although not strictly necessary, it is preferable that the IRI be:

- Simple and convenient

- Well known (i.e., already in use by some agencies.)

In order to qualify for these criteria, the IRI will be compatible to some extent with RTRRMSs (to be relevant to vehicular response), and must be defined by profile geometry (to be stable with time). In order to define such an IRI, a number of more immediate sub-objectives first had to be met:

Sub-Objective #1: Establish the correlation between different RTRRMSs. Different RTRRMS measures can be made somewhat "equivalent" through calibration, so that measures made from one system can be approximately reproduced with another. The IRRE was designed to help determine the degree of reproducibility that is possible, and the ranges of roughness, surface type, and operating speeds over which that reproducibility can be obtained.

Sub-Objective #2: Establish measurement requirements for profile-based roughness measures. One of the problems in transferring methods worldwide is that certain equipment may be feasible in one country but not another, for technical, political, or economic reasons. For example, the rod and level survey method is a labor-intensive method that is well suited to countries with low labor costs, whereas certain profilometers designed for use in more developed countries may require technical support that is not available in less developed countries. In the past, specific analysis methods have been associated with particular profile measurement methods, and some of the analysis methods depend, in part, on the specifics of the measurement method. The various measures of profile obtained in the IRRE can be processed identically and the results compared to determine whether certain profile analyses are compatible with different profilometric methods.

Sub-Objective #3: Establish correlations between profile-based numerics and RTRRMS numerics. Although there is a general agreement among users of RTRRMSs that the RTRRMS must be calibrated by correlation against a reference, a number of potential references have been proposed. The accuracy of the calibrated RTRRMS measure is limited by the degree of correlation between the RTRRMS and the reference; hence, the conditions for obtaining the best correlations must be investigated in order to specify an appropriate reference numeric **and** the appropriate operation of the RTRRMS to best match that reference.

Sub-Objective #4: Perform and document auxiliary analyses of the profile data. A wealth of profile information was obtained in the IRRE which can be processed to yield many detailed descriptions of the road that are not necessarily compatible with the simple numerics that can be obtained with RTRRMSs. These include waveband analyses used in Europe, Power Spectral Density (PSD) functions, and plots of profiles to show heterogeneities. These analyses are essential to understand some of the relationships observed between RTRRMS numerics, and the results are also a valuable resource for linking summary numerics obtained in the IRRE to potential future applications.

Report Organization

This report documents the experiment, the data obtained, and a number of analyses applied to that data. The findings are then applied to recommend an IRI. Many of the descriptions are technical and detailed, and most of the data, needed for verification and further analyses, will not be of interest to the average reader. Therefore, this main report is limited to an overview of the IRRE (chapter 2), an overview of the analyses and relevant findings (Chapter 3), and the rationale for selecting the IRI and a description of the IRI (Chapter 4). (Chapter 5 contains a summary and concluding remarks, while references are included in Chapter 6.) The bulk of the technical information is sorted and presented in the attached Appendices A - J.

CHAPTER 2

EXPERIMENT

This chapter describes the physical aspects of the International Road Roughness Experiment (IRRE). It summarizes the methods used to aquire roughness data, the ranges of road and operating conditions covered in the IRRE, and the testing procedure.

Participants

The experiment included the participation of eleven pieces of equipment, which are separated into three categories in this report: response-type road roughness measurment systems (RTRRMSs), static profile measurement, and dynamic profile measurement (profilometers). Appendix A provides a technical discussion for each piece of equipment and offers much greater detail than the following overview.

RTRRMSs. All of the RTRRMSs that participated in the IRRE consist of a vehicle equipped with special instrumentation. Although different designs are employed, all of the instruments are theoretically measuring the same type of vehicle response: an accumulation of the relative movement of the suspension between axle and body. The measurements obtained with these instruments are in the form of discrete counts, where one count corresponds to a certain amount of cummulative deflection of the vehicle suspension. When the host vehicle is a passenger car, the instrument is mounted on the body, directly above the center of the rear axle. Alternatively, some are mounted on the frame of a single-wheeled trailer to one side of the wheel, directly above the axle. Four types of RTRRMSs (seven total) participated in the IRRE:

1. **Opala-Maysmeter Systems.** Three RTRRMSs were provided and operated by the Brazilian Transportation and Planning Company (GEIPOT). These consisted of Chevrolet Opala passenger cars equipped with Maysmeters, manufactured by the Rainhart Co. of Austin, Texas [13] as modified by the researchers of the

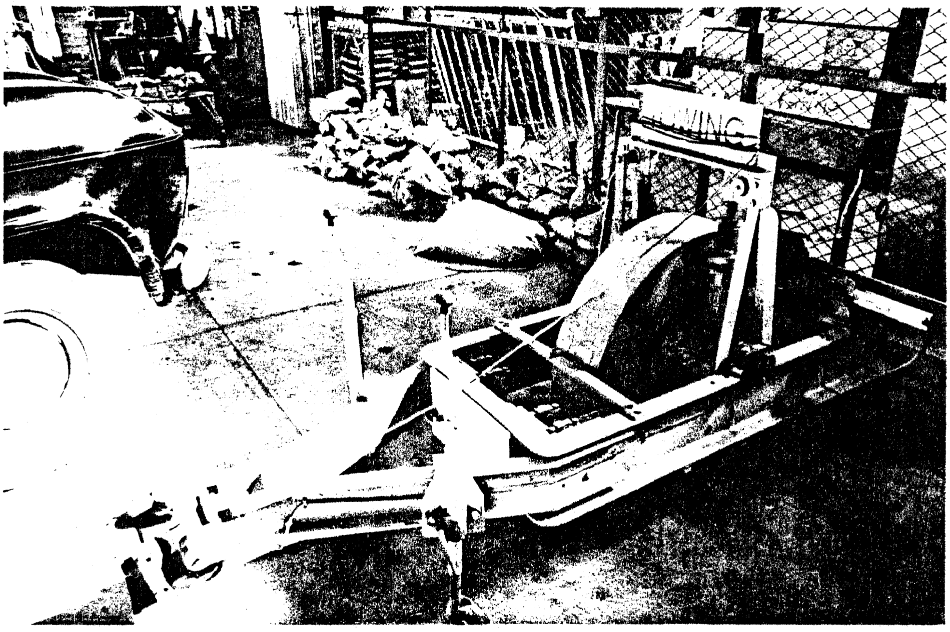
international project, "Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization" (ICR). The modifications were made to eliminate the strip-chart recorder normally used to read roughness measurements, replacing it with an electronic counter with a digital display [4]. The modified meters produce a display for every 80 meters of road travel, which is shown until the next 80 m is reached. The meter can also be adjusted to display every 320 m.

2. **A Caravan station wagon with two roadmeters.** A Bump Integrator (BI) unit, produced and operated by the British Transport and Road Research Laboratory (TRRL) [9], and a NAASRA Roughness Meter, provided by the Australian Road Research Board (ARRB) [14], were both installed in a single Chevrolet Caravan. The Caravan is made in Brazil and comes from the same automotive family as the Opala used for the Maysmeter systems. Both meters were installed and operated by the TRRL team, and all measures made with the NAASRA and BI units were made simultaneously.

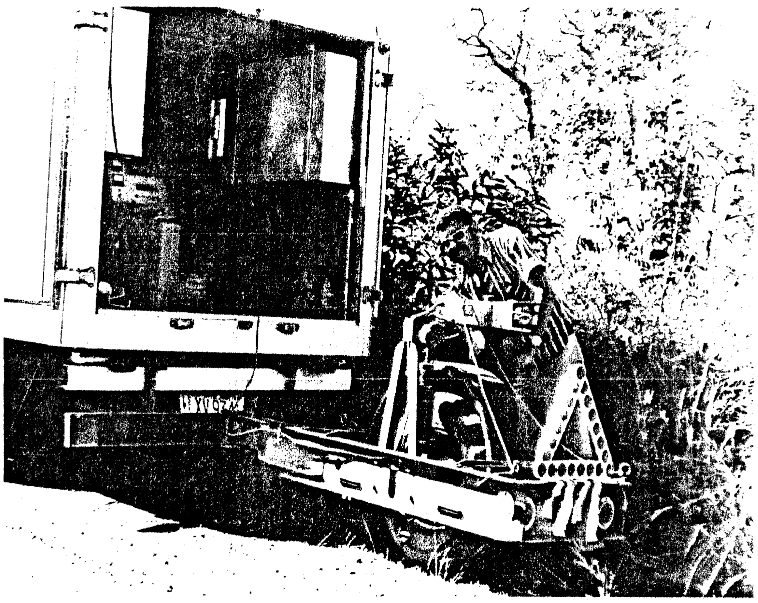
3. **Bump Integrator Trailer.** The BI Trailer, produced and operated by TRRL, is a single-wheeled trailer equipped with a BI unit (see Figure 1a) [9]. It is based on the old BPR Roughometer design [15], but has undergone a great deal of development by TRRL to achieve better standardization and more ruggedness.

4. **Soiltest BPR Roughometer.** A Road Roughness Indicator, made by Soiltest, Inc. of Evanston, Illinois [16] is owned by the Federal University of Rio de Janeiro (COPPE/UFRJ) and was operated by personnel from the Brazilian Road Research Institute (IPR/DNER). The trailer is built to the specifications of the BPR Roughometer (see Figure 1.b) [15].

Normal measurement speed for the two trailers is 32 km/h (20 mph). A standard speed does not exist for car-based systems, although 80 km/h (50 mph) is the speed often recommended and used. Standard speeds in the vehicle operating cost part of the ICR project were 80 (96% of the paved roads), 50 (94% of the unpaved roads), and 20 km/h [4, 36]. Standard test speeds for the



a. Bump Integrator Trailer



b. BPR Roughometer made by Soiltest, Inc.

Figure 1. Two RTRRMSs based on the BPR Roughometer design.

NAASRA Meter as used in Australia with a different vehicle are 50 and 80 km/h.

Static Profile Measurement. Two methods were used to obtain the elevations of the longitudinal profile of each wheel track over a test section. Each method uses a fixed horizontal reference as a datum line. Measures are then made of the distance between this datum and the ground at specific locations that are at fixed intervals.

One method is the traditional rod and level survey, shown in Figure 2. A surveyor's level provides the datum, while datum-to-ground measures are made with a marked rod. The level has a range of about 100 m. When it is moved to a new location (station), the change in elevation is established so that measures made from different stations are equivalent. Using a measurement interval of 500 mm, a trained crew of three can survey both wheel tracks of two 320 m test sections in an eight-hour working day (about 2500 elevation points for three man-days).

The second method used in the experiment is based on an experimental instrument that was in development by TRRL, the "TRRL Beam," shown in Figure 3. The horizontal datum is provided by an aluminum beam nominally three meters in length. The ground-to-datum measures are made with an instrumented assembly that contacts to ground through a small pneumatic tire and can slide along the beam on precision rollers. To operate the device, the Beam is levelled by an adjustment at one end, and the sliding assembly is moved from one end of the beam to the other. The moving assembly contains a microcomputer that digitizes the measures at pre-set intervals of 100 mm and prints them on paper tape. A trained crew of two or more can survey two wheel tracks of a 320 m test section in one day (about 6400 elevation points for two man-days).

Dynamic Profile Measurement (Profilometers). The two vehicle-based profilometer systems that participated are each designed to measure longitudinal profile over a selected wave number range (wave number = 1/wavelength). In both cases, an inertial datum is used that is not fixed, but is dynamic, providing a reference valid only for frequencies above a certain limit.

Figure 2. Measurement of longitudinal profile by the rod and level method.

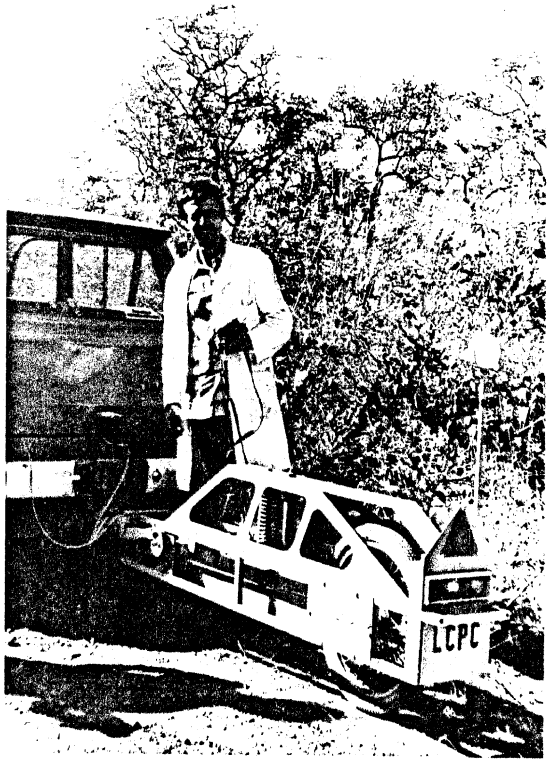
Figure 3. Measurement of longitudinal profile with the TRRL Beam.

The first type of profilometer, made by the French Bridge and Pavement Laboratory (LCPC), is called the Longitudinal Profile Analyzer (APL) Trailer and shown in Figure 4. This instrument has a design that isolates its response solely to profile inputs. Movements of the towing vehicle, applied at the towing hitch-point, do not elicit any measurement. The datum consists of a horizontal pendulum that has an inertial mass, a spring, and a magnetic damper. The response of the pendulum is designed to provide a correct datum for frequencies above 0.5 Hz. The trailer wheel also acts as a follower wheel, and has a response that allows measurement with fidelity for frequencies up to 20 Hz [18, 39]. The waveband (range of wavenumbers, wavenumber = 1/wavelength) measured by the APL Trailer is determined by its measurement speed, as its true response is always over the frequency range of 0.5 - 20 Hz.

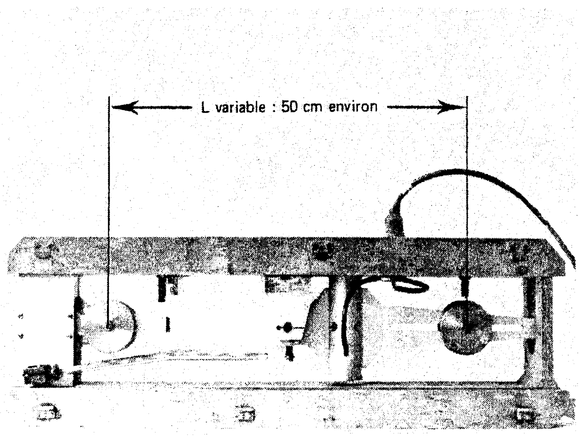
The APL Trailer is nearly always used by LCPC in conjunction with one of two standard analyses, called the APL 25 analysis and the APL 72 analysis [10, 18, 39]. These analyses require that the trailer be towed at specific speeds (21.6 km/h for the APL 25 and 72 km/h for the APL 72), and that the test sections be of certain length (integer multiples of 25 m for the APL 25, and multiples of 200 m for the APL 72). In Belgium, APL signals are analyzed to yield a type of numeric called coefficient of evenness (CP), based on a moving average, and computed for sections of 100 m [40]. All of these analyses are described in more detail in Appendix G.

A second dynamic profilometer also participated in the experiment, but the results have not been analysed. This was a General Motors Research (GMR) type of Profilometer (also called a Surface Dynamics Profilometer), manufactured by K. J. Law, Inc. of Farmington, Michigan. The GMR-type Profilometer uses an accelerometer to provide the reference datum, while the datum-to-ground measure is made by a follower wheel instrumented with a potentiometer [17].

This particular GMR-type Profilometer was used in the early portion of the ICR project [4, 5], but had not been in use for several years before the IRRE and as a result, considerable effort was spent preparing it for the IRRE. Due to an almost endless series of problems--mostly related to the vehicle portion of the profilometer--it was able to obtain data on little more than



a. APL Trailer



b. Inertial reference of the APL Trailer.

Figure 4. The APL Profilometer.

half of the sections. Due to a number of factors discovered by the Brazilian engineers in preparaton for the IRRE, use of the on-board data analysis equipment was not valid for the conditions covered in the IRRE. It was also found that the measures made during the ICR project were not valid profile-based numerics (see Appendix E). To avoid repeating past mistakes, processing of the data had to be done afterwards in the same manner as used for the APL system, even though this approach required much more time and a certain amount of software development. As other sources of profile data became avalable from the TRRL Beam and the APL Trailer, the importance of the measures from this profilometer assumed less importance, and the signal processing was never completed.

Subjective Rating Study

After the completion of the experiment (for the RTRRMSs), all test sections were evaluated by a panel rating process, documented in Appendix D. In this study, a panel of 18 persons was driven over the sections and asked to provide a rating ranging from 0 to 5. All panel members were driven in Chevrolet Opalas at 80 km/h over the paved sections, and 50 km/h over the unpaved sections.

Design of Experiment

Forty-nine (49) test sites were selected in the area around Brasilia. Thirteen of these were asphaltic concrete sections; twelve were sections with surface treatment; twelve were gravel roads; and the remaining twelve were earth roads. All of the candidate sections had been rated with an Opala-Maysmeter RTRRMS, to ensure that the selected sections demonstrated a uniformly spread range of roughness. Generally, six levels of roughness were sought for each surface type, with two sections having each level of roughness as measured by the RTRRMS. Most sections were fairly homogeneous over their lengths, and all were on tangent roads.

Each section was 320 meters long. This length was selected based on the following considerations:

1) RTRRMSs are limited in precision, resulting in random error if the sections are too short. Standard test lengths in use throughout the world range from 0.16 km to over 3 km. A length of one mile (1.6 km) is common in the United States.

2) The Maysmeters used in Brazil can only be used on sections with lengths that are integer multiples of 80 m.

3) The process of measuring profile by the rod and level method is slow and tedious. Given the number of sections, the available time, and the available manpower for the survey crews, sections much longer than 320 m were not possible if all wheeltrack profiles were to be measured.

4) Some of the necessary combinations of roughness, surface type, homogeneity, geometry, traffic density, and geographic location were difficult to find. The difficulty was increased with test length.

5) All sections had to have the same length for equal significance in the planned analyses.

The major disadvantage of the 320 m test length was its incompatibility with the APL 72 requirement of a multiple of 200 m length. This incompatibility was not known by the Brazilian team at the time of site selection, and could not be corrected for the equipment. For the normal APL 72 measurements used by LCPC, the values of Index (I), energy (W), and equivalent displacement (Y) were calculated for a 200 m length completely contained within the 320 m test site. The APL 72 measurements routinely used by CRR were obtained as the average of three 100 m subsections contained within the site. For the APL 25 measurements, the average value of the 12 or 13 individual CAPL 25 coefficients (each measured over 25 m) was reported.

Measurements were made with the RTRRMSs at four speeds when possible: 20, 32, 50, and 80 km/h. The 32 km/h speed is standard for the BPR Roughometer and the Bump Integrator from TRRL. The 80 km/h speed (50 mph) is the most common measurement speed for RTRRMSs on highways and is recommended by several roadmeter manufacturers. The other speeds of 20 and 50 were used as standard speeds in the ICR project. The APL trailer was operated at its standard speeds of 21.6 and 72 km/h.

The roughness went to sufficiently high levels that high speed measurements were not expected to be within the allowable range for any of the equipment on the roughest unpaved sections. The operators of the instruments were given the option of declining to make any measurements that they felt would either be invalid or damaging to the equipment.

Several measurements were made with the RTRRMSs to demonstrate repeatability and allow averaging to reduce some of the random error that occurs with RTRRMS measurement over short lengths. The RTRRMSs that were based on passenger cars made five measurements at each speed when possible, while the trailer-based systems made three runs in each wheel track (six per site).

Because the tests conducted at different speeds all covered a standard distance, longer times were needed to cover the 320 m distance at the lower speeds. Therefore, some random effects related to time (rather than distance) were subjected to greater averaging at the lower speeds. An experimental design in which both speed and site length were varied would have required a great deal more time and effort to conduct, and was not possible.

The sequence of tests was scheduled with several goals in mind. From a statistical point of view, it is helpful to randomize the sequence of each variable (roughness, surface type, speed, instrument). On the other hand, any measurements that risk damage to the instruments should be scheduled last when all of the low-risk measurements have been completed. Transit time to and from the sections is minimized by scheduling all measures in one day for sections that are near each other.

The actual testing sequence used was a compromise of the above considerations. All of the paved sections were tested before the unpaved sections, in an order dictated according to geographical convenience. The paved sections were not measured in any particular order in terms of their roughness. The smooth and moderate unpaved sections were measured according to geographical convenience, while the very roughest were measured last. Because of the logistics involved when a number of RTRRMSs are making measures on the same section, all repeats were made at one test speed before continuing to the next speed. The sequence of test speeds was randomized for each section when possible. However, some of the test sites were adjacent sections of road which were both tested in one pass of the RTRRMS; the same speed sequence was necessarily used for these tests.

Testing Procedure

The experiment took place over a period of one month, beginning on May 24 and ending on June 18, 1982. All of the vehicles underwent a speed calibration on the first day, based on a precision transducer on the APL Trailer, which was in turn checked by stopwatch. During the following month, about 1 - 1/2 weeks were unscheduled, allowing make-up runs for the equipment that had experienced problems. The research teams from GEIPOT, TRRL, and LCPC operated their equipmment, while the vehicles were driven by employees of GEIPOT.

The tests were performed in caravan fashion, with all of the measures being made by the RTRRMSs at one speed before beginning the next speed. The testing was supervised by two test site controllers, who kept track of the progress of each system. Ocassional spot checks were made of the test speed with stopwatches, to confirm that the test speeds were being maintained by the drivers. The APL Trailer, which operated at different speeds, did not follow the caravan, but made its measurements as needed on the same sites as the others.

The test sites were all located within a 50 km radius of the garage at GEIPOT used for storage and repair of equipment. The drive from the garage to the test sites served as a warm-up, to allow the shock absorber and tire temperatures to stabilize. The test sites on unpaved roads were located such that the last 10 minutes of driving to the sites was over unpaved roads; therefore, the RTRRMSs were never operated "cold" on any surface type. An exception to this was the Soiltest BPR Roughometer, which was towed only on the actual test sites, to minimize the damage to that system that seemed to occur on a daily basis.

The static measures of profile were much slower than those of the RTRRMSs, and were made on different days. Measurements with the rod and level were made on all of the paved sections before the experiment, and repeated for many of the sections during the experiment. When testing preceeded to the unpaved sections, the rod and level measures were made immediately (two days or less) before the RTRRMS tests.

The TRRL Beam did not arrive until the end of the experiment. Measures made with the Beam were made after the RTRRMS testing on sites selected by the TRRL team to cover the full range of surface types and roughness conditions. Ten sites were completely profiled by the Beam. An additional eight wheel tracks were profiled on sections that displayed nearly identical roughness levels on the right and left wheel tracks (as measured by the BI Trailer). Repeat runs with the BI Trailer on the sections that were profiled were used to confirm that the roads had not changed between the RTRRMS measures and the beam measures. (The IRRE took place during the dry season, and as usual, there was no rain during the months of June, July, and August. The unpaved roads used for test sites normally saw little traffic. Marks were made to define the test wheel tracks with paint on the paved roads, lime on the earth roads, and with colored ribbon nailed to the surface of the gravel roads. Even at the end of July, the markers were still intact.)

CHAPTER 3

ANALYSIS AND FINDINGS

Overview

The data obtained from the IRRE are possibly the most comprehensive ever obtained in the field of road roughness measurement. Each RTRRMS produced five or six repeat roughness measurements for each of the 49 test sections for each of the three or four measurement speeds. Every wheeltrack profile was measured by the rod and level survey method at least once, and typically twice for the paved roads, yielding 1282 elevation measurements for every one of the 140 profiles (70 two-track sites) obtained. LCPC provided profiles as measured with the APL trailer in the APL 25 configuration for 97 of the 98 wheeltracks (1281 numbers per wheeltrack) and 73 profiles obtained in the APL 72 configuration (6401 numbers per wheeltrack). The experimental Beam from TRRL was used on 28 wheeltracks, providing 3201 measures for each. In addition, all 49 sections were rated subjectively by 18 panel members.

A number of computer systems were employed in parallel to prepare the data for analysis during and immediately after the IRRE. The rod and level survey measures were copied by typists into the IBM 370 computer system at GEIPOT. The RTRRMS data, the subjective ratings, and the elevation readings from the TRRL Beam were all typed into an Apple II+ microcomputer, using special entry and checking programs written specifically for the project. The analog signals produced by the APL 72 system were digitized for plotting with a system based on a European ITT microcomputer, compatible with the Apple II+. Programs were prepared to store the APL data on the floppy diskettes used by the Apple. APL 25 profiles were digitized during measurement and stored on cassettes, and later played back into the LCPC microcomputer for copying onto Apple diskettes.

In the months immediately following the IRRE, most of the analyses described in this report were performed in Brazil. The APL numerics routinely used by LCPC were computed by the LCPC team during the IRRE and distributed to the participants then, along with samples of profile and roughness heterogeneities (as described in Appendix G). The RTRRMS measures were entered, checked, and rescaled to the same units of average rectified slope (ARS): m/km (scaling conversions are reported in Appendix A). The profiles were all processed on the GEIPOT IBM computer and two Apple computers to obtain the quarter-car and QI numerics (described in Appendices E and F). A number of fundamental correlation analyses were performed using the Apples, and presented in a preliminary version of this report dated December 1982 that was distributed to the participants.

Following this activity, analyses were performed by TRRL in Great Britain (Appendix H), by LCPC in France, and by CRR in Belgium. (Results from the LCPC and CRR analyses are reported in Appendices E, G, and J.) A meeting of the IRRE participants was held in Washington D.C. in July 1983, in which the findings to-date were presented and discussed, with the goal of obtaining a consensus towards defining an International Roughness Index (IRI). A number of issues were resolved, but several areas emerged where further analysis was needed, and therefore, selected analyses were performed at UMTRI to help fill in the gaps.

The analyses are covered in detail in Appendices C - J, and are therefore merely summarized in this chapter, so that the findings can be more clearly presented. The remainder of this chapter begins with the findings about the profile measurement methods and the wavenumber (spectral) contents of the roads, since these findings help to explain some of the other results. The chapter then proceeds by summarizing the profile analyses that were used in the IRRE, and the measurement requirements needed for those analyses. The agreement that is possible between RTRRMS measures is then shown, in order to place in perspective the correlations between RTRRMS measures and the profile-based numerics that follow. Finally, the subjective ratings are compared to the objective roughness measures to indicate which measures are more related to the public judgment of road roughness.

Spectral Analyses of the Road Profiles

Nearly all of the correlations and comparisons of roughness numerics that follow are influenced, in part, by the spectral content of the road profiles.

Therefore, the power spectral density (PSD) function of every profile obtained in the IRRE was computed, and most are presented in Appendix I.

The PSD functions obtained by the different profile measurement methods show that the rod and level, the TRRL Beam, the APL 25 system, and the APL 72 system are all valid methods for obtaining profile over their design wavebands. More specifically,

- The TRRL Beam measurements had the highest quality. They were performed statically and thus were known to 1) apply to the precise wheeltrack position marked on the road and 2) include the longest wavelengths and the mean slope of the wheeltrack. The 100 mm sample interval provided the widest waveband of any of the measurements.

- The rod and level measurements were equivalent to those of the Beam, but did not include the shortest wavelengths because a larger sample interval of 500 mm was used. Due to that sample interval (which was the smallest that could be used to include all 98 wheeltracks, given time and manpower constraints), the profile measures were not valid for all of the analyses considered.

- The APL Trailer bandwidth, measured in the laboratory to cover 0.5 - 20 Hz, was confirmed by the PSD functions. PSD functions from the APL 72 system matched the static measures for wavenumbers (wavenumber = 1/wavelength) between 0.025 and 1.0 cycle/m (wavelengths of 1 - 40 m), and PSD functions from the APL 25 matched the static measures over the wavenumber range: 0.08 - 1 cycle/m. (The sample interval for the APL 25 limited the upper wavenumber response, rather than the trailer dynamics.) While the agreement appears excellent for some of the wheeltracks, in other cases the APL PSDs differ from the statically measured ones, reflecting the additional testing variables (starting position and lateral wheeltrack location) introduced when profiles are measured at high speed.

The PSD functions alone (shown in Appendix I) are not adequate to determine the accuracy of each profilometric method (a more extensive PSD analysis would have been required). The only truly valid comparison of profile measurement methods for a particular analysis application is made by applying that analysis to the different profiles, and determining whether the differences in the resulting numerics are acceptable. These comparisons are made later for a number of profile-based summary numerics.

In addition to comparing the profile measurement methods, the PSD functions in Appendix I very clearly show the differences in the four surface types included in the IRRE. Figure 5 presents normalized aggregate PSD functions obtained by graphically overlaying the PSD functions corresponding to each surface type. The PSD amplitudes were all normalized by one of the roughness statistics, so that the plots show the relative distribution of the roughness over wavenumber when the amplitude scale factor is removed. Figure 5 shows that the different surface types have characteristically different "signatures," reflecting their distributions of roughness over wavenumber, and that:

- The asphaltic concrete (CA) sites have proportionately the least roughness at high wavenumbers.

- The surface treatment (TS) and gravel (GR) sites show a minimum at wavenumbers near 0.1 (10 m wavelengths), with more roughness at lower wavenumbers and also at higher wavenumbers.

- The earth sites generally show the highest concentration at high wavenumbers.

- Several of the sites show strong periodicities. When "outliers" occur in correlation plots ("outliers" are data points that do not fall within the scatter range exhibited by the rest of the data), the site often has a periodicity that causes one measuring system (or analysis method) to "tune in" and respond highly, while other systems are less responsive. Several of the surface treatment sites had a periodic variation occurring every 2.0 m (wavenumber = 0.5), as shown in Figure 5b.

These "signatures" are also evident from the waveband analyses used in

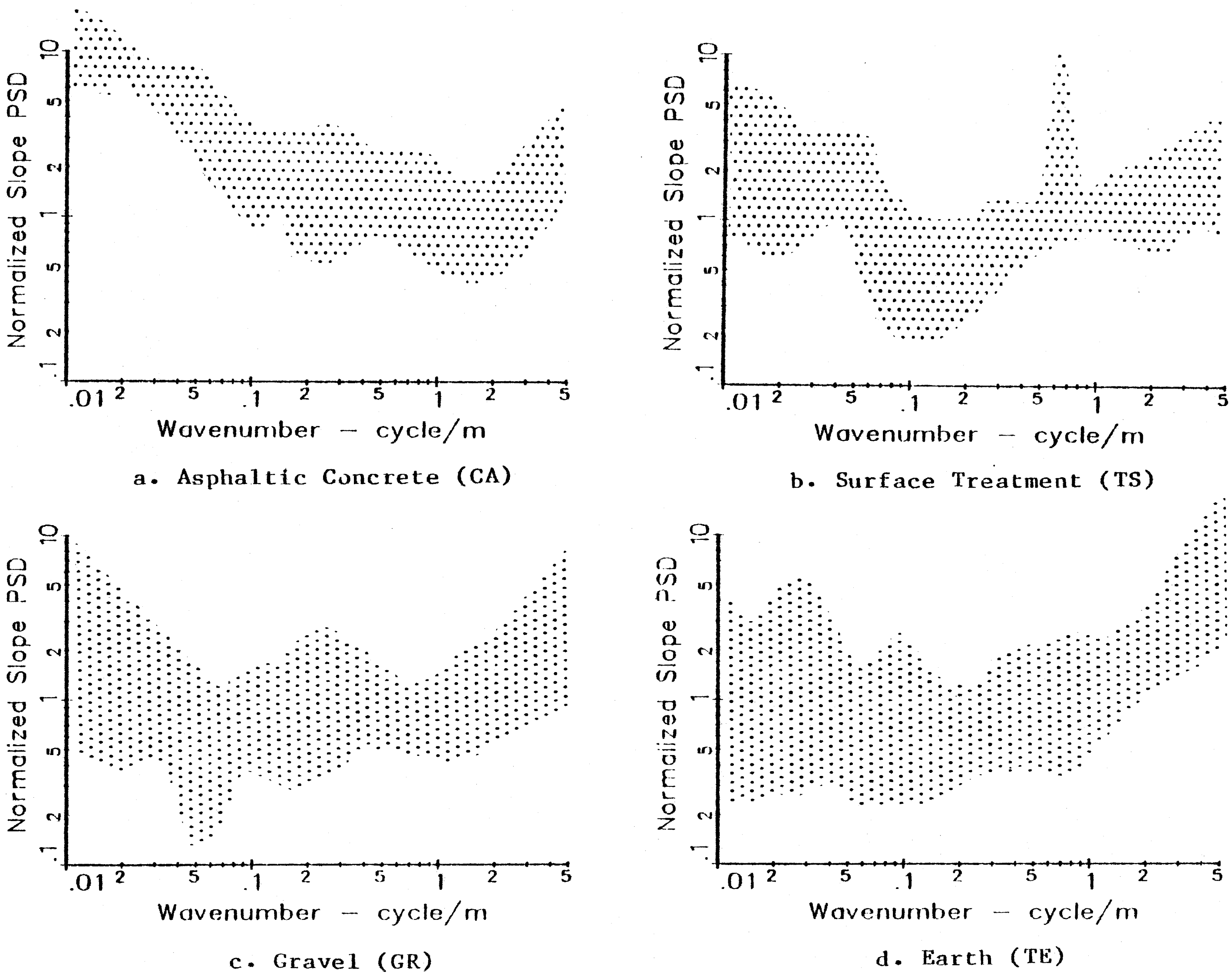


Figure 5. Aggregate PSD "signatures" for four surface types.

Europe by LCPC and CRR. (Appendix G.)

Computation of Profile-Based Numerics

The measured profiles were processed to obtain eight types of simple summary statistics.

1. **Reference Quarter-Car Simulation (RQCS).** The concept of using a reference RTRRMS has shortcomings when applied to a mechanical vehicle-based system that can be overcome by defining the reference as a mathematical description of such a system. The mathematical description (model) is used to process direct profile measurements to obtain the summary ARS-type of roughness numeric. The mathematical model needs to be standardized by a choice of parameter values that describe the simulated vehicle, namely: sprung mass, unsprung mass, suspension spring rate, tire spring rate, and suspension linear damping rate. The model also includes a baselength parameter for a moving average, corresponding to the finite contact area between a pneumatic tire and the road. When the model is used with a single wheeltrack (one wheel), it has been called a quarter-car. The model parameter values used in this project were selected in earlier work for maximum agreement with RTRRMSs that have stiff shock absorbers, because the use of stiff shock absorbers reduces many of the sensitivities of RTRRMSs to factors other than roughness and test speed [9]. To distinguish the QCS implied by this set of parameter values, it is called the reference QCS (RQCS).

The measured profile is used as an input to the RQCS, and the simulated motions of the suspension are accumulated mathematically, simulating an ideal roadmeter. The roughness numeric thus obtained with the RQCS is called reference average rectified slope (RARS), and can be reported with the same units of ARS used for a RTRRMS (m/km, mm/km, in/mile).

Since the RARS numeric varies with simulation speed, the simulation speed is usually noted as a subscript: e.g., $RARS_{50}$ means the simulation speed was 50 km/h.

The RQCS can be implemented any number of ways. Regardless of the method, four variables that describe the simulated vehicle must be computed. For analog profile measurements, an electronic analog of the mechanical model has been used in the past [7, 9, 22, 24]. (Different parameter values were used.) For digital measures, several methods have also been used. One of these is called the state transition method and has the form:

$$
\begin{aligned}
Z_1 &= S_{11}\,Z_1' + S_{12}\,Z_2' + S_{12}\,Z_3' + S_{14}\,Z_4' + P_1\,Y' \\
Z_2 &= S_{21}\,Z_1' + S_{22}\,Z_2' + S_{23}\,Z_3' + S_{24}\,Z_4' + P_2\,Y' \\
Z_3 &= S_{31}\,Z_1' + S_{32}\,Z_2' + S_{33}\,Z_3' + S_{34}\,Z_4' + P_3\,Y' \\
Z_4 &= S_{41}\,Z_1' + S_{42}\,Z_2' + S_{43}\,Z_3' + S_{44}\,Z_4' + P_4\,Y' \qquad (1)
\end{aligned}
$$

where $Z_1 \ldots Z_4$ are the four vehicle variables (velocities and accelerations of the sprung and unsprung masses) at the present position along the road x, and $Z_1' \ldots Z_4'$ are the values at the previous position: x - dx (where dx is the interval between elevation measures). The coefficients $S_{11} \ldots S_{44}$ and $P_1 \ldots P_4$ are constants that can be obtained from tables corresponding to the proper combination of simulation speed and measurement interval dx. Y', the input, is the average profile slope over a distance of 0.25 m, computed for the interval between x-dx and x.

The RARS numeric has several simple interpretations. It is the average slope of the profile, seen through the RQCS "filter." Hence it is easily visualized as a profile attribute. A perfectly smooth profile (no variation in slope) has an RARS value of zero. Also, the RARS is linearly proportional to the profile geometry, such that the units of RARS are determined by the scaling of the profile elevation. The second interpretation is that of a reference RTRRMS, where the RARS is equivalent to the ARS measure obtained with a mechanical RTRRMS. When the same units are used for RARS and the RTRRMS measure, a practitioner can see whether a RTRRMS is more or less responsive than the reference. (A third interpretation exists when the roughness is expressed as an RARV numeric, in which case the RARV is the average vertical velocity "seen" by a vehicle traversing the road at the simulation speed.)

A more complete description of the RQCS and the RARS numeric is provided in Appendix F.

2. Half-Car Simulation (HCS). A half-car is simulated simply by averaging the left- and right-hand wheeltracks, point by point, before processing with a QCS. The numeric obtained with a HCS is not the same as computing two QCS numerics and averaging the RARS values. This is because some of the variations in the two profiles will cancel when averaged for a HCS, whereas they contribute fully to the QCS numerics. The QCS is a closer simulation of a single-track RTRRMS such as the BPR Roughometer or BI Trailer, while the HCS more closely matches a two-track RTRRMS. For realistic road inputs, the numerics computed using a HCS will always be lower than when computed from two independent QCSs.

3. QI_r. The QI_r numeric was developed by Brazilian researchers during the ICR project as a means for using rod and level profiles to calibrate RTRRMSs [8]. Originally, QI_r was an estimate of a numeric obtained from a particular piece of hardware (that numeric, QI, was an abbreviation of Quarter Car Index). However, the QI_r numeric is independently defined strictly by profile geometry, and has been suggested as a definition of "true roughness" for calibrating RTRRMSs. The QI_r numeric is based on the RMSVA summary statistic. RMSVA is an abbreviation for root-mean-square (RMS) vertical acceleration [25], although the computation procedure that has been used results in a numeric that has no relationship whatsoever with vertical acceleration. Rather, RMSVA is equivalent to the RMS deviation at the midpoint of a rolling straightedge as shown in Appendix E (RMS mid-chord deviation). The equation for the variable VA is:

$$VA(x) = [\ Y(x-b) + Y(x+b) - 2\ Y(x)\ ]\ b^{-2} \qquad (2)$$

where Y(x) is the profile elevation at position x, and b is a baselength parameter. (Physically, the baselength is equivalent to half the chord length of a rolling straightedge.) Since RMSVA varies with b, the baselength should be specified for any RMSVA numerics: e.g., $RMSVA_{1.0}$ indicates a baselength of 1.0 m was used.

To obtain the QI_r numeric, the profile is processed to yield two RMSVA values for baselengths of 1.0 and 2.5 m, which are then combined as:

$$QI_r = -8.54 + 6.17 \, RMSVA_{1.0} + 19.38 \, RMSVA_{2.5} \quad (3)$$

The above equation assumes that elevation is measured in mm and that b is measured in m, resulting in RMSVA numerics with the units: $1/m \times 10^{-3}$.

Although the RMSVA "filters" are linear, when the two RMS values are combined in Eq. 3, the resulting QI_r numeric is not the result of a linear transform. Note that a perfectly smooth profile would have a QI_r rating of -8.54, and that care must be taken to convert the profile to the proper units before applying Eq. 3.

The QI_r numeric has been used in recent years as a RTRRMS calibration reference in Brazil, Bolivia [26], and South Africa [27]. A very similar numeric called MO, that is also a weighted sum of two RMSVA measures, is used as a calibration reference in Texas [28].

Appendix E provides more information about the QI_r numeric, and also the other QI numerics (QI and QI^*).

4. CAPL 25. This numeric is obtained by towing the APL Trailer at 21.6 km/h, and calculating the average absolute value of the signal produced by the trailer. The average is taken over sections of road that are 25 m long; hence the name APL 25 Coefficient (CAPL 25). CAPL 25 can be scaled to any convenient unit of displacement, such as mm. A perfect road has a CAPL 25 value of 0, and the coefficient increases with roughness.

Due to the simple nature of the computation, the CAPL 25 is defined in part by the response properties of the APL Trailer. Given the objectives of this report (which include compatibility with RTRRMSs), efforts were not made to characterize the APL Trailer response sufficiently to compute the CAPL 25 coefficients from other types of profile (APL 72, rod and level), although it is shown in Appendix G that suitable filtering of the APL 72 signal does indeed produce a "simulated" APL 25 signal.

The CAPL 25 numeric was developed to check quality of road layers during construction, and to isolate short sections that might require further work before proceeding with the next phase in the construction [15, 19]. Compared with some of the other roughness numerics, it is not the best calibration standard for RTRRMSs, and RTRRMSs in general cannot be used for the applications for which the APL 25 measure was designed. Examples of the use of the CAPL 25 coefficients are presented in Appendix G, along with a more complete description of the measurement methodology.

5. LCPC APL 72 Waveband Analysis. LCPC has developed this analysis method to summarize the present condition of roads [17, 18, 19]. The method is based on the recording of a road profile at a speed of 72 km/h (20 m/sec). At this speed, the APL Trailer transduces profile wavelengths from 1 - 40 m. The APL signal is played back into three electronic band-pass filters, each of which isolates a specific waveband from the profile. The filtered signals are squared and integrated to obtain mean-square "energy" values (W) calculated over a road length of 200 m. The mean-square values can be used to compute the "equivalent amplitude" (Y) of a sine wave within the waveband, which is reported with units: mm. However, more typically, the "energy" values (W) are used to assign a rating to the road. The rating index (I) goes from 1 (the worst) to 10 (the best), and was designed to cover the range of road quality seen in France. The result is that each 200 m section of road is described by three indices, corresponding to the relative road quality for short, medium, and long wavelengths.

In normal operation, the profiles of the right and left wheeltracks are measured simultaneously with two APL Trailers. During the IRRE, the wheeltracks were analyzed separately and roughness measures were reported for each wheeltrack. The indices (I) obtained in the IRRE on the unpaved roads were mostly 1, indicating that the roughness range covered in the IRRE goes far beyond the range considered typical in France. The (W) and (Y) numerics are more descriptive for the IRRE data, since they can increase with roughness to any level. A perfect road yields (W) and (Y) values of zero (for all three wavebands). The energy (W) numeric is proportional to the square of profile input amplitude, while the equivalent displacement (Y) is linearly proportional.

The response properties of the APL Trailer should play no role in determining the numerics for the three wavebands, because in all three cases, the frequency response of the APL Trailer is broader than that of the filters.

Thus, the same analysis could potentially be applied to signals obtained from other profilometric methods. However, since the filters are electronic, digital equivalents would need to be developed for use with profiles that exist only in numerical form, such as those obtained using rod and level. Since the CP analysis used by the Belgian CRR (described below) is used for the same purpose as the LCPC analyses, but is numerical rather than electronic, the CP numerics were tested for measurement with rod and level.

Further details concerning the APL 72 analysis are presented in Appendix G, along with the (W), (Y), and (I) values obtained for the test sections in the IRRE.

6. **Moving Average and CP.** A moving average analysis of profile has been used by TRRL and CRR [19, 20] to obtain roughness numerics from profile measurements.

The characterization of the measured profile used by CRR is obtained by evaluating the variation of the surface profile relative to a reference line obtained by smoothing the same profile. The process of applying a moving average to the signal acts as a filter, attenuating short wavelengths. For its application, the APL signal is digitized, triggering on a pulse train issued from the measuring wheel of the APL. The sample interval of 1/3 m is such that all of the information contained within the bandwidth of the APL Trailer is retained. (Information theory requires a sampling frequency at least equal to twice the higher cut-off frequency of the APL measuring device.)

After the recorded profile is sampled and converted to a set of numerical values, those values are, in turn, smoothed using a moving average over an arbitrary baselength. The mean absolute value of the difference between the original profile and the smoothed one has been defined as the coefficient of evenness (CP: "coefficient de planeite"). The CP unit has the following dimensions:

$$1 \text{ CP} = 10^{-5} \text{ m } (= 10^{4} \text{ mm}^{2}/\text{km})$$

Since the mean value is divided by two, one mm of the mean absolute value is equal to 50 CP units. It should be noted that the process of summation involving a moving average has a value dependent on the baselength used. Thus, the CP value must be associated with the baselength, e.g. $CP_{2.5}$ implies that the baselength for the moving average was 2.5 m. For a given baselength, the roughness level increases as the CP increases, with a CP of zero indicating a profile with no variation.

The APL 72 profiles obtained in the IRRE were processed at CRR, using the routine processing methods to obtain three CP numerics for baselengths of 2.5, 10, and 40 m for every 100 m of profile. Although the analyses differ from those used by LCPC, the CP numerics for these three baselengths correspond closely with the LCPC numerics (W), (Y), and (I) for short wavelengths (2.5), medium wavelengths (10), and long wavelengths (40).

Appendix G describes the CP analysis in more detail, and presents the CP numerics obtained from the APL 72 signals by CRR. A moving average analysis was also performed by TRRL, using a variety of baselengths and sample intervals. These results are presented in Appendix H. Appendix J presents additional information about the properties of the moving average filter, and includes numerics computed from APL 72, Beam, and rod and level profiles.

7. RMS Vertical Elevation (RMSVE). This numeric was tested by TRRL, and corresponds approximately to the area between a longitudinal profile and a datum line, over a specified baselength. The area is computed according to Simpson's rule. The RMSVE numeric depends on baselength, and to some extent, on sample interval. RMSVE values were computed from the TRRL Beam profiles using baselengths ranging from 0.4 - 10 m, and sample intervals ranging from 100 mm to 1m, in steps of 100 mm. The study using RMSVE was primarily for determining sensitivities to baselength and sample interval, and suggested that a statistic called RMSD, described next, might be a better numeric for the objectives of the IRRE. Details of the RMSVE analysis and a listing of the results are provided in Appendix H.

8. RMS Deviation (RMSD). From the results obtained using the Moving Average and the RMSVE numerics, a statistic called RMSD suggested itself. RMSD is computed over a baselength by determining the linear regression line

$$Y = A + B\,x$$

where Y is profile elevation, x is longitudinal distance, and A and B are the regression coefficients. RMSD is the RMS deviation of the original profile elevation, relative to the regression line. The RMSD numeric is influenced by the choice of baselength and sample interval, which were optimized by TRRL for correlation with RTRRMSs using data from the IRRE. A 1.8 m baselength and 300 mm sample interval were selected to standardize the RMSD computation and measurement.

The RMSD analysis was applied using both a moving baselength, and also by dividing the profile into separate segments, equal in length to the baselength (1.8 m), which were processed independently (discrete baselengths). When the moving baselength was used, a RMSD value was computed for every profile point (except for the beginning and end sections). Results were nearly identical. The second approach is very well suited to the TRRL Beam, since it means that a single RMSD numeric can be obtained for each setup of the Beam, and that consecutive Beam profiles do not have to be linked for computational purposes.

In order to present the RMSD numeric in the ARS units familiar to users of RTRRMSs, the displacement RMSD measures are rescaled according to a regression equation derived from the IRRE data. The BI Trailer, as it existed during the IRRE, is taken as the reference measure of road roughness that is estimated from RMSD. The regression equation is:

$$\text{"mm/km"} = 472 + 1437\ \text{RMSD} + 225\ \text{RMSD}^2 \qquad (4)$$

The RMSD numeric is approximately linear with profile amplitude; however, the scaling applied by Eq. 4 defines a roughness scale that varies nonlinearly with profile amplitude. Note that a perfect road would have a roughness of 472 "mm/km."

Appendix H contains the details of the RMSD analyses applied, the RMSD numerics obtained, and the correlations observed with several of the RTRRMSs. The appendix also includes the results and findings from a second experiment, independent of the IRRE, which was performed in 1983 in St. Lucia.

Comparison and Summary of Analysis Methods. Each of the above eight types of roughness numerics computed from profile is designed to isolate a particular waveband of interest from the original longitudinal profile. The LCPC APL 72 analyses do this directly with standard electronic band-pass filters, while all of the others "filter" the profile signal by subtracting the rapidly changing original profile from a slowly changing datum line. (The RQCS analysis uses a rapidly changing datum line rather than the original profile.)

The RMSVA "filters," used in the QI_r analysis, define the datum line as a rolling straightedge that contacts the profile at two points on either side of the present position, to provide a mid-chord deviation. The moving average analyses (including CP) use the average of the profile over a certain baselength as the datum. The RMSVE and RMSD analyses also have a datum determined at any position along the profile by a baselength. For these analyses, the selection of a baselength determines the degree to which the datum follows the profile closely: a longer baselength implies that the datum follows the profile less, resulting in larger deviations and thus higher roughness measures.

The datum for the CAPL 25 "filter" is the mechanical pendulum used in the APL Trailer, and in this case, the properties of the datum are determined by the towing speed of the trailer, rather than a geometric length. For the RQCS and HCS "filters," the simulated axle position is the rapidly changing component, while the simulated body position is the datum. In this case, the selection of simulation speed determines how closely the datum follows the profile contours. (Unlike the other analyses, the RQCS and HCS do not compute the difference between the original profile and a datum, but use two datum lines that are computed--one changing rapidly and one changing slowly with profile. Both are influenced similarly by the choice of simulation speed.)

Because each analysis is influenced by at least one choice of parameter value (baselength or speed), and usually more (sample interval, vehicle model parameters), specific standard values have been determined for each type of analysis. (The parameter values had been in use prior to the IRRE for every analysis except the RMSD and RMSVE developed by TRRL, using the IRRE data.)

Figure 6 compares the sensitivity of four of the analyses to wavenumber (wavenumber = 1/wavelength) for a slope input. Because the spectral contents of the four types of roads were shown in Figure 5 as slope inputs, these response curves can be interpreted as a "weighting" that is applied to the inputs shown in Figure 5. Since the slope input is fairly uniform over wavenumber, the plots shown in Figure 6 illustrate approximately the contributions of different wavenumbers to the numerics obtained with the different analyses.

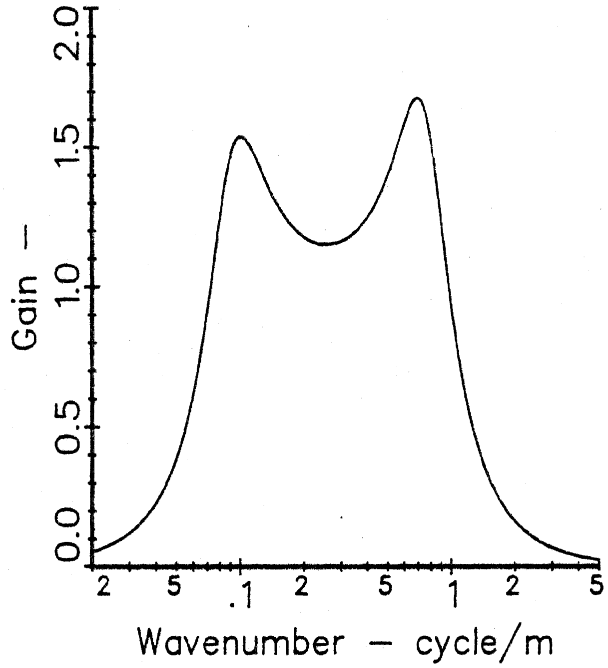
The plots shown in Figure 6 serve as a technical basis for determining the bandwidth needed in a profile measurement to obtain the "true" value of the associated numeric. They also help in interpreting some of the correlation results presented later.

Comparison of Profile Measurement and Analysis Methods

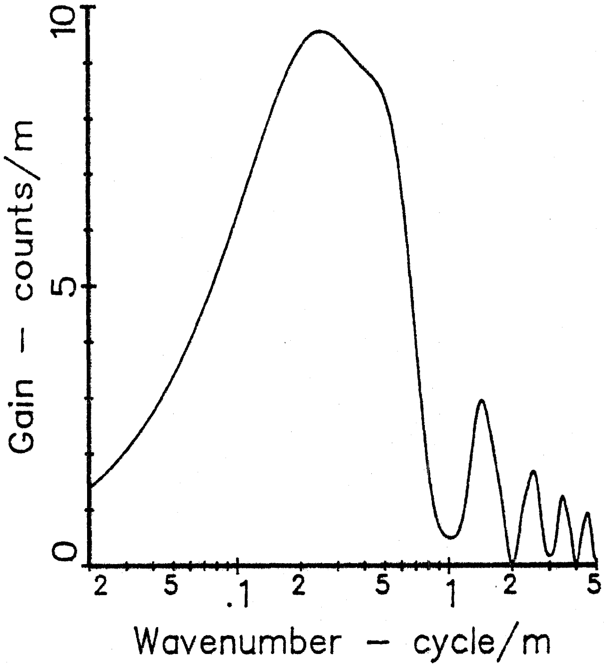
For a roughness measure to be transportable, it must be measureable by different profilometric methods. Accordingly, the profilometric methods used in the IRRE were evaluated as to their suitability for measuring the various profile-based numerics. The main advantage of a profile-based numeric is that it can be measured directly, without the need for a new correlation experiment every time a new piece of equipment is acquired or a new type of road condition is encountered. Therefore, correlations obtained between numerics obtained from different profile measures are irrelevant, and the level of agreement is determined simply by the absolute differences observed.

The RARS (RQCS), QI_r (RMSVA), and CP (moving average) analyses were applied to profiles obtained by different methods, and the results are summarized here.

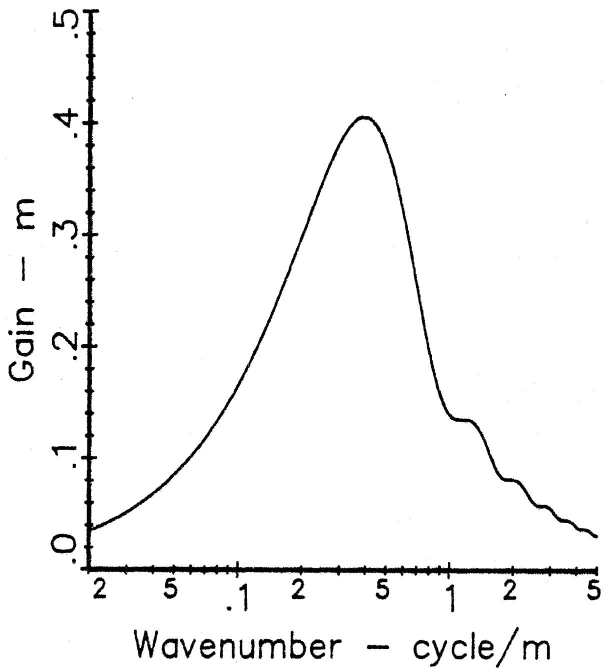
RARS. This method of profile analysis had been used mainly with GMR-type profilometers in the United States prior to the IRRE. For that application, the simulation speed is generally 80 km/h, and rough roads are not measured. As part of the research included in the IRRE, the procedures



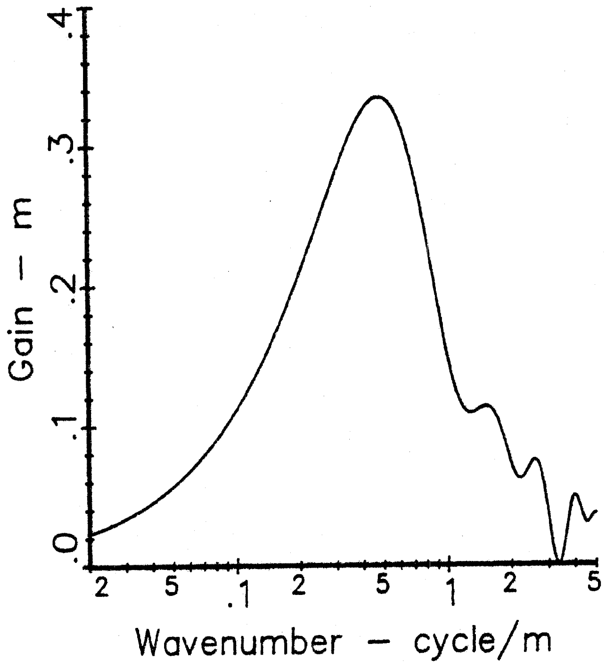
a. $RARS_{50}$



b. QIr



c. $CP_{2.5}$



d. RMSD (approximate)

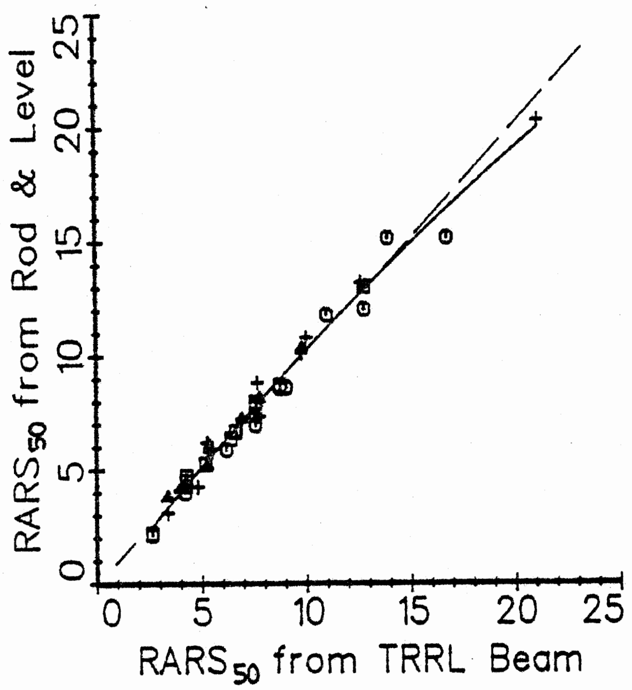
Figure 6. Sensitivity to wavenumber of four profile analyses.

for computing RARS were refined and simplified, and the measurement requirements for valid computation of RARS were quantified. The findings are presented in Appendix F, and include the following:

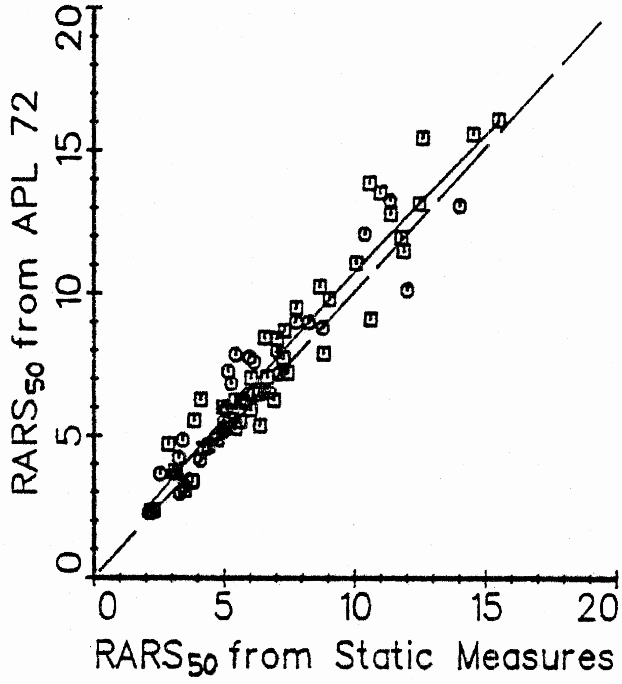
- **Sample interval.** Any sample interval up to 250 mm can be used for any simulation speed between 20 and 80 km/h. For simulation speeds of 50 km/h and higher, the sample interval can be as large as 500 mm. As sample interval decreases, slightly better accuracy is obtained, and the chances of error due to missing roughness in the measurement are reduced. Figure 7a shows a sample of the repeatability obtained using two static profile measurement methods, which also involved different sample intervals (100 mm for the TRRL Beam and 500 mm for the rod and level).

- **Waveband of measurement.** The waveband required for $RARS_{50}$ numeric is shown in Figure 6, while the wavebands needed for other simulation speeds are shown in Fig. F.2 in Appendix F. The RARS numeric can be computed directly from the APL signal, using the same procedure as used for the static measurements. It is essential that the towing speed of the APL Trailer be chosen to approximately match the simulation speed of the RQCS, although some difference is allowable because the APL Trailer has a wider bandwidth than the RQCS "filter." For a simulated speed of 20 km/h, the APL 25 signals could be used, while for the higher speeds of 32, 50, and 80 km/h, the APL 72 signals could be used. Figure 7b compares the measure of $RARS_{50}$ obtained statically (averages of the numerics obtained with rod and level and TRRL Beam) and with the APL 72 profile signal. Although there is more scatter than when two static measures are compared, there is negligible bias error.

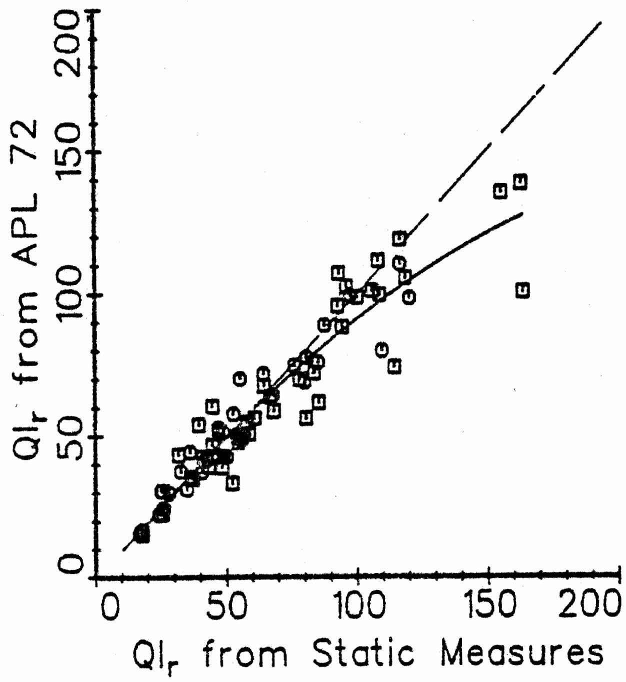
- **Precision of measurement.** A study was performed using the profiles measured with the TRRL Beam. The profiles, measured with a precision of 1.0 mm, were rounded off on the computer to determine the effect of a less precise measurement. It was found that the precision needed was directly proportional to roughness, with less precision needed on rougher roads. To obtain the same accuracy in the RARS numerics on all of the roads, the rather coarse resolution



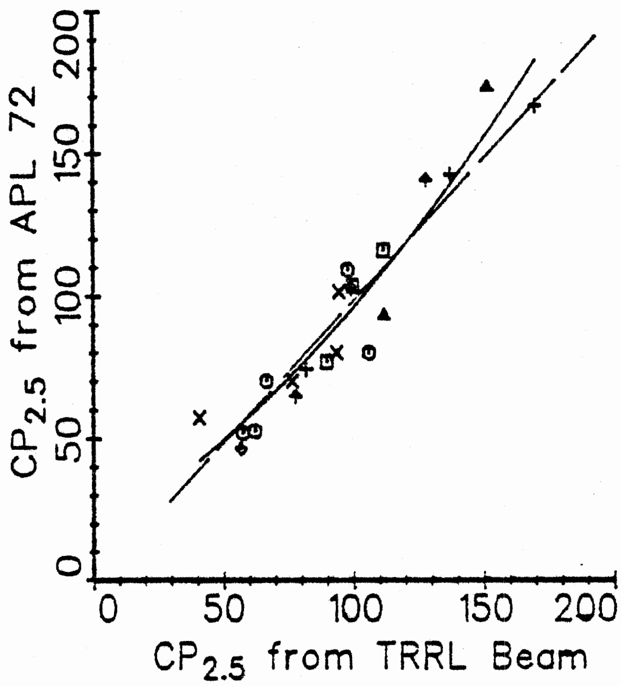
a. Two static measures of $RARS_{50}$



b. Static and dynamic measures of $RARS_{50}$



c. Static and dynamic measures of QI_r



d. Static and dynamic measures of $CP_{2.5}$

Figure 7. Comparison of roughness measures from different profilometric methods.

of 15 mm would have been adequate on the roughest sites. For negligible error, a precision of 0.5 mm should probably have been used on the three smoothest sites; a precision of 1.0 mm is recommended for all but the roughest paved roads; a precision of 2.0 mm is adequate for all of the unpaved roads; and a precision of 5.0 mm is adequate for the rougher unpaved roads.

QI_r. The QI_r numeric had been used only with the rod and level method prior to the IRRE. In its development, the RMSVA numerics were compared for rod and level and a GMR-type profilometer, and found to differ; hence, the QI_r analysis was recommended only for the static measurement methods. All of the profile measurements were processed to yield QI_r numerics, and certain measurement requirements were also investigated. The findings are reported in detail in Appendix E, and include the following:

- **Sample interval.** The RMSVA numeric requires that the sample interval divide evenly into the baselength. Because QI_r uses baselengths of 1.0 and 2.5 m, any sample interval that divides evenly into 500 mm can be used for the computation, such as 500, 250, 100, 50 mm. For other intervals, such as 300 mm or 1/3 m, the RMSVA numerics cannot be computed directly. Comparisons of QI_r obtained from repeated rod and level profile measures and with the TRRL Beam showed the same degree of agreement as with the RARS numerics, shown in Figure 7a.

- **Waveband of measurement.** The waveband required for QI_r is shown approximately in Figure 6 (an exact wavenumber sensitivity curve does not exist for non-sinusoidal inputs). Although most of the QI_r numeric derives from wavenumbers between .1 and .7 cycle/m (wavelengths from 1.4 - 10 m), the numeric also includes the effects of wavenumbers lying outside of that range. When the QI_r analysis is applied to the APL 25 and APL 72 profiles, the numerics obtained are too low because the signal from the APL Trailer does not include all of the wavenumbers that the static profiles contain. Figure 7c shows that for the APL 72, the effect is noticeable mainly on unpaved roads, where the significant presence of high wavenumbers (wavelengths shorter than 1 m) is included in the statically measured profiles but not the APL 72 signal. Measures of QI_r with the APL 25 show much greater error.

LCPC has derived alternate regression equations for estimating QI_r, using the APL measures of RMSVA obtained in the IRRE. These data, presented in Appendix E, show that the APL Trailer can be used to estimate QI_r, and also show the methods that are needed in adopting the QI_r analysis to a dynamic profilometer. In order to use the QI_r computation with band-limited profilometers, a correlation experiment must be performed for every new profilometer type and possibly road type. This is because the correlations are influenced by the wavenumber content of measured profile, which in turn is the result of both the road surface type and the profilometer characteristics.

- **Precision of measurement.** The study of required profile precision that was described above for the RARS computation was also performed for the QI_r computation, with nearly identical results. The precision needed for valid measurement of QI_r is proportional to the roughness (QI_r), and is almost exactly the same as the precision needed for the RARS computation.

Moving Average. The CP numeric used by CRR is obtained with a moving average, and all of the analyses applied by TRRL (moving average, RMSVE, and RMSD) are similar to a moving average. Since the numerics are all computed using numerical methods, they could be applied to all of the profiles obtained in the IRRE. Analyses of the mathematical properties of the moving average, and comparisons of numerics computed from the APL 72 and statically measured profiles resulted in the findings reported in Appendix J, which include the following:

- **Sample interval.** A true moving average is closely approximated if the baselength includes many profile points. When the sample interval is changed such that the number of points within a baselength goes from 20 to 100, no effect is seen on the output. However, when the ratio between sample interval and baselength is such that only a few points are included in the average, then the analysis is no longer a true moving average, and the sample interval influences the results. This is demonstrated both theoretically (Appendix J) and experimentally (Appendix H). The RMSD numeric has an associated baselength of 1.8 m and a sample interval of 300 mm. This sample interval must be used: a larger interval will result in lower numerics and a smaller interval will result in higher numerics. The CP_{10} numeric can be obtained using a 500 mm interval, but the $CP_{2.5}$ numeric requires a shorter interval. Figure 7d shows the agreement between the $CP_{2.5}$ numeric computed from APL 72 and TRRL Beam profiles. (Values computed from rod and level, with a sample interval of 500 mm, were lower than the others.) Comparisons for intervals of 333 mm, 100 mm, and 50 mm showed close agreement.

- **Waveband of measurement.** The wavenumber sensitivity plots shown in Figure 6 correspond to the $CP_{2.5}$ numeric computed from the APL 72 signals and (approximately) to the RMSD numeric computed from the TRRL Beam profiles. For longer baselengths, the plots have the same shape, but would be shifted to the left in proportion to the ratio of baselengths. For example the plot shown for a baselength of 2.5 m has a peak at 0.4 cycle/m (2.5 wavelength). For a baselength of 10 m, the peak would occur at 0.1 cycle/m (10 m wavelength)

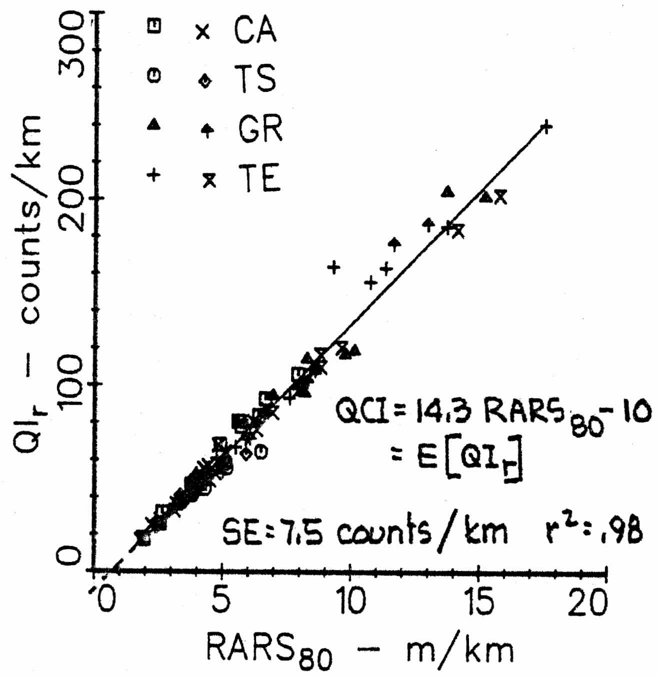
Numerics obtained from the APL 72 and the static profile measurements were in agreement for baselengths of 2.5 and 10 m (the comparisons of CP_{10} included some outliers, which were explained on the basis of differences in wheeltrack properties observed in Appendix I). For a baselength of 40 m, the APL 72 numerics were lower because the moving average analysis is influenced by long wavelengths not transduced by the APL Trailer at 72 km/h, but which appear in statically obtained profiles. To obtain a match between the CP_{40} numerics obtained for APL and rod and level, the analysis for rod and level would need to account for the long wavelength response properties of the APL Trailer.

Correlations Among Profile-Based Numerics

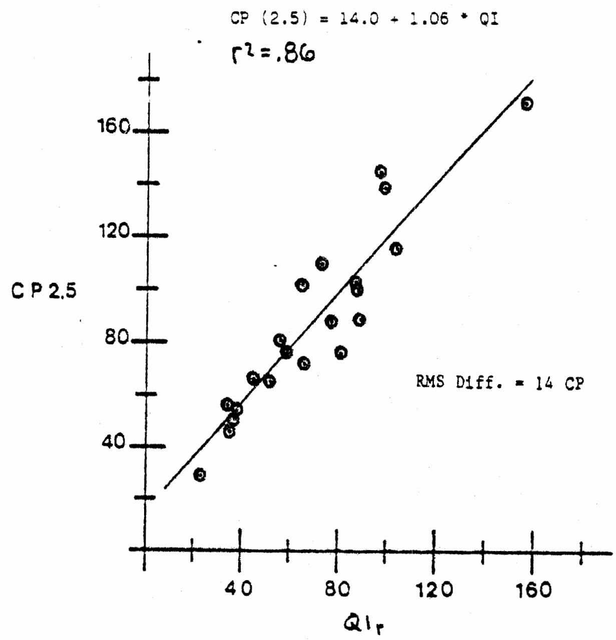
It was noticed that several of the profile-based numerics were highly correlated, as might be expected since they include wavebands that overlap. The closest agreement was between the half-car simulation (HCS) and the RQCS. (The analyses differ only in the order in which the two wheeltracks are combined. In the HCS, the profiles are averaged and then filtered; in the QCS, the profiles are processed separately and the RARS numerics are averaged.) For the roads included in the IRRE, the HCS numeric for any site was approximately 0.76 times the average of the two QCS numerics. This relationship should not be assumed to be universally valid for arbitrary road inputs. For example, if one wheeltrack is perfectly smooth, then the HCS numeric must equal the average of the two QCS numerics. (The ratio would be 1.0 instead of 0.76.) Since the two analyses gave what were essentially redundant measures, differing by a scale factor of 0.76, only the the RQCS numerics are discussed in any detail in this report. (HCS numerics are presented in Appendix F.)

The moving average and the RQCS are both analyses that have simple geometric interpretations: the RARS from the RQCS is the average slope of the profile as "seen" by the simulated vehicle, while the moving average numeric (CP) is based on a simple smoothing method. Both of these numerics can be measured with a variety of methods, including the APL Trailer, rod and level, and the TRRL Beam. On the other hand, QI_r cannot be measured directly with the APL Trailer, and the "standard" RMSD requires a sample interval of 300 mm. (The RMSD analysis was not tested with the APL signals.) Practitioners who cannot measure these numerics directly might estimate them from other profile-based numerics that they can measure, if there is sufficient correlation.

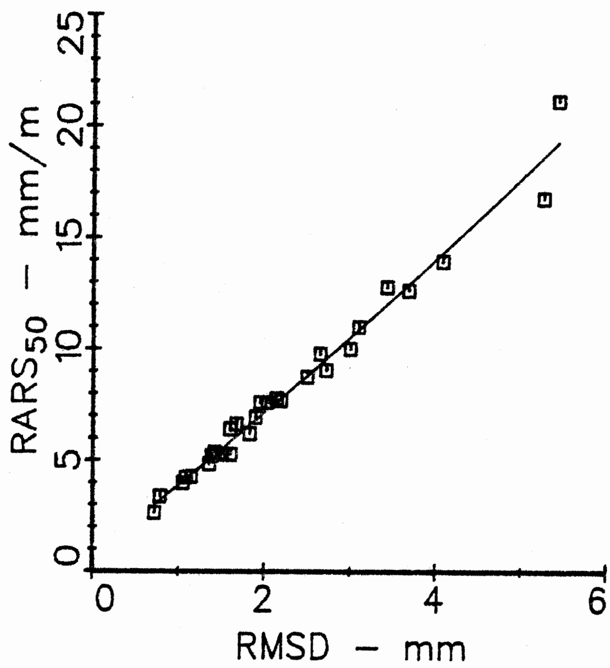
QI_r. CRR and LCPC have shown that the QI_r numeric is strongly correlated with the $CP_{2.5}$ numeric routinely used by CRR. An even stronger correlation was noted between the QI_r and $RARS_{80}$ numerics. These relationships are shown in Figure 8. Note that the relationship between QI_r and $RARS_{80}$ is nearly perfect on the paved roads, differing only for a few of the surface treatment sites. The main difference is that the $RARS_{80}$



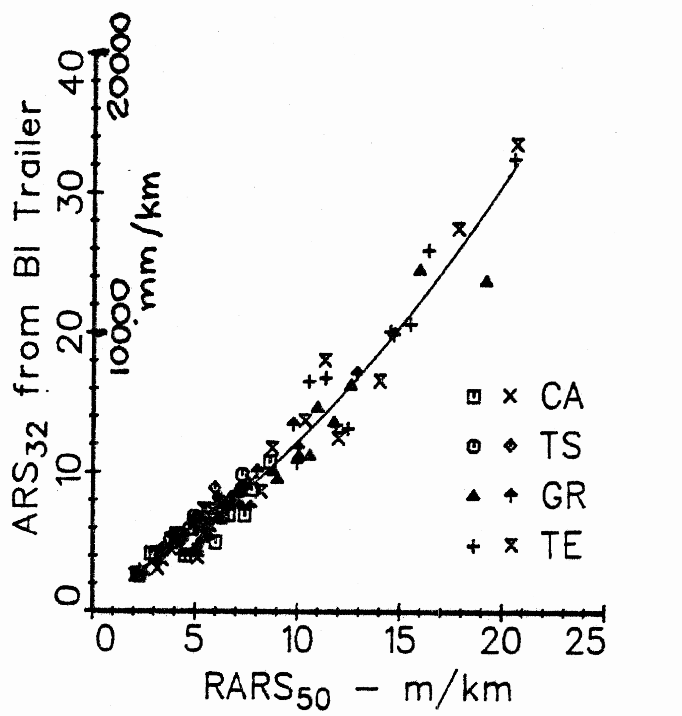
a. QI_r and $RARS_{80}$



b. QI_r and $CP_{2.5}$



c. RMSD and $RARS_{50}$



d. $RARS_{50}$ and the TRRL reference "mm/km" (BI Trailer)

Figure 8. Example correlations between profile-based roughness numerics

numerics can be obtained directly with a profilometer and arbitrary sample interval between 0 and 500 mm. (A sample interval up to 700 mm was valid for the profiles obtained in the IRRE.) The $RARS_{80}$ numeric can be scaled to approximate the QI_r roughness scale:

$$QCI = -10 + 14.3 \ RARS_{80} \tag{5}$$

where QCI has the same "counts/km" units as QI_r and $RARS_{80}$ has units m/km.

This finding about the close agreement between the QI_r and $RARS_{80}$ numerics helps return the QI roughness scale to its origins as the Quarter-Car Index. Since the QI^* roughness scale used in the ICR project was intended to rescale RTRRMS measures made at 80 km/h, the close relationship to a simulated RTRRMS running at that speed indicates that the physical interpretation of the QI scale is not affected if it is defined by the RQCS. Also, since the RQCS has physical units (m/km rather than counts/km), it is easier to grasp the relationship between physical RTRRMS measures and the reference.

The RARS computation is more complex than the RMSVA computation (compare Eqs. 1 - 3), but not so much so that any real penalty is involved. Both the RMSVA and RARS computation require several lines of coding in a computer program, and can be implemented on most microcomputers. (Many of the QI_r and RARS numerics computed in the IRRE were computed on an Apple II+ using programs written in BASIC.) On the other hand, a great benefit is realized by being able to use the same equations for computing the roughness numeric, regardless of whether the profile was measured statically or dynamically.

RMSD and "mm/km." The RMSD numeric is designed for a statically measured profile, sampled at 300 mm intervals, and has not been tested for rod and level or APL profiles. By using an analysis that works for discrete segments of profile as well as the entire profile, the roughness measure obtained using RMSD is very well suited to the TRRL Beam. However, this advantage disappears when an alternate profilometric method is used. The requirement of a standard sample interval also hampers the flexibility normally associated with profile measurement.

Figure 8c shows that the RMSD and $RARS_{50}$ numerics are highly correlated, and that the $RARS_{50}$ numeric could be used to estimate RMSD. CP could also be used as an estimator, but the correlation is not quite as high.

But since the RMSD numerics are converted to an ARS-type measure according to Eq. 4, a more direct equivalence can be obtained by comparing the $RARS_{50}$ numerics to the measures obtained from the BI Trailer in the IRRE, which were used to define the reference "mm/km." This reference can also be estimated from $RARS_{50}$, using the equation:

$$\text{"mm/km"} = 550 + 369\ RARS_{50} + 18\ RARS_{50}^2 \qquad (6)$$

A strong correlation also exists for the $CP_{2.5}$ numeric computed from the APL 72 profiles by CRR, although it is not as high as the correlations shown in Figure 8. (A correlation plot between the BI Trailer and $CP_{2.5}$ is shown in Appendix G.) While the $RARS_{50}$ numeric is not as convenient to compute when the profile is measured in short segments with the TRRL Beam, it has an advantage because it can be obtained with a wider variety of profilometric methods. Also, the relationship shown between BI Trailer ARS_{32} and $RARS_{50}$ may be more representative, because it is based on measures from all 98 of the wheeltracks included in the IRRE, rather than the 28 measured with the Beam.

RARS. The high correlations between RARS and some of the other numerics mean that RARS can be estimated from other profile-based numerics, such as RMSVA, CP, and RMSD. Since RARS can be measured directly with any of the profilometric methods included in the IRRE, there is little reason to estimate a quantity by correlation when it can be measured directly. One exception to this is when the TRRL Beam is used to measure RMSD over sections of profile 1.8 m long. In this case, computation of RMSD using the microcomputer of the Beam is much simpler than computation of RARS using the entire profile. The approximate equivalence between RMSD and $RARS_{50}$ shown in Figure 8c indicates that the RMSD measures could be rescaled to the RARS reference as well as the BI Trailer reference, using the equation:

$$CARS_{50} = -.76 + 3.06\ RMSD + .0028\ RMSD^2 \qquad (7)$$

where CARS is a "calibrated ARS" measure having the same numerical interpretation as RARS, but which is not a direct measure of RARS. The main advantage for using the RARS as a reference rather than the BI Trailer as it existed during the IRRE is that the RARS reference is available for future derivations, whereas the properties of the BI Trailer are known to change with time.

Correlation of RTRRMS Numerics

Regardless of the choice of a reference calibration standard, measures obtained with a RTRRMS are limited to the quality of the original ARS measure. Day-to-day changes in the properties of a RTRRMS, errors in using the instruments, and the normal random error of measurement cannot be reduced simply by rescaling the ARS measures according to a calibration equation. These factors cause variations in use that reduce the repeatability of the RTRRMS. The variations can be reduced through careful maintenance to control the variables that influence the measurement [9], and by standardized measurement procedures, such as those used in the ICR projects [7].

Assuming that good practices are used to ensure that day-to-day measures made with a RTRRMS are repeatable, the final "calibrated" RTRRMS measures may still have only limited equivalence if the different RTRRMSs are producing raw measures that are largely unrelated. No transformation will make the measures compatible if different systems rank the same set of roads in dissimilar order by roughness. A calibration can eliminate average differences that occur over an aggregate of conditions, but cannot ensure that a specific measure obtained by one calibrated RTRRMS is reproducible with another. Since the equivalence between measures based on independently calibrated RTRRMSs is necessarily "second best" to a direct side-by-side correlation of the RTRRMSs, the data collected in the IRRE can be examined to determine the degree of reproducibility that is possible between different RTRRMSs.

Appendix B contains all of the data from the RTRRMSs, and also presents the summary results obtained by averaging repeat runs. Appendix C reports the results of a correlation exercise, in which the measures of each RTRRMS were regressed against those of every other, for each of the 40 possible combinations of speed and surface type that exist when both instruments are operated at all four of the test speeds. The major findings of these Appendices are presented below.

Repeatability. The repeatability error is neither constant for all roughness levels, nor proportional to roughness, but something in between. By and large, the repeatability of the instruments in the IRRE was better than 5% (standard deviation of repeated ARS measurements divided by the mean value), and a repeatability of 3% is fairly typical. The measurement speed did not seem to be a factor, indicating that repeatability for a particular RTRRMS is only a function of section length. Although the effect of site length cannot be shown from the IRRE data, random signal theory indicates that random error can be reduced by either repeated measurements (ensemble averaging) or by using longer sites (averaging over length) for profiles that qualify as statistically stationary. (A profile is stationary if it has a relatively uniform roughness over the entire length.) In either case, the error in the mean measurement is inversely proportional to the square root of the total length. Thus, the repeatability should be improved by using longer sections. For sites that are four times longer than those used in the IRRE, the random error should be reduced by half.

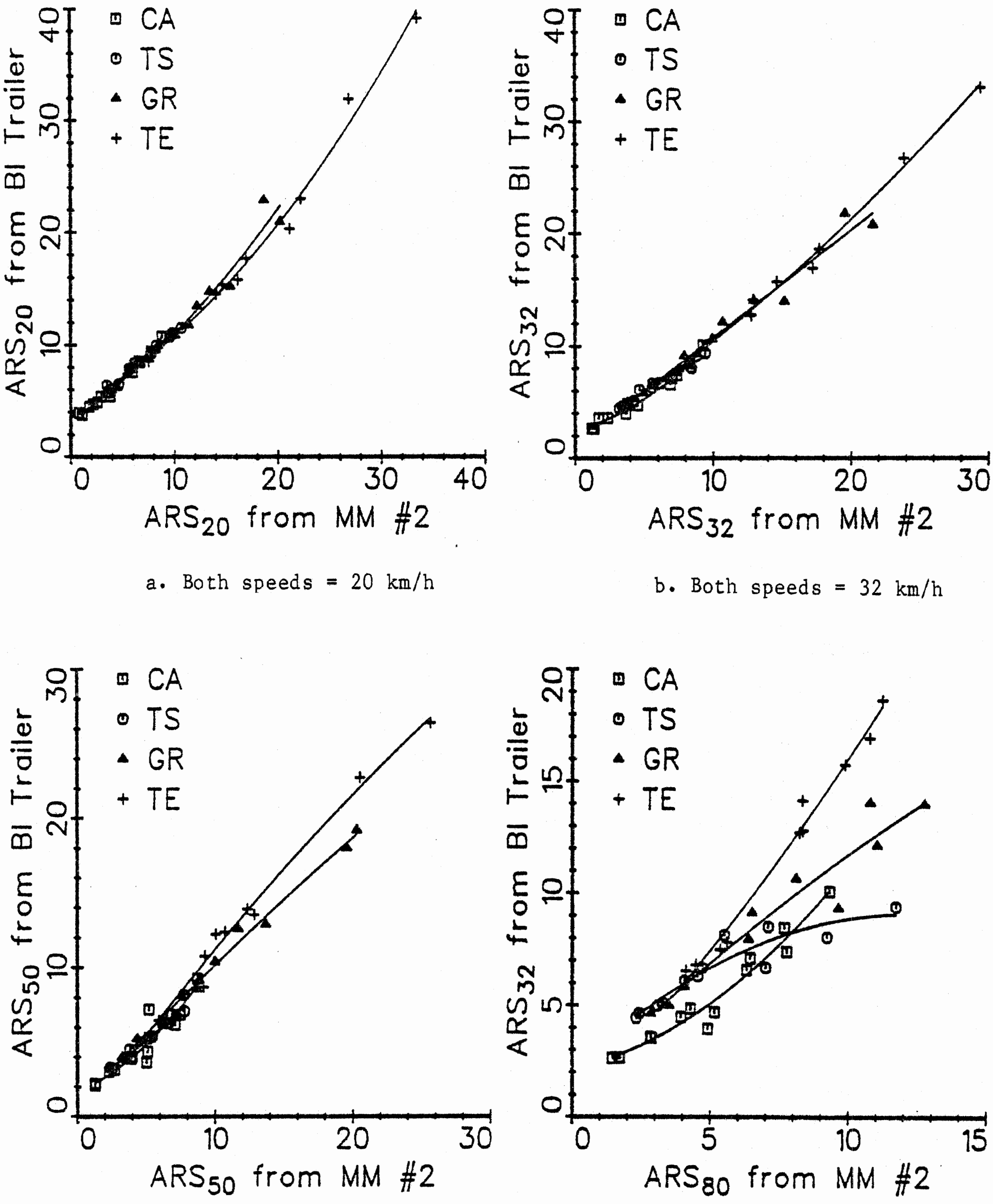
Choice of roadmeter. One of the RTRRMS vehicles was equipped with two roadmeters, one a BI unit and one a NAASRA unit. When the readings (in counts) were scaled to the same units of ARS (m/km), the measures were virtually interchangeable. (The BI numerics were higher by a constant but very small amount, which is an effect caused by two meters having different amounts of hysteresis.) For all practical purposes, the readings obtained from the BI and NAASRA units are redundant measures of the ARS of the Caravan vehicle. Because different roadmeters use different units for their displays (inches, mm, counts), and also because the manufacturers recommend different measurement practices, there is often a tendency to assume that the same brand of roadmeter instrument must be used in all vehicles for good agreement. Yet the theoretical understanding and the practical evidence obtained in recent years show that the choice of roadmeter instrument is not of primary importance. Instead, the critical factor is the methodology adopted to obtain and analyze the roughness data. It has even been shown (prior to the IRRE) that PCA meters can be used to measure ARS by eliminating the complicated PCA data reduction process [9].

Correlation for different RTRRMS speeds. In every case, the best correlations between two RTRRMSs are obtained when the instruments are operated at the same test speed, even when the test speed is not "standard" for one of the instruments. For example, the BI trailer is normally operated at 32 km/h, while the Opala-Maysmeter system is typically operated at 80 km/h. Figure 9 shows the agreement between the ARS measures obtained when both are operated at the same speed and at different speeds. The solid lines are quadratic regression curves, calculated separately for each surface type. When operated at the same speeds (Figs. 9a, 9b, and 9c), there is very little scatter about the regression lines, and the ARS measures from one RTRRMS could be "converted" to those of the other, with good reproducibility. Also, the four regression lines are very similar, indicating that a single relationship holds for the different surface types. In contrast, there is a more scatter when different speeds are used (Fig. 9d), and different underlying relationships appear (as shown by the regression lines) for the different surface types. The reason for this is that the waveband "seen" by the RTRRMS is a function of the speed, as shown in Fig. F.2 in Appendix F.

Correlation across surface type. When the same speed is used for two RTRRMSs, the regression lines obtained for the different surface types collapse into a single relationship. Even though the sensitivity of each RTRRMS to wavenumber is unique, the overall waveband "seen" is approximately the same when the speeds are matched.

Distribution of scatter. In most of the plots, the variation about the regression line (scatter) is fairly constant for all roughness levels. The "errors" do not increase in proportion to roughness. This indicates that when regression equations are used, a simple least-squares fit can be applied to the original measures, without any transformations. Because the relationships often appear to show some curvature, a quadratic regression is suggested as a general purpose model.

This observation is not true when the RTRRMSs speeds are not matched **and** different surface types are not identified. In Figure 9d, the scatter would appear to increase with roughness if only the data points were shown.



a. Both speeds = 20 km/h

b. Both speeds = 32 km/h

c. Both speeds = 50 km/h

d. Different speeds (32, 80 km/h)

Figure 9. Example correlations between two RTRRMSs.

The reason is that a different relationship exists for each surface type, and when they are plotted together, those trends diverge with increased roughness. The different regressions are obtained because of a combination of two factors: 1) the two RTRRMSs "see" different wavebands when operated at different speeds and 2) the different surface types have different "signatures" of spectral content, as shown earlier in Figure 5. At the low speed of 32 km/h, a RTRRMS sees the shorter wavelengths, which Figure 5 shows are most significant in the earth (TE) sites and least significant in the asphaltic concrete (CA) sites. Hence, the ARS_{32} measures are highest for the TE sites and lowest for the CA sites.

Although regressions of transformed measures (such as log values) are not recommended for RTRRMS measures made at the same speed, they may be necessary for the conditions described above, where much more uncertainty exists due to improper speed matching and missing surface type information.

Correlation across speed. RTRRMS measurements made at more than one speed might be required for some applications. There is then a question of whether a relationship between the measurements that is shown for one speed is valid at other speeds. The IRRE data support an earlier finding [9, 29] that correlation across speed can be obtained with more success when the RTRRMS measures are converted to units of average rectified velocity (ARV), by the equation:

$$ARV = ARS \times speed.$$

If the above equation is used with typical metric units for ARS (m/km) and speed (km/h), then ARV would have units: m/h. When data are taken at just one speed, the choice between ARS or ARV as a roughness measure is arbitrary because the two statistics differ only by a constant scale factor which is eventually eliminated through calibration to a reference. But when data taken at different speeds are compared, the two statistics have different interpretations. ARV is a direct measure of vehicle response: a higher ARV value always indicates more vehicle vibration, regardless of the circumstances causing the excitation. (When artificial excitation is used to characterize a RTRRMS, the roadmeter measures must be converted to ARV to obtain a valid calibration [9, 30].)

When all of the measures from the IRRE are expressed as ARV, a single relationship between instruments usually exists for all speed/surface type combinations. However, the relationship generally has an offset, due to vehicle and roadmeter nonlinearities. (That is, a zero reading from one instrument corresponds to a non-zero reading from the other.) The constant offset in the "true" ARV relationship becomes a function of speed when converted to an equation between ARS measures from the two instruments. Thus, an ARS correlation across speed introduces an artificial bias with speed, and is usually not valid.

Limitations of different RTRRMSs. Most of the instruments were capable of testing almost the full roughness range available. Still, the individual RTRRMSs did show some limitations.

Correlations involving the Soiltest BPR Roughometer were usually lowest, even in the best of cases, when it was compared to the BI trailer. This BPR Roughometer was the most fragile of the RTRRMSs, and experienced constant breakdowns. It was not operated at high speeds on the rougher surfaces.

All of the other systems were able to cover about the same levels of vehicle response. (The Opala-Maysmeter systems were the only ones operated at the highest speed of 80 km/h, but the maximum ARV excitation occurred on the roughest sites which were measured at a maximum speed of 50 km/h.)

As noted earlier, the measurements obtained from the BI and NAASRA roadmeters installed in the same vehicle were nearly identical (when scaled to "m/km""), and were compatible with those of the other RTRRMSs. The exception to this was the case of the data taken at 80 km/h. The BI and NAASRA data did not agree as well as for the other speeds. Correlations with the Maysmeters and the profile-based $RARS_{80}$ numeric were higher for the NAASRA meter than for the BI meter.

Effect of individual wheel track roughness. The ARS measures obtained by the two RTRRMS trailers in each wheeltrack were averaged to obtain a single ARS measure for the test site. The correlations between these averages and the measures from the two-track RTRRMSs were excellent, being as good as the correlations between the different two-track systems.

In addition to the average, a difference can be calculated from the two trailer measures. The difference measures were found to be uncorrelated to the measures of the two-track vehicles.

Correlation of Profile-Based Numerics with RTRRMS Numerics

Calibration of RTRRMSs. At the present time, profilometric methods needed for direct computation of the profile-based numerics are not available to many road agencies. The primary purpose of the profile-based roughness numerics is viewed in this report as being for the calibration of RTRRMSs. (Naturally, as high-speed profilometers are acquired by more agencies, the role of RTRRMSs is expected to diminish, with the RTRRMS calibration reference being measured directly by profilometer when a historical link to RTRRMS data is needed.)

A calibration involves the rescaling of the "raw" RTRRMS measures of ARS to "calibrated" roughness measures. The calibration is intended to eliminate bias errors over a large number of measurements so that aggregate data from one RTRRMS will be neither higher nor lower than aggregate data from another RTRRMS over the entire range of surface type, roughness, and speed.

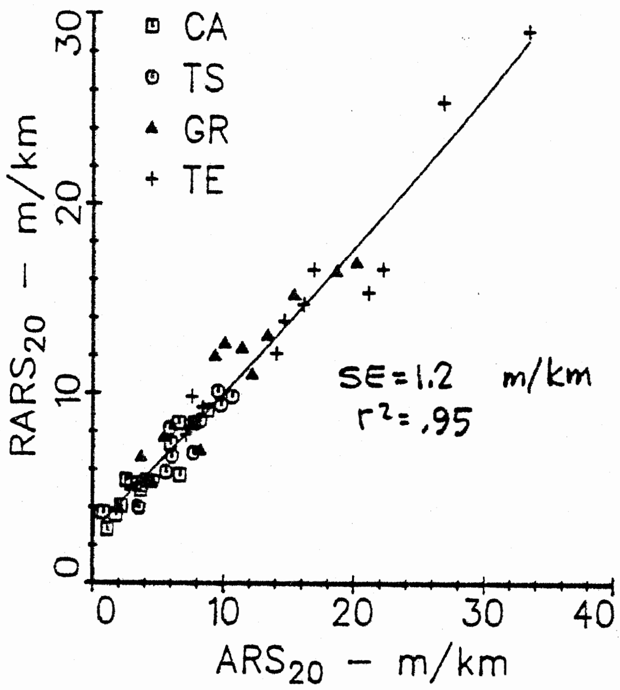
Although many calibration methods for other types of instruments (for example, thermometers, scales, voltmeters) require only one or two measurements, the complex nature of "roughness," together with the crudeness of a RTRRMS, requires that many measures be taken to obtain a calibration. In essence, the calibration is achieved by correlation.

An individual calibrated RTRRMS measurement will not be perfectly reproduced by another calibrated RTRRMS or even a direct profile measure due to the differences in how that particular RTRRMS "sees" the road, relative to the reference. A RTRRMS might consistently produce high calibrated measures on a certain road, even though it produces measures that are neither high nor low when averaged over a number of roads. This error can be reduced if the RTRRMS and the reference measure "see" the road in nearly the same way. In other words, the accuracy (reproducibility) of a calibrated RTRRMS measurement is improved with better correlation between the RTRRMS and the reference.

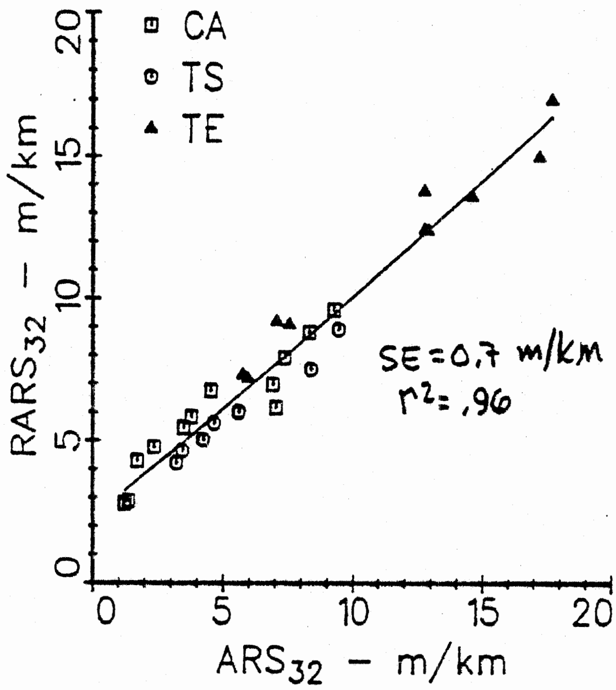
Correlations between the candidate roughness standards and the RTRRMSs were calculated to determine the accuracy and minimum complexity needed for calibrating the RTRRMSs to the candidate standards. The prevailing opinion among practitioners is that a single calibration is desirable for all surface types, rather than separate calibrations for each condition. Therefore, the sample calibration curves plotted here and in the appendices were all computed without segregating by surface type, even though slightly better correlations were obtained when data points were segregated by surface type. Bias in the regression equation (i.e., calibration error) is not a problem due to the design of the IRRE, in which each surface type is represented at the different roughness levels. If the presence of several smooth unpaved sites tends to bias the regression in one direction (relative to the aggregate), the effect is balanced by several paved sites having the same roughness that bias the regression in the other direction.

RARS. When the RQCS speed is set equal to the RTRRMS measurement speed, correlations between RARS and the ARS measures obtained from the RTRRMSs are very good at all speeds and surface types, with the one exception of the 80 km/h data from the surface treatment sections. Figure 10 shows calibration plots for one of the RTRRMSs at each of the four speeds.

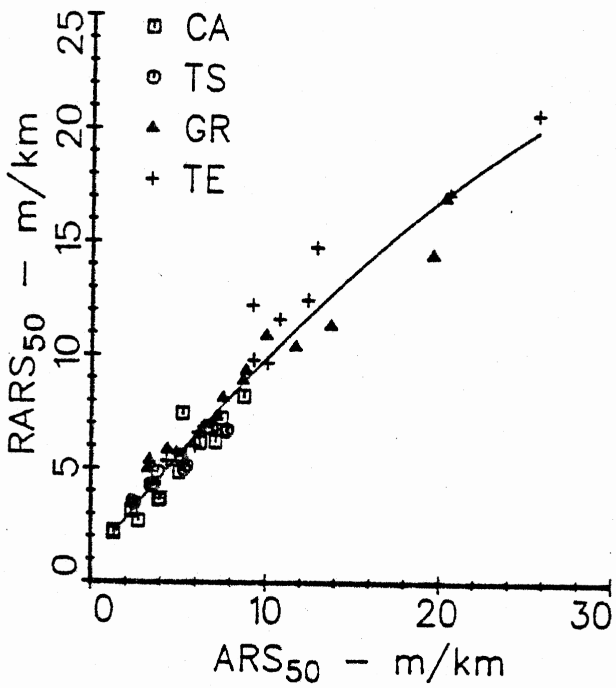
The four surface treatment (TS) sites that appear as "outliers" when measured at 80 km/h were examined and found to have a periodic unevenness that occurs over 2 m intervals. At 80 km/h, this appeared at 11 Hz, which is a typical axle-tire resonance in vehicles. Even though the $RARS_{80}$ has its maximum sensitivity at that wavenumber, the mechanical RTRRMS responded even more. This behavior was not reflected in any of the other roughness numerics, nor in the subjective ratings (discussed later). (These four sites appear as outlier data points when comparing the ARS_{80} measures to any of the profile-based numerics, with the problem being smallest for $RARS_{80}$.) In this case, the RTRRMS measurements appear to deviate from the general concept of road roughness. Rather than attempting to define a standard having this peculiar characteristic, a better approach is to prevent that sensitivity in the RTRRMS by selecting "stiff" shock absorbers, to prevent such specific



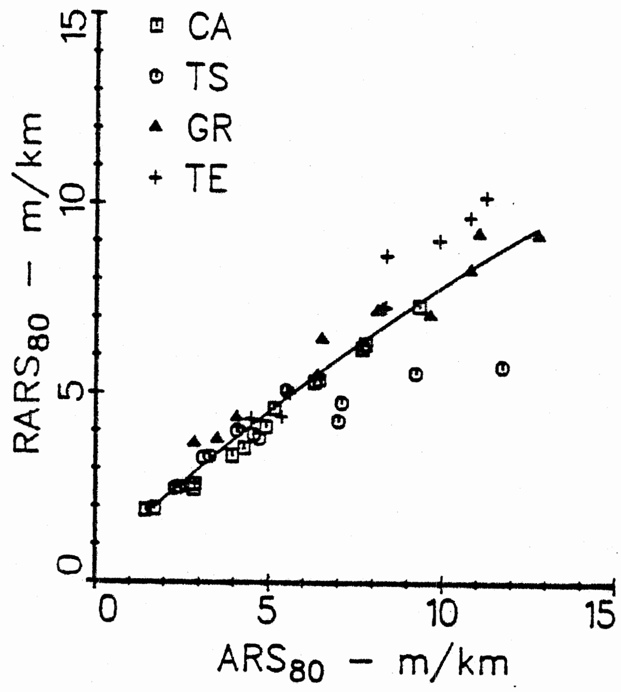
a. 20 km/h. $RARS_{20}$ from APL 25.



b. 32 km/h. $RARS_{32}$ from APL 72.



c. 50 km/h. $RARS_{50}$ from static measures.



d. 80 km/h. $RARS_{80}$ from static measures.

Figure 10. Example calibration plots to estimate RARS with the Opala-Maysmeter RTRRMS.

"tuning."

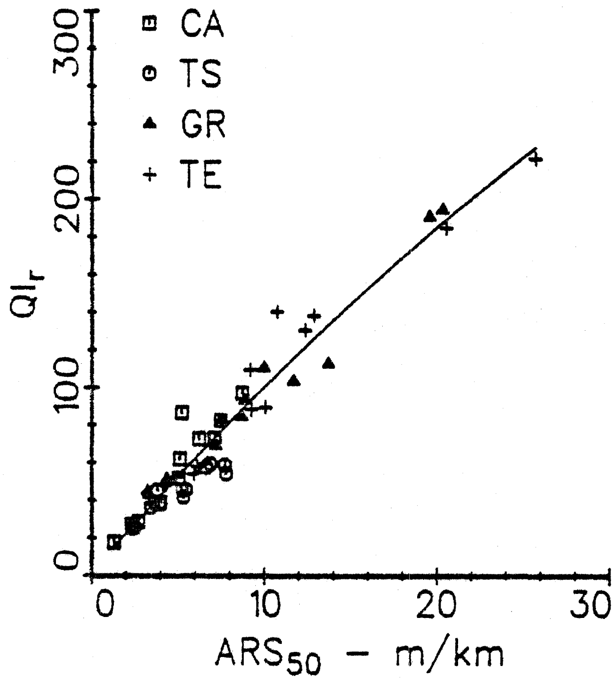
A small bias also exists for some of the RTRRMSs between paved and unpaved roads, with the RARS numerics being high on the unpaved roads and low on the paved roads. This effect can occur when: 1) roadmeters have hysteresis and 2) the different road types have different spectral compositions [9]. On the unpaved roads, where there is less low-frequency content in the vehicle vibrations, the hysteresis results in a greater loss of counts for the RTRRMS. This effect was also seen to a lesser degree between the BI units and the Maysmeters. The effect was least for the BI unit, which apparently had the least hysteresis of the roadmeters.

Overall, correlations between RARS and the RTRRMSs were the highest of any obtained between ARS and a profile-based statistic, matched only by the correlations obtained with the RMSD numeric (based on fewer measurements). Even so, the agreement between RARS and the ARS measures of the RTRRMSs is not as good as the agreement between the RTRRMSs themselves. In part, this reflects the fact that the RTRRMSs made repeated measurements that were averaged to reduce random error, whereas most of the profiles on unpaved roads were measured just once with rod and level. Given the repeatability associated with profile measurement on site lengths of 320 m (Figure 7), it may be that this correlation cannot be improved much without repeating the profile measurements, and/or using longer section lengths. (Since both options are relatively easy to do with a profilometer, they should be considered when a profilometer is used to calibrate a RTRRMS.)

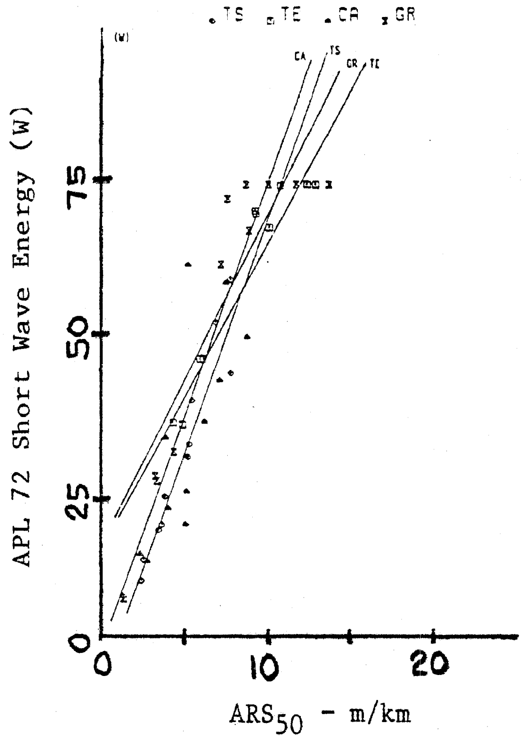
Further correlation information for the RARS standard is included in Appendix F, including example calibration plots for three of the other RTRRMSs.

QI_r. The QI roughness scale provides a single roughness rating for any given section of road, and as a consequence, there is a "best" speed that should be used by RTRRMSs whose measurements are calibrated to this scale. The best of the four test speeds used in the IRRE is 50 km/h. An example correlation plot is shown in Figure 11.

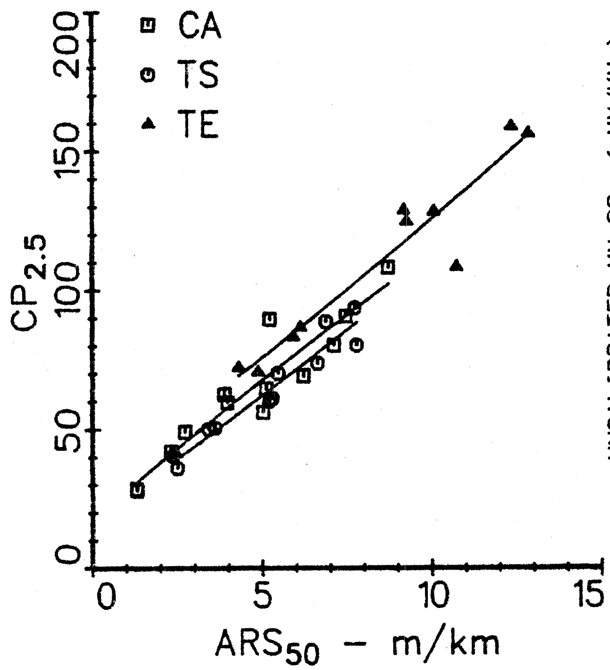
Given that QI was originally based on a QCS with a simulation speed of 55



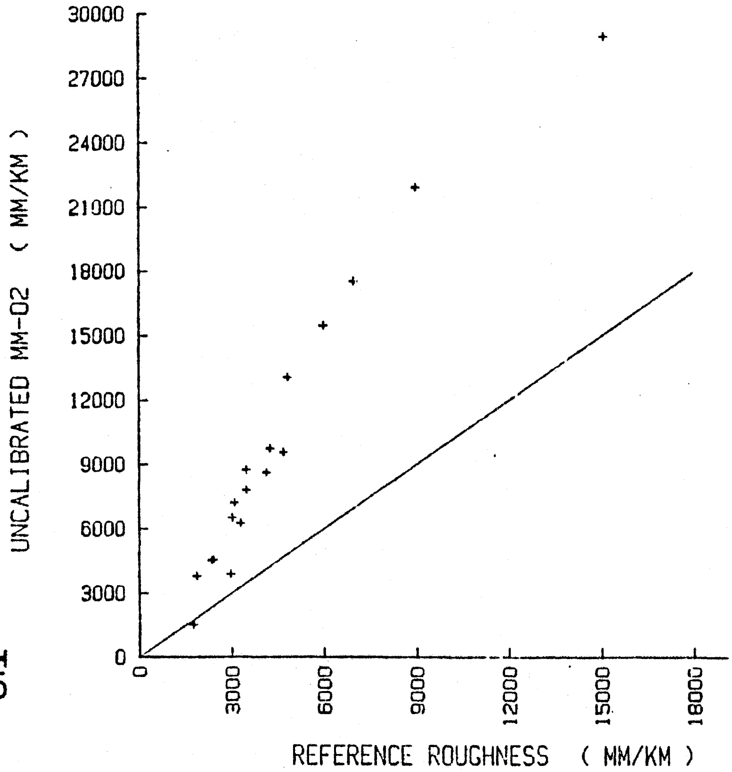
a. QI_r



b. APL 72 Short Wave Energy (W)
(200 m sections)



c. APL 72 $CP_{2.5}$



d. RMSD reference "mm/km"

Figure 11. Example Calibration plots for four profile-based numerics and one RTRRMS operated at 50 km/h.

km/h (see Appendix E for details), it is not completely unexpected that 50 km/h is the best RTRRMS speed for estimating QI_r. Yet, in light of the finding that QI_r is nearly the same as the $RARS_{80}$ numeric, it is surprising that the best correlation is not obtained at 80 km/h. The problem with the correlation at 80 km/h is the presence of several "outliers," including the four surface treatment (TS) sites described above that had the 2 m periodicity. Without these "outliers," the correlation is about the same at 50 and 80 km/h.

At all speeds, the surface type biases the calibrated measure that would be obtained using QI_r as the reference. On asphaltic concrete (CA) sites, the QI_r numerics tend to be higher than would be predicted, while on surface treatment sites, the QI_r values tend to be lower. At 50 km/h, this bias is minimized, but is still noticeable. The reason is that the QI_r analysis has its maximum sensitivity at wavenumbers near 0.3 cycle/m (Figure 6b), where the surface treatment sites have relatively little roughness (Figure 5b).

Even with the surface type bias, the correlations observed between QI_r and the ARS measures are quite good at 50 km/h, and would also be good at 80 km/h if the "outliers" were eliminated by using vehicles with higher damping. More example calibration plots and correlation data are included in Appendix E.

Appendix E also describes the calibration procedures used in the ICR project, to obtain the calibrated RTRRMS measurement called QI^*. The QI^* method is shown to be invalid for general use with arbitrary RTRRMSs, because it depends in part on the response properties of the vehicle portion of the RTRRMS and is effective only for carefully maintained Opala passenger cars (as they existed during the ICR project). The QI_r and QI^* roughness scales are shown to match only for the asphaltic concrete sites: on the other three surface types, the two are not equivalent.

CAPL 25. The relationship between the CAPL 25 numeric and the RTRRMS measures is strongly dependent on surface type, and good correlations are found only on the asphaltic concrete (CA) surfaces. Because the CAPL treatment is an amplitude analysis of wavenumbers between .07 and 3 cycle/m (wavelengths between .3 and 15 m), it is dominated by the lower wavenumbers where only the CA surfaces have significant content.

LCPC APL 72 Wave Band Numerics. The best correlations are seen for the short-wave numerics (W) and (Y). (The long-wave numerics are generally uncorrelated with the measures of the RTRRMSs, except on the CA surfaces. The medium-wave numerics are correlated to some extent with the RTRRMS measures on three of the surface types, but not at all for the TS surfaces.) The short-wave index (I) has a problem in that the available roughness range is not sufficient to discriminate among the unpaved roads in the IRRE, most of which had an index value of 1 on a scale of 1 to 10. But when the short-wave energy (W) and equivalent displacement (Y) numerics were considered, very good correlations were obtained, as shown by the example in Figure 11b. The best correlations were found for a RTRRMS speed of 50 km/h. Appendix G presents the correlation data and several other example calibration plots using the short-wave energy (W) numeric.

APL 72 CP numerics. As with the LCPC numerics, the highest correlations were observed for the short-wave numeric, $CP_{2.5}$. When the medium-wave numeric, CP_{10}, was used, the surface treatment (TS) data points fell well below the regression lines. However, when $CP_{2.5}$ was considered, no surface effect was noticeable when the RTRRMS speed was either 32 or 50 km/h. (Separate regressions were needed for the two speeds, of course.) The best correlations were found for a speed of 50 km/h. Figure 11c shows an example calibration plot using $CP_{2.5}$ as the reference.

Of the APL analyses normally used in Europe, the $CP_{2.5}$ numeric produces the best correlations with the RTRRMSs. It is possible that even better correlations could be obtained by optimizing the baselength parameter, as TRRL did in developing the RMSD "mm/km" numeric. When the objective is calibrating a RTRRMS, or providing a numeric similar to that of a RTRRMS, the RARS numerics can be computed directly from the APL signal, to obtain the best correlation possible.

RMSD "mm/km." The RMSD-based "mm/km" numeric was developed for optimum correlation with the IRRE data and shows correlation with the ARS_{32} measures that is virtually identical to that obtained with $RARS_{32}$. Figure 11d shows an example. The form of the RMSD analysis is ideally suited to the

TRRL Beam, and is probably the most convenient calibration statistic that can be used when the Beam is used to measure profile. Due to the fact that RMSD was derived empirically using the IRRE data, care must be taken not to apply the RMSD on surface types that are distinctly different than those covered in the IRRE. Although it is optimized for a RTRRMS speed of 32 km/h, excellent correlations are seen for the speed of 20 and 50 km/h as well. Appendix H includes more correlation data, as well as the results from a second experiment conducted by TRRL in St. Lucia to validate the RMSD calibration.

Calibration Requirements

The correlations observed between the ARS measures obtained from different RTRRMSs and between ARS and the profile-based numerics indicate the calibration requirements needed for a RTRRMS:

1) Measurement speed must be standardized, and matched to the profile-based numeric to maximize correlation.

2) The calibration sites should be selected to cover the total range of roughness that will be measured with the RTRRMS. Extrapolation can lead to errors of 100% or more.

3) Each approximate roughness level should be equally represented.

4) Separate calibrations should be provided for each surface type. If the different surface types are equally represented at each level of roughness, then the effects of surface type can be noted, and a single aggregate calibration can be considered if the bias with surface type is negligible.

5) The calibration equation should be computed by regressing the reference measures against the direct RTRRMS measures, using a simple least-squares error minimization. Transformations of the variables (log, square root, etc.) alter the error weighting and should not be used. (The need for transformations of the variables should be eliminated by selecting a reference closely matched to the

RTRRMS.)

6) Due to nonlinearities of vehicles and roadmeters, a linear regression model may not be adequate when wide ranges of roughness are covered. A quadratic regression model is suggested of the form:

$$y = A + B\ ARS + C\ ARS^2$$

Where A, B, and C are determined to minimize the mean-square difference between y and the reference measures. If the curvature is small, than a linear regression model (C = 0) can be used for simplicity.

Comparison of Subjective Ratings with Roughness Measures

Road roughness has long been thought of as the primary factor influencing the public opinion of road quality, which is largely dependent on perceived ride quality. The Pavement Serviceability Rating (PSR) developed for AASHO for evaluating pavement condition was found to be most highly correlated with "roughness" as it was then measured, and the conceptual linking between user opinion and roughness has remained today [31]. Although there are now cases in which roughness data are used for other objectives in the management of a road network system, "rideability" as perceived by the public is always an important factor. The subjective rating (SR) survey is described in Appendix D.

In determining the SR for each road section, the ratings for each member were normalized by subtracting the mean value and dividing by the standard deviation calculated for that member. Therefore, the final SR scale is scaled in terms of "standard deviations" for the 49 test sections, and has no absolute physical meaning. These SR numerics cannot be used to assign absolute roughness numerics to the test sections, but instead are used to rank them in order, from smoothest to roughest, and to show the correlations between SR and various objective roughness measures. Figure 12 shows four scatter plots of SR against some of the objective measures obtained. (More plots are included in Appendix D.)

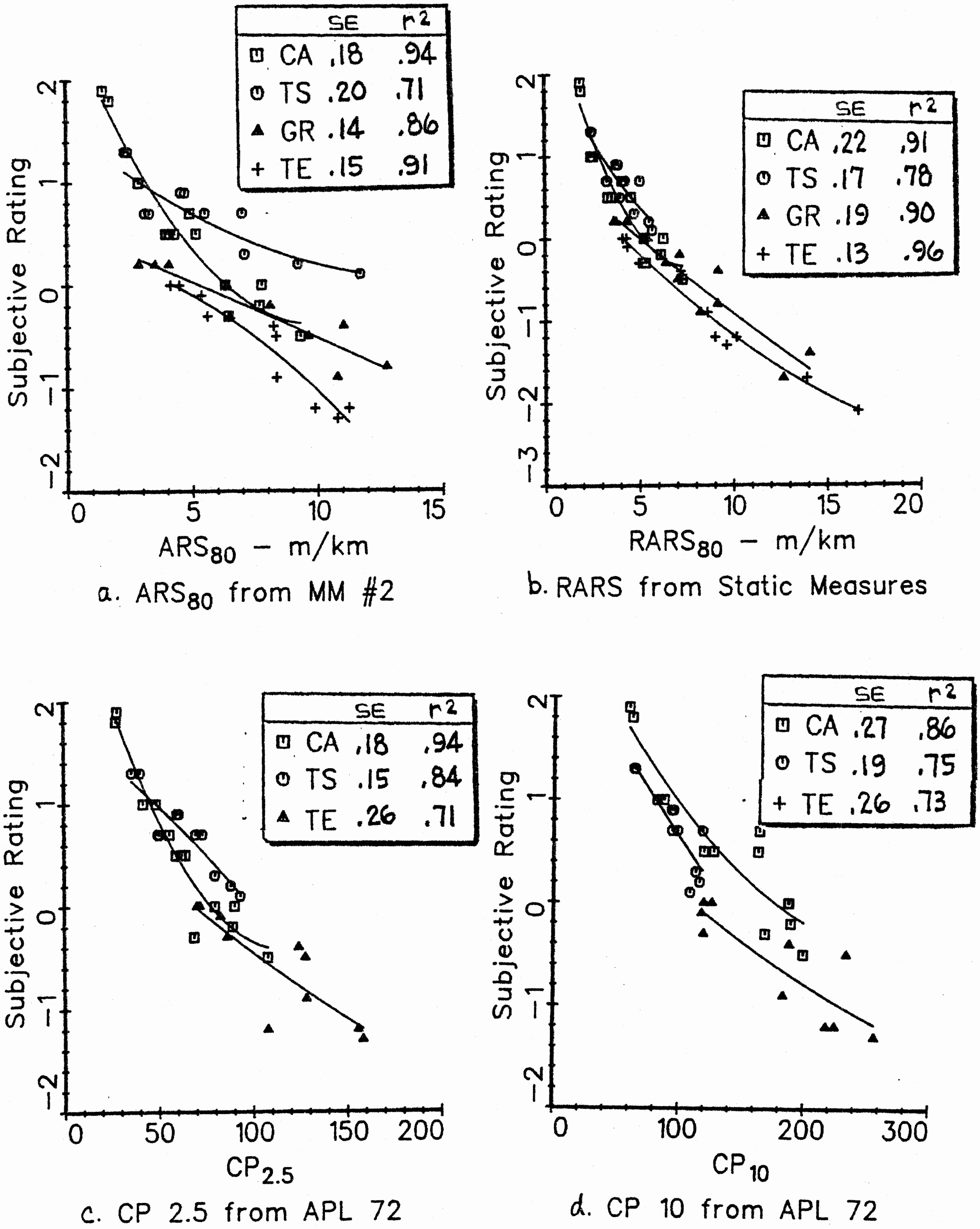


Figure 12. Comparison of subjective panel ratings with profile-based numerics.

The relationships between the objective measures and the normalized SR numerics were seldom linear, and the quadratic regression form that is used throughout this report appears to be necessary for computing correlations that are meaningful.

The profile-based numerics $RARS_{50}$, $RARS_{80}$, and QI_r (similar to $RARS_{80}$) show the most consistent relationship with SR, even more so than the ARS measures obtained from the Opala-Maysmeter RTRRMS used to transport the raters. (Compare Figs. 12a and 12b.) Good correlations are also obtained with the other profile-based numerics that correlate well with ARS. Figures 12c and 12d show that $CP_{2.5}$, which showed the highest correlation of any of the APL numerics with ARS measurements, is also a better predictor of SR than the medium-wave CP_{10} numeric. The surface treatment (TS) sites which had periodicities that influenced the ARS_{80} measures appear as outliers when ARS_{80} measures are compared to any other roughness numeric, but not when SR is compared to the profile-based roughness measures. On these sites, the profile-based numerics represent "rideability" better than the RTRRMS. (The 11 Hz vibration is typically one of the axle, and although it is sensed by a roadmeter, the passenger is mostly isolated from it.)

CHAPTER 4

SELECTION OF AN INTERNATIONAL ROUGHNESS INDEX

The International Road Roughness Experiment (IRRE) was motivated by the present difficulties in exchanging roughness information at the international level. While some exchange of roughness data can be made by using empirical "conversions" between various measures, a far better long-term solution is to adopt a single roughness scale that can be used when data exchange is anticipated. This chapter applies the findings of the IRRE towards the selection of a single International Roughness Index (IRI) that can be used in future projects, and the defining of the important variables in its measurement.

Criteria for an International Roughness Index (IRI)

The criteria for the IRI that were summarized in the introduction to this report are discussed below.

Time Stable. The IRI should be defined by a roughness numeric that will not change with time. It must be valid on any road surface type, and cover all levels of roughness.

To achieve this goal it is the consensus of most practitioners and researchers that the IRI must be defined by a mathematical function of the longitudinal profile of the road. That mathematical function then establishes a precise standard roughness value for any road. Historically, panel ratings provided the first standard for roughness, but there are no means to prevent subjective judgements from changing with time. For example, the PSR roughness scale used in the AASHO experiment [31], which served as a model of "true roughness" for many of the roughness scales used by agencies within the United States, has no direct physical interpretation. Although many of the state highway agencies estimate PSR, the numerics from different agencies are not equivalent [9]. Attempts to standardize a roughness scale to a specific piece of hardware (either in the form of a synthesized roughness such as the TRRL pipe course, or a roughness measurement instrument) have never been completely successful because of the complexity of road roughness.

Transportable. To be truly transportable the IRI should be compatible with road profile measurement methods available in all parts of the world. In particular, it should be compatible with manual methods for obtaining profile (rod and level, TRRL Beam), and also be suited for present and future high-speed profilometers.

Relevant. While recognizing that the IRI will represent a compromise, it should nonetheless be a meaningful measure of roughness that reflects road condition as it affects the public using it, in terms of vehicle operating costs, ride quality, and safety.

Without question, the most popular instrument used to measure roughness throughout the world today is the response-type road roughness measuring system (RTRRMS). When operating as intended, i.e., without instrumentation error, nearly all roadmeters used in RTRRMSs are capable of obtaining a measure of accumulated suspension motion, called average rectified slope (ARS), which is relevant to the road condition as it affects vehicle response.

When operated under the same conditions, the measures from any two different RTRRMSs were shown in the IRRE to be so highly correlated that the standard error remaining after a regression is sometimes within the repeatability associated with the individual instruments. The poor correlations that are often reported between different RTRRMSs were seen to be caused more by differences in procedure, rather than the equipment. Thus, the IRI must be defined in consonance with specification of proper RTRRMS operating procedure.

When RTRRMS operating procedure is standardized, the measures are seen to be highly correlated, even though the vehicles may appear to have little in common. Even though vehicles appear outwardly much different, or are disparate in size, the dynamic properties are only slightly affected [32].

When all of the cosmetic differences are overlooked, the selection of the IRI must deal with only two fundamental characteristics of RTRRMSs:

1) Operating speed
2) Whether the RTRRMS runs over a single track or two tracks.

Valid. The procedures use to measure the IRI must ensure that methods used with different pieces of hardware will result in approximately the same measured roughness numeric when applied to the same road. For profilometric methods, this means that the measurement method must be adequate for the analysis applied. For RTRRMS measurements, a calibration method must be used that rescales the measures so that, on the average, they are no higher or lower than the reference over all combinations of roughness, surface type, and speed for which they will be used. The IRI definition can be tested against the data obtained in the IRRE.

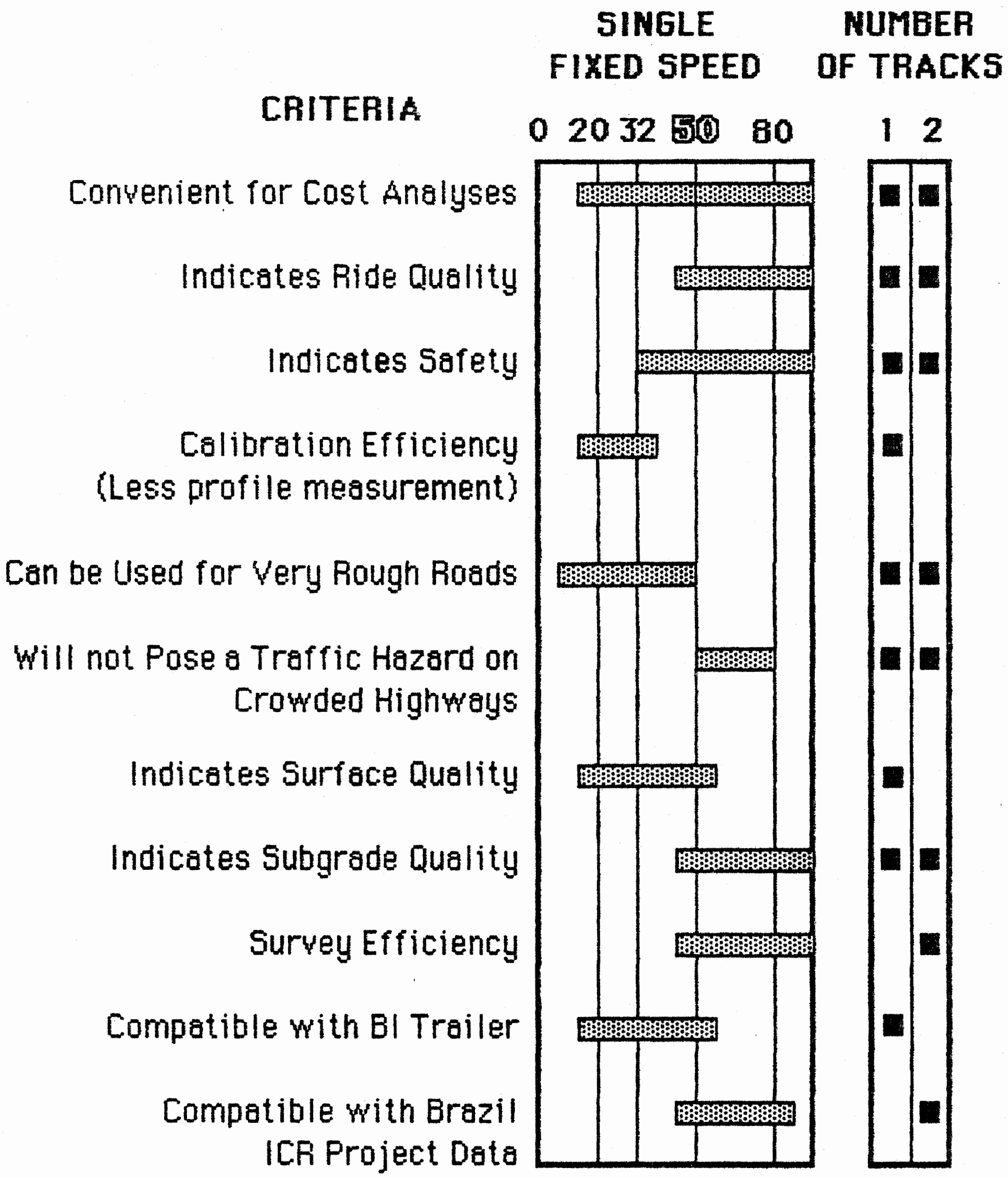
Definition of the IRI

Choice of RTRRMS speed. On any particular road the roughness level measured by a RTRRMS will depend on the test speed. The "best" speed for testing depends on local circumstances and the end use of the data. The fact that roughness varies with speed implies that a standard speed must be selected as a reference point for establishing the IRI.

Table 1 lists the speeds most commonly used and their relationship to factors important to the selection of the IRI. The speed range covered by the bars carries the interpretation that any fixed speed within that range would be acceptable. In general, the testing in the IRRE covered all four of the listed speeds.

The Table visually indicates that the speed of 50 km/h satisfies the broadest range of factors, and is therefore the most relevant and convenient. From the standpoint of road-user cost studies, where roughness is treated as a fixed geometric property of the road and traffic speed is included as a separate variable, the median speed represented by 50 km/h is very reasonable. Measurements at this speed are correlated well to the 32km/h speed of the BI Trailer reference standard used in many past road-user cost studies, as well as the 50 and 80 km/h test speeds used in the Brazil ICR project.

Table 1. Choice of standard RTRRMS vehicle type and measurement speed.



As far as roughness impacts on road-using vehicles in other ways, specifically the vibrations affecting rideability and safety, the roughness observed at the prevailing traffic speed is the most appropriate measure [4, 9]. This is most acutely evident, for example, when examining the road damaging dynamic loads under a vehicle's tires [34]. For these purposes a roughness measurement at 50 km/h is reasonable for ranking roads, so long as the practitioner is aware that different traffic speeds will influence the severity of these effects.

The only factors that argue for a lower test speed are calibration efficiency and the occasional concern for testing safety on roads that are very rough or restricted. Shorter calibration sites can be used with lower speeds reducing the effort when manually measuring profiles. Yet, this is not recommended because the envelopment properties of pneumatic tires play an ever more important role as speeds decrease, adding one more variable to RTRRMS performance. With regard to the concern that 50 km/h might be unsafe on very poor roads, it was found that even the very roughest sites included in the IRRE could be measured by most equipment at a speed of 50 km/h. Though restrictive geometry or congested traffic may make testing at 50 km/h difficult at some times, it would be more often true that a lower speed would seriously compromise the surveying efficiency that is a major advantage in the use of RTRRMS equipment, and pose a hazard when used on highways where the median speed is generally higher han 80 km/h.

It should also be noted that the RTRRMS speed of 50 km/h represents the best choice for roughness measures indicative of surface and subgrade condition. The correlations obtained in the IRRE with the short-wave, medium-wave, and long-wave numerics used by LCPC and CRR indicate that the RTRRMS measurements primarily reflect the short-wave numerics at speeds of 50 km/h and less. The waveband seen by a RTRRMS varies with speed for speeds higher than 32 km/h (approximately). However, for lower speeds, the RTRRMS does not detect ever shorter wavelengths due to the enveloping characteristics of the pneumatic tires [9]. Although the waveband sensed by a RTRRMS is so broad that the ARS measures reflect both the short-wave surface quality and the longer-wave subgrade quality, the longer-wave condition is seen more completely by the RTRRMS at the higher speeds indicated in the chart.

Single or two-track RTRRMS. In addition to the choice of measurement speed, there is also the matter of whether a single-track or two-track RTRRMS should be used. The measures obtained are not completely equivalent because portions of the roughness in the two wheeltracks excite only roll motions of the axle that are not sensed by the roadmeter in a two-track RTRRMS. Yet these variations are included in the measure obtained with a single-track RTRRMS. The vehicle vibrations that affect user cost, ride quality, and tire loading (safety), involve motions that are not sensed perfectly by either single-track RTRRMSs nor two-track RTRRMSs and therefore, most of the above criteria do not support one choice over the other.

A single-track RTRRMS has the advantage of requiring less profile measurement for calibration (since two-track RTRRMSs require the measurement of both wheeltrack profiles for any site). It also provides more detailed information about the pavement condition, by providing separate numerics for individual wheeltracks. When summary roughness measures are desired for the travelled lanes in a road network, a two-track RTRRMS is preferable because it obtains the information in a single pass, whereas a single-track RTRRMS must make one pass for each wheeltrack.

Because the single-track RTRRMS is more versatile, and can be used to obtain the same numeric for a travelled lane as a two-track system, it is selected as a basis for the IRI. That is, the IRI should be a roughness measure for a single wheeltrack, rather than a travelled lane. With this definition, both travelled lanes and wheeltracks can be characterized using the same scale.

Selection of a Calibration Reference.

Table 2 summarizes the qualifications of the roughness measures that have been proposed as calibration standards for RTRRMSs. Only those numerics that are well known, and which are the most compatible (correlated) with the ARS_{50} measures obtained from RTRRMSs are listed. (Therefore, neither the CAPL 25 numeric and the APL medium and long wave numerics are included, nor are the half-car simulation and RARS numerics that are not appropriate for a

Table 2. Choice of standard profile-based roughness definition for the IRI

	Subj. Rating (PSR)	Std. Hardware	PROFILE-BASED MEASURES				
			$RARS_{50}$	QI_r	RMSD	APL 72 SW (W)	$CP_{2.5}$
Time Stable			✓	✓	✓	✓	✓
Transportable			✓	✓	✓		✓
Valid for: Rod & Level (500 mm intervals)			✓	✓			
TRRL Beam			✓	✓	✓		✓
APL Trailer			✓			✓	✓
Physical Meaning	Public Opinion	Instrument Response	1. Profile Slope* 2. Ref. RTRRMS		BI Trailer 1982 (Approx.)	Mean Square disp.*	Ave. Rect. disp.*
Correlation with RTRRMS at 50 km/h	Good	Varies with instrument	Excellent	Excellent	Excellent	Very Good	Excellent
Present and Past Usage	AASHO Road Test, New York	BPR Rough, BI Trailer, NAASRA, others	NCHRP 228, Ohio, W.Virginia, Minnesota, Projects in USA	ICR Project, Brazil, Bolivia, S. Africa	IRRE, Past TRRL projects (approx.)	France, Int'l Projects	Belgium

*Indicates filtered profile

standardized single-track RTRRMS and speed of 50 km/h. The CHLOE profilometer is also omitted because it has been shown repeatedly to be poorly correlated to RTRRMS measures [8, 9].)

The choice for an IRI calibration reference that has the broadest application is the $RARS_{50}$ numeric. It can be measured with any of the profilometer methods included in the IRRE, including rod and level measures made at 500 mm intervals. It is correlated with the ARS_{50} measures obtained with all of the RTRRMSs as well as any of the profile-based numerics (better than all but RMSD). It is also an easy numeric to understand because: 1) it describes a simple profile characteristic (slope) and 2) it is a standardized RTRRMS.

Although it is selected on its technical merits, the $RARS_{50}$ numeric would be a reasonable choice based on present usage. RARS is the profile-based numeric that is emulated by the majority of roughness measurement equipment (primarily RTRRMS) used in the world today. Even the technically more sophisticated GMR-type profilometers made by K.J. Law, Inc. have been equipped with either the QCS or HCS implementation of the RARS computation since the late 1960's. Among the other established roughness statistics that have been developed, the most common goal has been to relate as closely as possible to RTRRMS response to road roughness, usually by establishing correlations and using regression equations to accomplish what the RARS does directly. (It is a standardized RTRRMS.)

Important points that should be noted with regard to the other numerics included in Table 2 are discussed briefly below.

Subjective Ratings. Subjective panel ratings are rejected as a standard not only because they are relatively slow and expensive, but also are not stable with time.

Standard Hardware. Although standardization of hardware has been attempted many times, this approach has yet to be demonstrated in practice. It also has a conceptual ambiguity: in order to be assured that the properties of the hardware do not change (that it is time stable), a test procedure is needed to quantify its properties and correct them. This test procedure becomes the "true" standard, rather than the hardware.

QI_r. The correlations between QI_r and the ARS_{50} measures from the RTRRMSs were nearly as good as for the $RARS_{50}$ numeric, and the QI_r computational simplicity may be appealing to some. Yet, the computational simplicity has a cost in terms of compatibility with alternate profile measurement methods and correlation with RTRRMSs.

Due to limitations in the waveband response of the APL, QI_r cannot be computed from the defining equations using the profile signals measured directly by the APL Trailer. At best, it can only be estimated using an alternative computation method devised by LCPC. This illustrates an undesirable conceptual characteristic of the QI scale, which is that it does not describe any simple property of profile and actually has a negative value for a perfectly smooth road. As such, there is not an obvious methodology that can be applied when measurement problems are encountered or when road surface conditions are encountered for which the QI_r measures indicate roughness differently than a RTRRMS operated at 50 km/h. A hint of this problem is seen in the IRRE results by the tendency of QI_r numerics to be higher for asphaltic concrete roads than for surface treatment roads, relative to ARS_{50} measures. With continued development of the QI scale, it is possible that an additional waveband component will be required to correct for this anomaly.

Although the QI scale was used in a major cost study, the IRRE data show that the QI_r scale is not equivalent to the QI^* measures (used in the ICP project cost equations) on three of the four surface types included in the IRRE. If it were to be used as a calibration standard, the "new" QI obtained by calibration of a RTRRMS to the QI_r scale would not be equivalent to the "old" QI^* of the historical data base.

Because the QI_r scale is very close to the $RARS_{80}$ scale, the $RARS_{80}$ numeric can be used when compatibility with QI data from the ICR project is needed. ($RARS_{80}$ can be measured directly by a wider range of profilometric methods.) While this is not exactly equivalent to the $RARS_{50}$ numeric selected as the IRI, it is a simple variation: the standardized RTRRMS measurement at the (nonstandard) speed of 80 km/h.

RMSD "mm/km." The correlations between RMSD and several of the RTRRMSs equalled the correlations obtained with $RARS_{50}$, although this finding must be viewed with the understanding that the analysis was limited to data acquired in the IRRE, and then only a portion of that data was used. Being fine-tuned for measurement with the TRRL Beam, the RMSD computation is not as well suited to alternate profilometric methods. It has not been demonstrated that RMSD can be obtained directly with the APL Trailer, and the required 300 mm sample interval precludes applying the analysis to the rod and level data.

The RMSD "mm/km" numeric is similar to the QI_r numeric in that it does not describe a simple profile characteristic, being essentially a numeric that correlates well with other measures and has been scaled to yield the ARS-type of measure computed directly by the RQCS. Because the RMSD numeric is rescaled to a "reference" defined by the BI Trailer, there is a potential for further evolution of the RMSD scale if the measures from a BI Trailer correlate poorly with RMSD on a road type not included in the IRRE (for example, corrugated unpaved roads).

The good results obtained with the RMSD analysis indicate that it is a useful and convenient roughness numeric, particularly when measured with the TRRL Beam. Yet the actual reference is the BI Trailer (a specific piece of hardware), rather than the RMSD numeric itself. The BI Trailer ARS measures, the RMSD numeric, and the $RARS_{50}$ numeric were all highly correlated for the data collected in the IRRE, and therefore, the reference defined by the BI Trailer can be estimated from $RARS_{50}$ as well as by RMSD. ($RARS_{32}$ is also highly correlated.) That is, the $RARS_{50}$ numeric can be used with other profilometer methods to determine the "mm/km" roughness with the same accuracy as with RMSD. Also, the RMSD numerics can be rescaled to $RARS_{50}$ as well as to BI "mm/km," so that the RMSD analysis can be used to estimate a more rigorously defined reference.

APL Short-Wave "Energy" (W). The measurement requirements for this numeric have not been determined for rod and level measurement, as it has only been used with analog profile signals. Thus, it is not as completely developed as the other numerics. The correlations with ARS_{50} are not as high as those obtained with $RARS_{50}$, so estimates of (W) based on RTRRMS measures would be less accurate then estimates of $RARS_{50}$.

APL $CP_{2.5}$. The CP analysis has several advantages. The moving average concept is easily visualized and relates to a property of the profile, so that there is no ambiguity as to its meaning. It can be measured with a variety of profilometric methods, and does not have specific requirements as to sample interval. The $CP_{2.5}$ measures are correlated with the ARS_{50} measures obtained from RTRRMSs, and the relationships appear to be unaffected by surface type. $CP_{2.5}$ was not selected as the IRI because: 1) the correlations with ARS_{50} are not as good as with $RARS_{50}$, which implies less accuracy when calibrated RTRRMSs are used and 2) the $CP_{2.5}$ analysis requires a fairly small measurement interval. The details concerning measurement requirements were not investigated as thoroughly as for $RARS_{50}$, but it was determined that a 500 mm interval is not adequate.

Classification of Measurement Methods

Having defined an IRI, it is appropriate at this point to define the classes of methods for its measurement in terms of accuracy. The many potential methods, including those demonstrated in the IRRE, are divided into four classifications, each pertaining to a different conceptual approach. A wide range of instrumentation can be used within each class, with better accuracy being obtainable with better instrumentation.

Class 1: Direct Measurement of $RARS_{50}$. Methods in this class are the best that can be obtained, and require a measurement of profile that is of such high quality that no change in the $RARS_{50}$ numeric could be observed with improvements. For static (manual) measurement of profile, the interval between measurements should be sufficiently small to "capture" all roughness features that affect the $RARS_{50}$ numeric. For most surface types, an interval of 250 mm is acceptable: further decreases in the sample interval (down to zero) will not affect the $RARS_{50}$ value computed. If a surface has obvious isolated "bumps" that would be poorly represented by samples at 250 mm (patches, tar strips, etc.), then a shorter interval should be used. The 500 mm interval used in the IRRE for rod and level measures does introduce some random error, and thus this interval does not qualify as "class 1."

The required precision of the elevation measures depends on the roughness level, and is approximately equal to $RARS_{50}/3$, where $RARS_{50}$ has units "m/km" and the precision has units of mm. Better precision does not improve the quality of the measurement.

Even with zero measurement error, there is a certain amount of imprecision associated with measuring road roughness that is caused by variations in selection of the exact wheeltrack to be profiled. The replicate measures made in the IRRE indicate that the normal uncertainty in a $RARS_{50}$ measure appears to be several percent for the 320 m section lengths used. It is expected that less variation should be obtainable with longer sections, while more uncertainty would be expected for shorter sections.

To maintain a rigorous concept of "true" roughness, the results of the IRRE are used to specify a measurement quality for static measures that goes beyond the quality used for most of the measures in the IRRE. Only the TRRL Beam data and six of the rod and level measures would be considered "class 1," and even these exclude the smoothest three sites, where better precision can now be recommended. This is to ensure that the methods used to obtain true $RARS_{50}$ roughness have the accuracy that should be associated with a standard.

When profile measurements are obtained with a dynamic profilometer, the frequency response should be adequate to cover the wavelength range from 0.5 - 20 m, within an accuracy of several percent. Although the APL Trailer qualifies on paper, the measures obtained in the IRRE showed more random effects than the static measures; hence the APL Trailer does not qualify at this time as a Class 1 measurement. It is possible that refining the measurement procedures specific to the APL Profilometer could improve the agreement between $RARS_{50}$ measures from the trailer and from static profile measures, such that the APL Trailer (or other high-speed profilometers) would qualify as "class 1" methods in the future. This is simple to demonstrate, requiring that several sites covering the range of conditions (roughness, surface type) be measured by the profilometer and also by static methods.

Appendix F provides a thorough background of the measurement requirements for $RARS_{50}$. Step-by-step instructions for its measurement have also been prepared for use by practitioners [35].

Class 2: Estimation of $RARS_{50}$ Using an Independently Calibrated Instrument. This class includes all methods which may be considered time stable, by using an independent laboratory-type calibration of the instrumentation, but which are not directly capable of measuring $RARS_{50}$. This could be simply a case of a profile measurement method that does not have the accuracy or repeatability required for a "class 1" measurement, or it could be a case where the instrumentation produces a numeric other than $RARS_{50}$ that is highly correlated with $RARS_{50}$. In the second case, the measures obtained can be related to $RARS_{50}$ through a regression equation derived for certain conditions.

The measures of $RARS_{50}$ computed from the profiles taken by rod and level at 500 mm intervals are "Class 2" numerics, as are the APL 72 measures. (Even though both methods are in the same class, the rod and level measures were shown to be much more accurate.)

Use of the RMSD numeric to estimate $RARS_{50}$ using the TRRL Beam and Eq. 7 is also a "Class 2" method.

Virtually every profile-based statistic also falls within this class, including $CP_{2.5}$, APL 72 short-wave energy (W) and QI_r. In most cases, there is no advantage in using one of these statistics to estimate $RARS_{50}$, since $RARS_{50}$ can be estimated from a profile-type signal by simply applying the $RARS_{50}$ computation method. However, when the actual profiles used to compute summary statistics are no longer available, $RARS_{50}$ can be estimated using correlated statistics. While equations could be developed to estimate $RARS_{50}$ from **any** profile statistic, some are so incompatible with $RARS_{50}$ that there is little purpose (i.e., CAPL 25, CHLOE Slope Variance, APL 72 long wave energy (W)).

Methods for estimating $RARS_{50}$ that fall within this class should be validated for a particular type of road and roughness range through regression with $RARS_{50}$ as measured with a Class 1 method. Since the Class 2 methods are stable with time, this "calibration by correlation" only needs to be performed once for a set of roughness and surface conditions.

Class 3: Measures that are Calibrated through Correlation. This class includes all methods for determining roughness for which the problem of time stability has not been solved, such as the RTRRMS. At the present time, most roughness measurements collected would fall within this class if calibrated to $RARS_{50}$. In order to estimate $RARS_{50}$, a calibration is needed which is performed on actual road surfaces, following the normal operating procedures used to measure roughness. The true $RARS_{50}$ values of the calibration sites are obtained using a Class 1 method if possible, or a Class 2 method if less accuracy is required.

The calibration requirements for a RTRRMS were discussed in Chapter 3, and have also been presented as step-by-step instructions intended for practitioners [35].

The QI^* measures obtained in the ICR were conceptually equivalent to a Class 3 measure for the asphaltic concrete roads, with the distinction that they were calibrated to the QI_r numeric at 80 km/h, rather than the $RARS_{50}$ numeric recommended here. Measures on other surface types are not equivalent to Class 3 numerics because the calibration was inadequate.

Class 4: Uncalibrated Roughness Measures. This class includes the roughness measures that do not fall within the previous classes. In order to relate measures to a standard scale such as $RARS_{50}$ without performing a calibration by correlation, it is necessary to make a number of assumptions that cannot be confirmed. Depending on the validity of those assumptions, a Class 4 measure might be related to an absolute roughness scale such as $RARS_{50}$ without much extra error, but there is no means to confirm this.

Most measurements made in the past with RTRRMSs fall within this class, including the "mm/km" measures made with the TRRL BI Trailer, and the QI^* measures on unpaved roads.

Demonstration of the IRI

The test for validity of a road roughness calibration method is to see whether instruments calibrated independently will produce the same measures for the same roads. To some extent, the data collected in the IRRE allow this kind of comparison. Figure 13 was prepared to show the quality of agreement that can be expected using calibrated RTRRMSs. Four combinations of equipment are represented in the figure.

1) The BI Trailer was calibrated against the TRRL Beam; i.e., the 28 $RARS_{50}$ measures from the Beam were regressed against the corresponding 28 ARS_{50} measures from the Trailer to determine a calibration equation. Then all 98 of the ARS_{50} measures from the BI Trailer were corrected to the $RARS_{50}$ scale using this equation.

2) One of the Opala-Maysmeter systems (MM #2) was calibrated against the rod and level. Using the same calibration method, the 49 ARS_{50} measures from MM #2 were rescaled to the $RARS_{50}$ scale. The calibration curve was shown in Figure 10c.

3) The APL 72 signals were processed to yield the $RARS_{50}$ numeric directly.

4) The Caravan-NAASRA system was calibrated against the APL 72 system. The APL measures of $RARS_{50}$ on 31 of the sites were regressed against the ARS_{50} measures of the NAASRA meter, and the resulting equation was used to rescale all 49 measures. This calibration does not include any gravel test sites, and the comparisons indicate the type of error that can be expected when aggregate calibration equations are used that do not include all surface types.

The figure shows the levels of agreement that can be realistically expected when comparing measurements from very different RTRRMSs that have been calibrated using very different profile measurement methods. In all three plots shown, the agreement is sufficient to exchange roughness information in general terms: over a range of 2 to 20 m/km, the largest difference is about 3 m/km, with reproducibility within 1 m/km more typical.

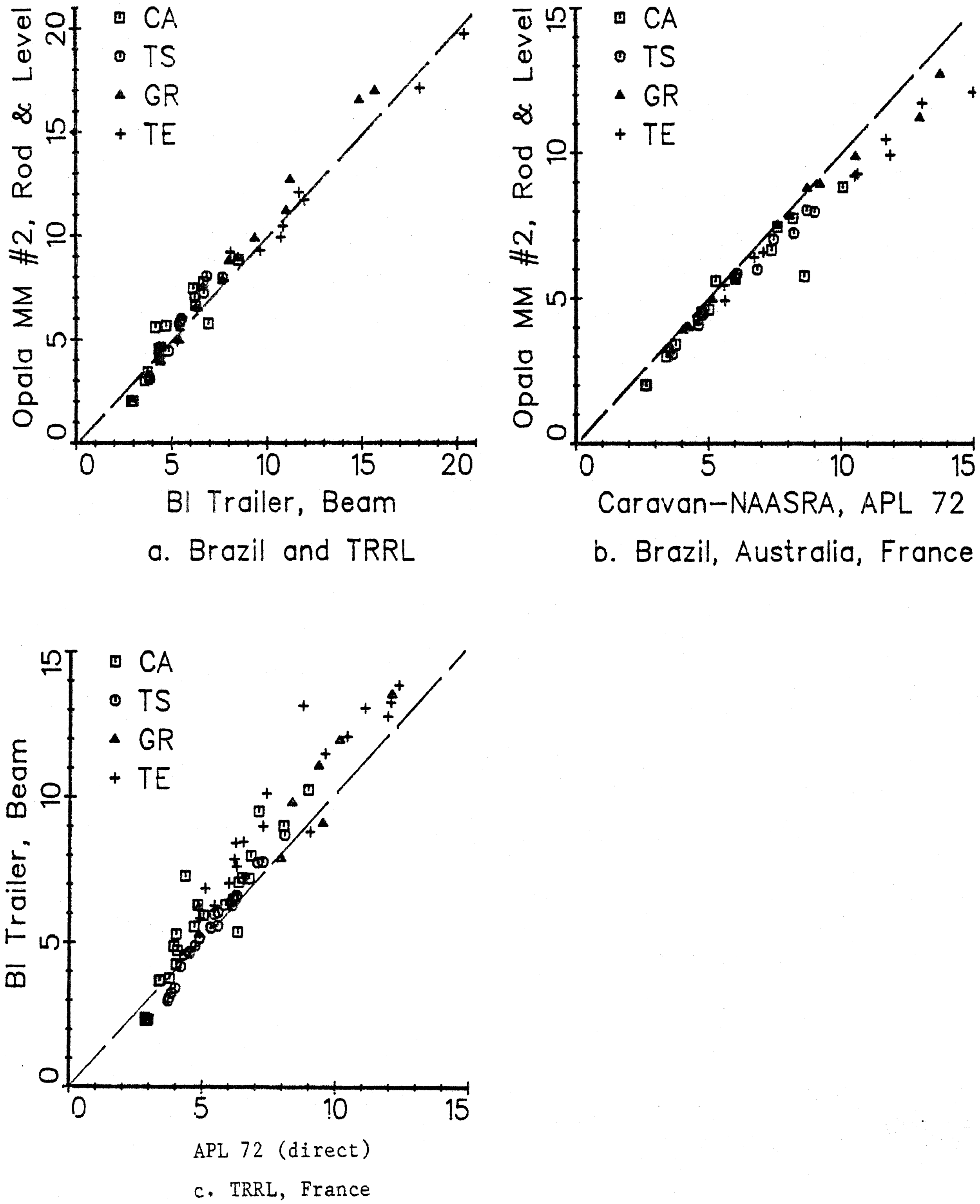


Figure 13. Examples of the agreement that is obtained using alternate measures of the IRI.

Figure 13a illustrates the good agreement obtained when RTRRMS calibrations include all four surface types. Figure 13b shows measures based on an incomplete calibration, lacking any of the gravel (GR) sites. While the agreement is still excellent on the smoother roads (paved), a bias is evident on the rougher unpaved roads, due to the limited number of rough sites included in the calibration. Even with this bias, the agreement is sufficient for most applications involving roughness data from different sources. Figure 13c shows that slightly greater scatter appears when single-track measures are compared, because the averaging involved in two-track measureents is missing.

These examples show errors that are larger than would be obtained by comparing each calibrated RTRRMS to the reference, because they are based on more limited data, independently measured by the very different profilometric methods.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The International Road Roughness Experiment (IRRE) brought together representative equipment and methodologies used throughout the world to characterize road roughness, resulting in a substantial data base of profile measurements, measures from response-type road roughness measuring systems (RTRRMSs), and subjective panel ratings. The data show the degree of correlation between different summary roughness numerics, and link the simple average rectified slope (ARS) measures from RTRRMSs to more extensive profile-based analyses. It also shows the similarities and differences in the a profile as measured statically and by a profilometer, and indicates which analyses of profile are compatible with the different measurement methods.

The IRRE constitutes a major step forward in facilitating the exchange of roughness data worldwide.

1) It has demonstrated that the roughness measures from diverse types of RTRRMSs are, in fact, compatible and can be compared when appropriate controls on their calibration and operation are observed.

2) It has demonstrated the link between RTRRMS measures and profile-based analyses, clearly defining the degree of equivalence with various profile measurement methods and various profile analysis methods.

3) It has provided a basis for rationally choosing an IRI to serve as a standard scale on which roughness properties of roadways may be quantified and communicated.

Findings from the IRRE that are of particular significance are presented under topical headings below.

Profile measurement. The completely manual rod and level method and the partly automated TRRL Beam gave results that were nearly interchangeable, other than the differences due to the selected sample interval. Although the profile signals obtained with the APL Trailer appear to have little in common when shown graphically with the statically measured profiles, spectral analyses and some of the roughness numerics validate the APL Trailer as a profiilometer over its design frequency bandwidth of 0.5 - 20 Hz. The two static measurement methods were validated over the entire roughness range covered in the IRRE, while the APL was able to cover all but the roughest sites at 72 km/h, and was able to measure all sites at a lower speed of 21.6 km/h. Although the APL Trailer is validated as a profilometer, the repeatability is not as good as with the static measures for the 320 m site length used in the IRRE.

RTRRMSs. There were four roadmeter designs represented in the IRRE, and all appeared to produce the ARS measure with approximate equivalence. Side-by-side comparisons with two roadmeters installed in the same vehicle gave measures that were nearly redundant. Only one of the roadmeters was an unmodified commercial instrument (the roadmeter in the BPR Roughometer), and it was the most fragile and least reliable. The others, developed or modified by TRRL, ARRB, and GEIPOT for their own use, were able to operate over the entire range of test conditions and produce valid measurements. All experienced some degree of trouble though, indicating that practitioners must be ever alert to the condition of the instrumentation.

There were also four types of vehicles used in the RTRRMSs, and the choice of vehicle was shown to be relatively unimportant except for ruggedness.

The conclusion regarding equipment is that both the vehicle and roadmeter should be chosen on the basis of robustness and convenience. When calibrated to a valid reference, cosmetic differences (whether the roadmeter is a Maysmeter, BI unit, or NAASRA meter; whether the vehicle is a sedan, station wagon, or a towed trailer) are negligible. (Naturally, earlier findings regarding the maintenance of the vehicle and roadmeter still apply: the test vehicle must be maintained more carefully than a routine transportation vehicle to ensure that its response properties remain as constant as possible.)

The good agreement between measurements from two RTRRMSs holds true only when they are operated at the same speed. When operated at different speeds, the relationships are influenced by surface type and roughness level, and degraded correlations are obtained.

It should be noted that the relationships between the Brazilian Maysmeters and the BI Trailer observed in the IRRE are only valid for that point in time, although other data available from the ICR project may be used to relate measurements backward in time. The same is not true for the NAASRA meter which was installed in the Caravan station-wagon for the experiment. Because of vehicle differences, the data acquired in the IRRE cannot be validly related to measurements in Australia by the ARRB.

The IRI. In order to define an IRI that can be measured with a RTRRMS, it is necessary to standardize the RTRRMS measurement procedure, and to find a profile-based numeric that is suitable for most profilometry techniques and which has maximum correlation with the RTRRMS measures. The consensus of the participants in the IRRE was that the IRI should reflect a single standard speed (rather than a traffic speed concept such as ARV), and that the speed of 50 km/h was the best choice for meeting the many criteria involved. A number of profile-based numerics were correlated against the ARS_{50} measures obtained from the RTRRMSs (where the subscript 50 indicates a measure made at 50 km/h), and the reference ARS_{50} ($RARS_{50}$) numeric computed with a simulated RTRRMS was shown to be the best choice in terms of accuracy and measurement flexibility.

Guidelines for measuring the $RARS_{50}$ roughness numeric are available [35], which describe the procedures for planning and operating programs for monitoring road roughness using the $RARS_{50}$ scale with RTRRMSs, calibrated to rod and level.

Other profile analyses. A number of other analyses are described and applied to the profiles measured in the IRRE. The power spectral density (PSD) function was computed and plotted for every measured profile, and Appendix I presents about 300 of these plots. This information provides a very detailed look at the roughness properties of both wheeltracks of every site in the IRRE. The plots show the actual differences between the surface types covered in the IRRE, and should be useful for many future applications in which details of road roughness are needed to test hypotheses and candidate analyses.

In addition to the PSD functions, the IRRE roads are characterized using the analyses applied by LCPC and CRR in Europe. Both agencies use waveband analyses (the APL 72 energy (W), equivalent amplitude (Y), Index (I), and coefficient of evenness CP) that also indicate the spectral content of the road, but using simpler numerics that are more suited for survey purposes than PSD functions. A simple numeric used for evaluating road quality during construction, the CAPL 25 numeric, was also provided for all of the IRRE sites, and several examples were shown illustrating how the CAPL 25 describes the heterogeneity of a road along its length.

Several profiles are also shown to demonstrate the diagnostic information that can be obtained using characterization methods more sophisticated than is possible with a RTRRMS-type of summary measure.

Other summary numerics that are presently used were also studied, and shown to be highly correlated with both the RTRRMS ARS measures and the profile-based RARS numerics. These include 1) QI_r, computed as the weighted sum of two RMSVA numerics and developed in Brazil for the rod and level profilometric method, 2) the APL 72 short wave energy (W), normally measured electronically in France using the APL 72 system, 3) $CP_{2.5}$, computed digitally in Belgium from the APL 72 signal using a moving average, and 4) RMSD, developed by TRRL for use with the Beam. The data from the IRRE have been used to demonstrate the correlation among these numerics, and can be used to tie into past measures made with these numerics.

Concluding remarks. The major questions that motivated the IRRE have been answered, and procedures have been demonstrated that allow the standardized measurement of roughness with a wide variety of equipment. Since the representation was by no means complete, other equipment and methods should also be investigated.

Other high-speed profilometers are in use, and newer designs are in development. Faced with the obvious problems of poor time-stability that can be seen with RTRRMS, the acquisition of a profilometer or other instrument that is stable with time at first appears to solve all of the problems. However profilometers will not generally be suited for all profile analyses. Therefore, the validity of profilometers should be demonstrated experimentally for every analysis used (including $RARS_{50}$) by direct comparison with rod and level.

As profilometric methods become more common, profile analyses can be developed that are specific to various applications. One measure might be used as a pavement condition index, while another could be used as a ride quality index. The various numerics used by LCPC and CRR already show this philosophy. As data become available indicating how qualities of a road can be best determined from a profile measurement, a number of profile analyses fine-tuned to specific applications should be considered for standardization.

The influence of site length on accuracy has not been investigated. As high-speed profilometers become more common, variations due to random effects such as the lateral positioning of the instrument in the travelled lane can be reduced by selecting longer standard lengths. When site lengths other than 320 m are used, the accuracy of the measurements (as characterized by reproducibility) should be determined.

In addition to the four surface types included in the IRRE, the RARS numeric has also been demonstrated to be valid for PCC roads [9]. Other surface types that have not been tested include roads constructed manually in developing countries, and unpaved roads with severe corrugations. Care should be taken when performing calibrations on these types of surfaces, and the procedures developed as a result of the IRRE [35] should be refined as necessary.

CHAPTER 6

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