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

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DRAFT REPORT TO WORLD BANK

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An International Road Roughness Experiment (IRRE) was conducted in Brazil in May-June 1982. The purposes were to examine the correlations between different road roughness measurement equipments in use throughout the world, and to identify a standard roughness measure (an International Roughness Index) as a basis for calibrating and comparing these roughness data. The IRRE was a cooperative effort initiated by the World Bank and conducted by researchers from Brazil, England, France, and the United States, with the additional participation of equipment from Australia. The Experiment involved evaluation of the roughness on a wide range of paved and unpaved roads. The roughness was measured at a number of speeds by seven Response-Type Road Roughness Measuring Systems (RTRMS). The longitudinal profiles were measured by a number of available methods to evaluate the profilometry techniques, and allow evaluation of various means for processing that information to analytically assign a roughness value to the surfaces. In addition, the road sites were evaluated subjectively by a rating panel for their roughness qualities.

The data obtained show that correlations between any two RTRMSs are excellent when they are operated at the same test speed, and that a single equation is adequate to relate readings among devices for all types of roads. Four candidate methods for analyzing the profile measures were tested as calibration references for RTRMSs, with various degrees of success. The best available method proved to be a suitable calibration reference for nearly all RTRMSs in use today, with the condition that separate calibrations be developed for certain road types.

17. Key Words
road roughness, road profile measurement, ride quality, roadmeters, serviceability, subjective rating, profile analysis

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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), and the British Transport and Road Research Laboratory (TRRL). The Australian Road Research Board (ARRB) and the Federal University of Rio de Janeiro (COPPE/UFRJ) provided roughness measuring equipment. The University of Michigan provided personnel and computer support through contract with the World Bank.

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CHAPTER 1
INTRODUCTION

Background

The roughness history of road surfaces has long been recognized as an important measure of road performance. As used in this report, the word "roughness" means the variations in surface elevation along a road that cause vibrations in traversing vehicles. By causing vehicle vibrations, roughness has a direct influence on ride comfort, safety, and vehicle wear [1]. In turn, the dynamic wheel loads produced are implicated as causative factors in roadway deterioration.

As a consequence, the characterization and measurement of road roughness is a major concern of highway engineering worldwide. As the highway networks in the United States and other developed countries near completion, the maintenance of sophisticated 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 the United States, ride comfort has been emphasized because it is the manifestation of roughness most evident to the public. This philosophy has resulted in the concept of Present Serviceability Rating [2] used broadly throughout the United States to judge road roughness quality.

In less developed countries, the same concerns face administrators from the very beginning; faced with limited resources, they must choose between quantity and quality in the development of public road systems. Optimizing road transport efficiency involves tradeoffs 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 [3], Brazil [4,5], Kenya [6], 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—that are also a consequence of roughness involve 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 profilometry or measurement of vehicle response to roughness. These latter measurement methods make use of an instrumented vehicle that produces a numeric that is a measure of the vehicle response to road roughness as the vehicle traverses the road at a constant test speed. The systems have acquired the name Response-Type Road Roughness Measuring Systems (RTRRMSs) and represent development from a practical approach to the problem without a thorough technical understanding. As a result, the relationship between different measurement methods is uncertain, as is also the relevancy to ride comfort or road-user costs. Nonetheless, most of currently popular instrumentation systems share a commonality in configuration and operation, and are in such widespread usage that drastic changes in measurement methodology are not imminent.

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 traveling speed, can be difficult to control. While great effort is spent limiting the variability of these other factors, there is growing agreement that some variation can 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 an empirical correlation of the RTRRMS with a reference measurement [7]. The calibration is performed by running the RTRRMS over a number of "control" road sections that have been concurrently measured by the reference method. Validity of the calibration is guaranteed by selecting control sections that cover the roughness range of interest for each surface type, and performing separate
calibrations for each combination of surface type and measurement speed. 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 wheel tracks traversed by the RTRRMS. It also requires a method for processing the profile data to yield a single roughness measure for the correlation.

Although there is general agreement worldwide that RTRRMSs provide useful and meaningful data, and that they must be calibrated to a reference, there is no consensus as to how they should be operated, and what calibration reference should be used. 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 adoption of a single Roughness Index (RI) 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 (TPR/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)). Each of these agencies has been responsible for obtaining and analyzing road roughness data in different parts of the world, using different methods and analyses [4,5,6,7,8,9].

The IRRE included the participation of a variety of equipment: seven RTRRMSs, two methods for directly measuring profile, and two vehicle-based profilometers. 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 of the Experiment

The project had three immediate objectives toward the ultimate goal of defining and validating a RI for all international use:

Objective 1: To establish the correlation between different RTRRMSs.

Different RTRRMS measures can be made somewhat "equivalent" through calibration. The IRRE should help determine the degree of equivalency between the measurements obtained by different systems, and the ranges of roughness, surface type, and operating speeds over which these equivalences are valid.

Objective 2: To evaluate profile-based roughness measures for the calibration of RTRRMSs.

Although there is agreement that profile measurement is needed to determine a RI for calibrating RTRRMSs, a number of analysis methods have been proposed to define RI. While they are generally unique, one aspect they all have in common is that they emphasize the roughness in only a portion of the wave number (wave number = 1/wavelength) range of the profile. Depending on the form of the analysis, the waveband selected may simulate the response of a vehicle (Quarter-Car Simulation, as developed for the NCHRP [7]); it may correspond to a waveband related to pavement features ("waveband analysis," as employed by LCPC in the APL 72 analysis [10]); or it may produce a statistic that has been empirically correlated with other measures (RMSVA [11,12]—used in Brazil and Texas—and QI [4,5]—the standard roughness scale in Brazil). Prior to the IRRE, none of the potential RI analyses had been demonstrated on unpaved roads.

Objective 3: To evaluate candidate profile measurement methods.

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 vehicle-based profilers may require the technical support that is only to be found in the more developed countries. In the past, specific analysis methods have been associated with particular measurement methods. There is a need to determine whether different measurement methods can provide acceptable accuracy for calibrating RTRRMSs to an international roughness standard. A major requirement of any "profilometer" system is that it is able to be calibrated independently, without resorting to correlations with another instrument that measures road roughness. Four profile measurement methods were employed in the IRRE: the rod and level survey method, the APL Trailer from LCPC, an experimental Beam device from TRRL, and a vehicle-mounted GMR Profilometer. At this time, the measurements have only been analyzed for the first three of these methods.

Report Organization

The main purpose of this report is to document the experiment and data. This involves describing the participating equipment, presenting the summary roughness numerics obtained from the RTRRMS, describing the subjective rating procedure, and presenting those candidate RI statistics that have been calculated from the profiles. Many of the descriptions are technical and detailed, and most of the data, needed for further analyses, will not be of interest to the average reader. Therefore, this main report is limited to an overview of the IRRE and the results of the first analyses. The bulk of the technical information is sorted and presented in the attached Appendices A-G.

The next chapter describes the experiment and the participating equipment. Chapter 3 discusses the analyses performed to date, and presents the important findings from the data obtained in the IRRE.
Chapter 4 ties these findings into the immediate needs of the world highway community by discussing the relevancy of the different findings to the objectives of the project. When possible, specific recommendations are made concerning future use of RTRRMSs. Recommendations are also made regarding further analysis of the IRRE data with the objective of the development of a universal RI, and validation of future roughness measuring systems.
This chapter describes the physical aspects of the International Road Roughness Experiment (IRRE). It summarizes the methods used to acquire roughness data, the ranges of road and operating conditions covered in the IRRE, and the testing procedure.

Participants

The experiment included the participation of 11 pieces of equipment, which are separated into three categories in this report: Response-Type Road Roughness Measurement Systems (RTRRMSs), direct profile measurement, and indirect profile measurement. 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 cumulative 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. Seven RTRRMSs participated in the IRRE:

1. Mays Meter Systems. Three RTRRMSs were provided and operated by the Brazilian Transportation and Planning
Company (GEIPOT). These consisted of Chevrolet Opala passenger cars equipped with Mays Meters, manufactured by the Rainhart Company 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 Bump Integrator (BI) unit.** This instrument was produced and operated by the Transport and Road Research laboratory (TRRL) from the United Kingdom [9]. It was installed in a Chevrolet Caravan, which is a station wagon from the same automotive family as the Opala used for the Mays Meter systems.

3. **A NAASRA Roughness Meter.** The instrument was provided by the Australian Road Research Board (ARRB) [14], and operated by the research team from TRRL. It was installed in the same Caravan station wagon as the BI unit, and all measures made with the NAASRA and BI units were made simultaneously.

4. **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.
a. Bump Integrator Trailer

b. BPR Roughometer made by Sciltest, Inc.

Figure 1. Two RTRMSs Based on the BPR Roughometer Design.
5. **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 1b) [15].

Normal measurement speed for the two trailers is 32 km/h (20 mph). A standard speed does not exist for the Mays Meter systems, although 80 km/h (50 mph) is the speed recommended by the manufacturer and widely used in the United States. Standard speeds in the ICR project were 80, 50, and 20 km/h, although in actuality little data were collected at 20. Standard test speeds for the NAASRA Meter are 50 and 80 km/h.

**Direct 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 apart.

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 50 cm, a trained crew of three can survey both wheel tracks of two 320 m test sections in an eight-hour working day.

The second method used in the experiment is based on an experimental instrument being developed by TRRL—the "TRRL Beam"—that is shown in Figure 3. The horizontal datum is provided by an aluminum beam three meters in length. The ground-to-datum measures are made with an instrumented assembly that contacts the Beam on precision rollers. To operate the device, the Beam is leveled by an adjustment at one end, and the sliding assembly is moved from one end of the Beam to the other.
Figure 2. Rod and Level Survey of Longitudinal Profile.
Figure 3. Measurement of Longitudinal Profile with TRRL Beam.
The moving assembly contains a microcomputer that digitizes the measures at pre-set intervals of 10 cm 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.

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

The General Motors Research (GMR) Profilometer (also called a Surface Dynamics Profilometer), manufactured by K.J. Law, Inc., of Farmington, Michigan, uses an accelerometer to provide the reference datum [17]. The datum-to-ground measure is made by a follower wheel instrumented with a potentiometer. The signal from the accelerometer signal has no meaningful information at very low frequencies that correspond to long wavelengths, therefore the "profile" signal is intentionally filtered to remove the very low frequency content. The result is intended to be a signal with the same wave number amplitude content as the true profile for wave numbers corresponding to frequencies above the filter frequency at the test speed.

The GMR Profilometer had not been in use for several years before the IRRE and as a result, considerable effort was spent preparing it for the IRRE. The effort was justified by the need to obtain profile measures on the smoother sections with smaller measurement intervals and better resolution than was possible with the rod and level method. Another reason was that the IRRE offered a chance for side-by-side comparison between the profilometer and the rod and level method, to establish a roughness range over which the profilometer results are valid. 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 half of the sections, although the roughness range covered was probably already beyond its capabilities. Measurements made with the profilometer were made much later than most of the others. The combination of limited time and limited computer facilities made the complete
processing of all profilometer measurements impossible. Early analyses of the TRRL Beam data were promising, so the decision was made to stop all work involving the profilometer to concentrate on other tasks. No further mention of the GMR Profilometer is made in this report.

The second profilometer, made by the French Bridge and Pavement Laboratory (LCPC), is called the Longitudinal Profile Analyzer (APL) trailer shown in Figure 4. The trailer 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 been designed to allow measurement with fidelity for frequencies up to 20 Hz [18]. The wave number band 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 in conjunction with one of two standard analyses, called the CAPL 25 and the APL 72 [10,18]. 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).

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.
a. APL Trailer

b. Inertial Reference of APL Trailer.

Figure 4. The APL Profilometer.
Design of Experiment

Forty-nine (49) test sites were selected in the area around Brasilia. Thirteen of these were asphaltic concrete sections; 12 were sections with surface treatment; 12 were gravel roads; and the remaining 12 were earth roads. All of the candidate sections were rated with a Mays Meter-based 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 Mays Meter RTRRMS. All sections were fairly homogeneous over their lengths and 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 Mays Meters 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 sections were to be profiled.

4. Some of the necessary combinations of roughness/surface type/homogeneity/geometry/traffic density/location were difficult to find. The difficulty was increased with test length.
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. The APL 72 measurements were obtained for the 200 m section completely contained within the 320 m test section, whereas the APL 25 output was the mean of the 12 APL values obtained over the test section.

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 in the United States, and is recommended by several manufacturers of RTRRMS instruments. 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 levels of 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.

Because of the relatively short section lengths, several measurements were made with the RTRRMSs to improve precision and demonstrate repeatability. 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.

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). At the same time, 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 sequence of testing is included as Appendix H. 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 equipment, 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. Occasional 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 required that the last 10 minutes of driving be over unpaved roads, so that the RTRRMSs were never operated "cold" on any surface type. An exception to this was the BPR Roughometer, which was towed only on the actual test sites to minimize the damage that seemed to occur on a daily basis.

The direct 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 proceeded 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 a 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

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 section was profiled by the rod and level survey method at least once, yielding 1,282 elevation measurements for every one of the 70 section profiles obtained. LCPC provided profiles as measured with the APL trailer. In the APL 25 configuration, 97 of the 98 wheel tracks were profiled, yielding 1,281 numbers per wheel track. In the APL 72 configuration, each wheel track was described by a series of 6,401 digitized values. The experimental Beam from TRRL was used on 28 wheel tracks, providing 3,201 measures for each. In addition, all 49 sections were rated subjectively by 18 panel members.

All of the data had to be converted to a format suitable for computer analysis and checked for errors. The achievement of this task is one of the major accomplishments of the project. Three computer systems were employed in parallel to prepare the data for analysis. 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 for the project. The electronic analog signals produced by the APL trailer were digitized for plotting with a system based on a European ITT microcomputer that is compatible with the Apple II made in the United States. Programs were prepared to store the APL data on the floppy diskettes used by the Apple.
The analysis of all this data included five distinct tasks:

1. Correlation of response-type road roughness measurement systems (RTRRMSs) with each other. This study is straightforward: the RTRRMS data cover seven instruments, four surface types, up to four measurement speeds, and 12 or 13 test sites in each category.

2. Computation of profile-based roughness numerics. Profile signals that are entered on a digital computer consist of a large number of individual sampled elevation values that must be processed to yield a roughness numeric. Several processing methods are in use and have been proposed as candidates for defining an international standard roughness scale. Two of these that are widely known were applied to all of the profile signals obtained by the different methods. The first is the QI analysis, used in Brazil, that was developed as part of the ICR project and is based on two RMSVR statistics calculated for different baselengths. The second is the RRV developed for the NCHRP in the United States that is based on a Quarter-Car Simulation (QCS). APL roughness numerics were provided by LCPC based on the measures made by the APL trailer.

3. Correlation of profile-based numerics with RTRRMSs. The calibration of a RTRRMS is accomplished by regressing measures obtained on control road sections with corresponding reference measures, obtained by profiling the control sections and processing the profiles according to a standard method. In devising a good calibration method, the influences of variables that are known to affect both measures must be considered.

4. Comparison of profile measurement methods. No profile measurement method is without error, but some methods are superior to others when a certain analysis procedure is required. Five independent profile measurements were made
in the experiment; at the time this Draft Report was prepared, measures from four of the methods had been processed (the GMR Profilometer was excluded). Although direct comparisons between profiles (point for point, PSDs, etc.) are desirable, the time constraints for the Report made it necessary to use RTRRMs numerics obtained with each "profile" to indicate the reproducibility of the measures and the limitations of the different profiling methods for RTRRMs calibration.

5. Comparison of subjective ratings with other measures.
In some applications, the relationship between roughness measurements and opinion of the roughness by the using public is important. The panel ratings obtained for the test sections can shed light on these relationships.

Prior to analyzing the RTRRMS data, the "raw" measures recorded in the field were averaged and rescaled to the same engineering units to facilitate direct comparisons between the different systems. The actual measure is inevitably a number of counts produced in a test. These counts were rescaled by the amount of suspension deflection in either direction needed to produce one count, and divided by the length of the test section to produce a measure of vehicle response that has the units: meters of suspension deflection accumulated in one traveled kilometer \( (\text{m/km} = \text{slope} \times 1000) \). Users of this type of measure often refer to it by the _nits used, such as "counts/km," "inches/mile," or "\( \text{mm/km} \)." A more technical name is "Average Rectified Slope" (ARS) [19], which is used in this report, while recognizing that the variable whose slope is being rectified and averaged is difficult to visualize.

The two RTRRMSs that are based on the BPR Roughometer design (see Figure 1) obtained measures of the left- and right-hand wheel tracks separately. The two ARS values were averaged for each section for comparison with the single measures obtained from the RTRRMSs based on passenger cars.

Appendix B contains all of the data from the RTRRMSs, and also presents the summary results obtained by averaging repeat runs. When comparing measures from RTRRMSs over more than a single test speed, a
statistic called Average Rectified Velocity (ARV) has been proposed as a more useful roughness measure that is based on the raw reading of a RTRRMS [7,20]. Therefore, ARV values of all the RTRRMSs are also presented in Appendix B. Finally, Appendix B contains the QI and RARV values obtained by processing profiles (as described later in this chapter).

Correlation of RTRRMS Numerics

A calibration procedure that can be used with different RTRRMSs can have only limited effectiveness 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. Since the equivalence between measures based on separate RTRRMSs obtained with an independent calibration is always "second best" to a direct side-by-side comparison of the RTRRMSs, the correlation study was performed to determine the highest levels of agreement that are possible. This provides a standard that can be applied later for evaluating different candidate calibration methods.

In this correlation exercise, reported in Appendix C, 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. A number of effects and interactions were examined.

1. **Comparison of Measures Made at Different Speeds** — The most important finding of this study is that 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 a Mays Meter system is typically operated at higher speeds. Figure 5 shows that the measures obtained from the BI trailer at 32 km/h are correlated with those of the Mays Meter at 50 and 80 km/h, and that
Figure 5. Comparison of RTRRMS Measures Taken at Different Speeds.
different regressions are required for different surface types. In contrast, Figure 6 shows a single relationship between the two instruments when the measures are made at the same speed of either 32 or 50 km/h. Besides showing a more simple relationship, the amount of scatter is greatly reduced.

2. **Effect of Including Different Surface Types** -- Separate regression equations are usually not needed when the measures of two RTRRMSs are made at the same speed, while different regression equations are required if the speeds differ.

3. **Effect of Including Different Speeds** -- Even when comparing measurements made by different RTRRMSs at the same speed, several "standard" speeds could be required, depending on the intended uses of the measurements. A separate regression equation is usually needed for each speed when the measures are expressed in the form of an ARS (m/km, mm/km, in/mi, etc.). That is, the equation used to "convert" BI readings taken at 50 km/h to Mays Meter readings at 50 km/h is not valid for converting measures made by the BI at 32 km/h to Mays Meter measures made at 32 km/h. The errors are largest on smoother sections.

4. **Effect of Converting Measures to ARV** -- When the counts obtained from the roadmeter instruments are converted to "accumulated deflection per unit time," the result is the Average Rectified Velocity (ARV) of the suspension. Given the configuration of most roadmeters now in use, ARV is most easily calculated by multiplying the ARS numeric by the test speed, with an optional units conversion (see Appendices C and F for details). When data are taken at just one speed, the choice between ARS or ARV as a roughness measure is irrelevant: 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
Figure 6. Comparison of RTRRMS Measures Taken at Identical Speeds.
circumstances causing the excitation. On the other hand, ARS measures taken at different speeds are not comparable because the variable whose slope is being measured has a definition that depends on speed. This speed effect confounds with nonlinearities in the vehicle and roadmeter, requiring the separate calibration curves for each speed noted above (or alternatively, the resignation to accept larger amounts of scatter and less accuracy in the calibration). Figure 7 shows that when all of the measures are expressed as ARV, a single relation can be used for all speed/surface type combinations.

5. Limitations of Different RTRRMSs -- None of the speed/surface type conditions seemed uniformly good or bad when comparisons were made between RTRRMS measures made at the same speed. Most of the instruments were capable of testing almost the full roughness range available. Still, the individual RTRRMSs did show different 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.

The Mays Meter systems were operated at the 80 km/h test speed on all surface types, although the operators did not run them on the four roughest test sections at this speed. As a result, the highest levels of vehicle excitation occurred at 50 km/h, with ARV levels being as high as 390 mm/sec. This roughness limit could also be measured with most of the other RTRRMSs, even though none of the others were operated at speeds over 50 km/h on most of the sections.

The BI trailer was never operated at the 80 km/h test speed, but was able to run on the roughest section at 50 km/h. Given the ARV results from the Mays Meters, the 50 km/h speed limit cannot be attributable to the level of vehicle excitation.
Figure 7. Comparison of RTRRMS Measures of ARV Taken at Identical Speeds, Over a Range of Speed and Surface Conditions.
The vehicle equipped with the NAASRA meter and a BI unit was not operated at 80 km/h except on 11 of the asphaltic concrete sections. Nearly all of the measurements obtained from the two roadmeters 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 Mays Meters and a simulated RTRRMS (using profile measurements as input) were higher for the NAASRA meter than for the BI meter.

6. **Effect of Different Roadmeter Instruments** — Figure 8 shows that when the results of the BI and NAASRA roadmeters were rescaled to the same physical units of ARS (m/km = slope x 1000), the two gave readings that were virtually interchangeable. There were no PCA meters in the IRRE, but a similar correlation experiment performed in the United States showed that PCA meters can also be used to measure ARS and ARV by eliminating the complicated PCA data reduction process [7]. Because different manufacturers of roadmeters 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.

7. **Effect of Individual Wheel Track Roughness** — Theoretically, the measures obtained from two-track vehicles such as an automobile are best correlated to the measures obtained from single-track trailers if the trailers are towed over each wheel track and the ARS numerics averaged. The empirical correlations between these averages and the measures from the two-track RTRRMSs were excellent, being as good as the correlations between 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.
Figure 8. Comparison of ARS Measurements from Two Meters in One Vehicle.
Computation of Profile-Based Numerics

Four candidate roughness statistics were tested as a calibration reference for RTRRMSs:

1. **QI** — The roughness standard used in Brazil, developed during the ICR project [5], is based on the RMSVA summary statistic calculated from a measured profile. RMSVA is the Root-Mean-Square (RMS) value of a signal that is the simulated response of a rolling straight-edge, sometimes called a Mid-Chord Deviation (MCD), as shown in Figure 9. When the baselength is very short, the signal approximates the second derivative—the Vertical Acceleration—of the profile [11]. The baselengths used for road roughness characterization result in a signal that only approximates the true VA for very long wavelengths (100 m and longer), so in a sense the name RMSVA is deceptive. QI is defined by the equation:

\[
QI = -8.54 + 6.17 \times \text{RMSVA}(1.0) + 19.38 \times \text{RMSVA}(2.5)
\]

where RMSVA (1.0) and RMSVA (2.5) use baselengths of 1.0 and 2.5 meters and have units: slope x 1,000,000. The baselengths are equivalent to rolling straight-edges with chord lengths of 2.0 and 5.0 meters, respectively. Appendix E presents a complete technical description of QI, its development, its wave number sensitivity, and the QI data obtained from the different profile measurements.

2. **RARV** — 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, and using that "simulation" to calculate the response of the reference from profile measurements. The model, shown in Figure 10, defines that simulation and replicates the two essential resonances shared by all vehicle-based RTRRMSs. Because it has just one wheel, it is called a Quarter-Car Simulation (QCS), although the effects of both wheels on an axle are included by averaging the profiles of the two wheel tracks prior to input to the simulation. The model parameters
\[ \text{MCD} = \frac{Y(x+B) + y(x-B)}{2} - Y(x) \]

"VA" = 2 × MCD/B^2

"RMSVA" = \( \frac{1}{L} \int_0^L (VA)^2 \, dx = \frac{1}{N} \sum_{i=1}^{N} VA_i^2 \)

Figure 9. Geometric Interpretation of RMSVA.
\[ M_s \ddot{Z}_s + C_s (\dot{Z}_s - \dot{Z}_u) + K_s (Z_s - Z_u) = 0 \]

\[ M_t \ddot{Z}_s + M_u \dot{Z}_u + K_t Z_u = K_t Z \]

\[
\begin{align*}
K_s / M_s &= 62.3 \text{ l/sec}^2 \\
K_t / M_s &= 653 \text{ l/sec}^2 \\
M_u / M_s &= .150 \\
C_s / M_s &= 6.00 \text{ l/sec}
\end{align*}
\]

\[ \text{RARV} = \frac{1}{T} \int_0^T | \dot{Z}_s - \dot{Z}_u | \, dt \]

\[ T = \text{Measurement time (sec)} \]

\[ = 3600 \cdot \frac{L}{V} \]

\[ L = \text{Road length (miles)} \]

\[ V = \text{Speed (mph)} \]

---

**Figure 10. Quarter-Car Simulation Model.**
were selected 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 [7]. The simulated response is summarized by the ARV, called Reference ARV, or RARV. A further discussion of the RARV statistic is presented in Appendix F, along with computational details and the RARV values obtained for the test sections at the four simulated test speeds.

3. CAPL 25 -- LCPC determines the quality of newly constructed pavements by towing an APL trailer over the section 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). In a sense, this analysis is not truly profile-based, because it depends on the unique response properties of the APL trailer. However, the properties are claimed to be so consistent from trailer to trailer, due to the elimination of most sources of variation in less sophisticated RTRRMSs, that the APL trailer could conceivably be characterized mathematically and its results predicted from profile measurements by other methods such as rod and level. Correlations between CAPL 25 measures and those of the RTRRMSs were not good, however, due to time constraints and the objectives of the Report, no attempt was made to obtain estimates of the CAPL statistic from the other profile signals. Appendix G describes the sensitivity of the CAPL 25 to wave number, presents the data provided by LCPC, and discusses the reasons for the poor correlation with the RTRRMSs.

4. APL 72 Wave Band Indices -- LCPC has developed this analysis method to summarize the present condition of roads. Two APL trailers are simultaneously towed at a speed of 72 km/h, with one trailer following each wheel track. The signals are played into six electronic band-pass filters (three per signal) to separate the original signals into three band-limited signals. The filtered signals are squared and integrated, to obtain mean-square values calculated over road sections that are 200 m in length. The mean-square values for the right- and left-hand wheel tracks are summed, and a table is then used to assign
a rating from 1 to 10 for that section of road. The filters separate the profile into three frequency bands, and a separate table is used for each band. The result is that the road is described by three quality indices, for short, medium, and long wavelengths. In theory, the response properties of the APL trailer play no role in determining the three indices, because the frequency response of the trailer is broader than the bands left after filtering. Thus, the same analysis could be applied to signals obtained from other profiling methods. However, because the correlations between the APL 72 indices and the RTRRMSs included in the IRRE, were not good, further studies of the APL 72 analyses were not justified within the objectives of the Report. Further details concerning the APL 72 analyses are presented in Appendix G, along with the indices obtained for the test sections in the IRRE.

Correlation of Profile-Based Numerics with RTRRMS Numerics

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. Details of the analyses are presented in Appendices E, F, and G. The findings are summarized for each of the proposed methods:

1. **QI** — 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. This finding was not unexpected because QI was originally based on a QCS with a simulation speed of 55 km/h (see Appendix E for details). In general, separate calibrations are sometimes needed for different surface types. (Example calibration curves are shown in Appendix G.) At 50 km/h, the correlations between QI and the ARS measures from the RTRRMSs are very good for three of the surface types, having approximately the same quality as the direct correlations between RTRRMSs. On the sections with surface treatment, however, correlations with QI are significantly lower; for every RTRRMS/speed combination, a separate calibration would be needed for surface treatment roads.
Correlations are always high on the asphaltic concrete sections, but other correlations are not as good at speeds other than 50 km/h.

The QI scale can be an effective and accurate reference for calibrating RTRRMSs, but the calibration effort needed is substantial because separate transformations are needed for the different surface types. The fact that RTRRMSs should only be operated at a single speed of 50 km/h might be a deterrent for those users of RTRRMSs who have experience with different test speeds. (While RTRRMS data taken at speeds other than 50 km/h can, of course, be correlated with QI, the estimates of QI made from the RTRRMS measures will have greater error.)

2. RARV — The RARV roughness statistic (the measure obtained from a simulated reference RTRRMS) is not a unique value for a given road surface, but will vary with speed just as a vehicle sees different roughness at different speeds. Not all RARV values could be calculated for the speeds of 20 and 32 km/h due to profiling limitations described below, but the results that were obtained indicate good agreement with the RTRRMS data at these speeds. Correlations between RARV and the ARV measures obtained from the RTRRMSs are usually very good at all speeds and on all surface types, with the one exception of the 80 km/h data from the surface treatment sections. Overall, correlations between RARV and the RTRRMSs were higher than with the other candidate standards.

Figures 11 and 12 show sample calibration equations that are each calculated for just one speed/surface type combination and plotted only over the roughness range covered by the measures (inference space). With most of the RTRRMSs, better accuracy can be obtained by using separate equations for different speed/surface type conditions, although in the best of cases—the BI trailer—a reasonable calibration can be obtained with just two equations: one for paved surfaces at any speed, and one for unpaved surfaces.

If the RARV is used as a reference, the measurement speed is still a variable; a given section of road can be assigned a range of roughness values, each corresponding to a different (simulated) measurement speed. For the purpose of standardizing roughness measurement, a logical step
Figure 11. Calibrations of BI Trailer to Reference.
Figure 12. Calibrations of Mays Meter to Reference.
would be to select one or more measurement speeds to be used with the 
QCS and for the RTRRMSs that are used to estimate RARV. Given the fact 
that roughness data are used for a variety of purposes, a single "best" 
speed would compromise the usefulness of the data for everyone except 
those, for whom that speed is optimal. A standard speed of 80 km/h is 
reasonable for ride quality-related work that is typical of developed 
countries. On the other hand, it is not recommended for engineers in 
developing countries to base their roughness measurements on estimates 
of what the ride quality would be at 80 km/h if the roads being studied 
are normally used at speeds no greater than 30 km/h. For this reason, 
a roughness standard based on RARV—or a similar statistic that includes 
a speed effect—will also require that a few representative speeds be 
standardized.

Even though RARV is demonstrated here as a reference that can 
be used for any surface type or speed, the agreement between RARV and 
the ARV measures of the RTRRMSs is not as good as the agreement between 
the RTRRMSs themselves. This indicates that the RTRRMSs are responding 
to something that is missed by the QCS, or vice versa.

3. CAPL 25 — Correlation between the CAPL 25 and the RTRRMS 
is not good for any surface type or test speed. The reason is 
that the wide band displacement response of the CAPL 25 transforms 
to a narrow wave band response to the road slope, which is seen 
by RTRRMs. Therefore, the correlation is mainly dictated by the 
correlation between the "roughness" contained in the wide band 
slope excitation to RTRRMs (that is dependent on test speed) and 
the narrow band affecting the CAPL 25.

4. APL 72 Wave Band Indices — None of the three indices would 
make an acceptable reference for calibrating RTRRMSs. The long wave 
index is almost completely uncorrelated with the measures of the RTRRMSs, 
except on asphaltic concrete surfaces. The medium wavelength index is 
correlated to some extent with the RTRRMS measures, but the degree of
correlation is much lower than the correlation between two RTRRMSs. The short wavelength index has a problem in that the available roughness range is not sufficient to discriminate among unpaved roads (most of the unpaved sections had an index value of 1 on the scale of 1 to 10 which was developed for paved roads). It appears that if the range were extended, the correlation between the RTRRMSs and the APL 72 short wavelength would be the best of the three. Further development here is unwarranted, however, because the RARV is already proven as a much better calibration reference.

The APL 72 numerics are in essence not compatible with the numerics obtained with RTRRMSs. It might be argued that they are more useful to the pavement engineer than the ARS or ARV measure obtained with a RTRRMS, but the measures are so dissimilar that there is little advantage in trying to estimate an APL index from a RTRRMS measure.

Comparison of Profile Measurement Methods

The ability of four profile measurement methods to obtain signals with the resolution, accuracy, and bandwidth needed to provide the candidate roughness standards was evaluated theoretically through analyses of the methods, and experimentally by comparing the QI and RARV numerics obtained from each profile signal. The rod and level surveying procedure as practiced in the IRRE was established to obtain QI estimates with minimum effort. The resolution of 1.0 mm and the measurement interval of 50 cm had been found to give acceptable accuracy in an earlier study [5]. The question of resolution had been addressed in the context of the RARV calculation, and the level of 1.0 mm was found to be acceptable for the roughness range covered in the IRRE, although better resolution is needed on very smooth roads that can be found in the United States and other countries [21]. Profiles measured at 10 cm intervals in the ICR project were used to determine the effect of sample interval on the RARV calculation. It was found that the RARV for 50 km/h was slightly lower when the interval is 50 cm, and that RARV estimates at lower speeds are not valid for all spacing. The TRRL Beam data were theoretically valid for all RARV calculations needed, and results at
50 and 80 km/h agreed with those obtained from the rod and level. The rod and level and Beam are shown to give more-or-less equivalent results, although the results from the TRRL Beam tend to be slightly and consistently higher. The bias was so slight that it was neglected in analyzing correlations between RARV and RTRRMSs.

The APL trailer is claimed to respond accurately to profile excitation over the frequency range of 0.5-20 Hz, which corresponds to a wave number band that is dependent on the towing speed. For the APL 25 towing speed, the wave number band is theoretically suitable for determining the RARV at simulated speeds of 20 and 32 km/h. The results obtained did not agree acceptably well with the results based on the TRRL Beam, for reasons that are not known. When operated at 72 km/h, the wave number band is theoretically adequate for the RARV calculations for simulated speeds of 50 and 80 km/h. Yet the RARV estimates calculated from the APL signals did not agree with the RARV values obtained from the rod and level and the TRRL Beam well enough to validate the use of APL RARV values for RTRRMs calibration at this time, although the APL potential deserves further consideration.

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. 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, which also contains a sample rating form, identification of the panel members, analysis procedures, all of the individual ratings before and after "normalization," and illustrations of correlation with candidate calibration references. 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 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. The appendix also presents scatter plots of SR against various RTRRMS measures and the proposed candidate calibration statistics. The relations between SR and measures of the RTRRMSs were not formally determined through a comprehensive regression analysis because such an effort was beyond the scope of the project. Because the relationships were visibly non-linear, discussions of quality of prediction and correlation are based loosely on visible examination of plots and on linear correlation coefficients.

An interesting finding is that the measures obtained from the RTRRMS agree equally well with the SR numerics regardless of the RTRRMS measurement speeds (20, 32, and 50 km/h), even though the SR rankings are based on travel speeds of 50 km/h for unpaved sections and 80 km/h for paved roads. Agreement was poorer between SR and the RTRRMS results on the roads with surface treatment than those with other surface types.

The QI and RARV roughness measures agree well with SR, although different relations appear necessary for paved and unpaved surfaces. The highest correlation between SR and a roughness measure on the roads with surface treatment is for RARV with an associated simulated measurement speed of 80 km/h. The second highest is for QI. This is interesting because the worst agreement between these candidate roughness standards and the RTRRMSs is on the surface treatment sections. The RTRRMSs seem to respond to something present on these sections that do not cause the same sensitivity in the QI, RARV, and SR evaluations. Comparisons of the SR data with the APL numerics show correlations with some of the APL roughness measures on paved roads, that are comparable to that with the RTRRMs.
CHAPTER 4
CONCLUSIONS AND RECOMMENDATIONS

The International Road Roughness Experiment (IRRE) was motivated by present difficulties in exchanging roughness information at the international level. Hence, the primary objectives of the IRRE have been to:

1) Establish the correlation (or equivalence) between road roughness measurements being made with various RTRRMSs in use at this time throughout the world.

2) Identify a standard road roughness statistic to which measurements in different countries can be calibrated.

In this chapter, the findings from the IRRE will be discussed in the context of the conclusions reached and recommendations that can be made.

Correlation Between RTRRMSs in Use Today

In the IRRE, five types of RTRRMSs were assessed to various degrees. The Brazilian Mays Meter systems, the Bump Integrator (BI) Trailer, and the BPR Roughometer were tested in states representative of their normal operating condition. In addition, a BI meter and a NAASRA meter were tested as installed in a Brazilian vehicle. The conclusions with respect to the comparative performance of these various devices are subject to certain limitations, because the IRRE examined the performance of these RTRRMSs over a brief period of time on Brazilian roads. No attempt was made to establish how the performance of these systems may have changed over their lifetimes; hence, the quantitative relationships observed today may differ from those that existed in the past. The qualifier that the comparisons are limited
to Brazilian roads is not as strong a concern in every case. It is believed that the asphaltic concrete roads in Brazil are characteristically similar to such roads elsewhere in the world, and thus the comparisons would probably hold in other locations. On the other hand, it is not known to what degree the surface treatment and the unpaved roads in Brazil compare to those elsewhere. Therefore, quantitative comparisons shown for these surfaces may not be as accurate for application in other locations.

The BI meter and the NAASRA meter installed in a Brazilian vehicle are compared quantitatively. However, comparisons between these two systems and other RTRRMSs cannot be applied when the meters are installed in other vehicles elsewhere in the world.

The comparative performance of the RTRRMS systems observed in the IRRRE can be summarized as follows:

1) Roughness Meters -- The various roadmeter instruments (i.e., the meters - Mays Meter, BI meter, and the NAASRA meter) are functionally equivalent in their measures of vehicle dynamic motion. Despite their cosmetic differences, they all measure suspension travel in a comparable fashion. Thus the choice of which type of meter is used in an RTRRMS is of little direct influence of the ability to measure roughness with these devices. It may be noted that the BI meter produced unexplained erratic readings at the speed of 80 km/h, and that the Mays Meters that were tested had been modified to permit them to measure higher roughness levels than would be possible with the commercial meter system.

2) RTRRMS Systems - All RTRRMS systems (i.e., the Mays Meter cars, the BI trailer, and the BI/NAASRA car) measured road roughness in qualitatively similar fashions. Though the measures obtained are not compatible unless they are re-scaled to a reference, they are in agreement in ranking the roughness of all roads tested, for all surface types, when a single measurement speed is used. When the measurements of the right- and left-hand wheel tracks obtained with the single-wheeled trailers were averaged, the resulting numerics agreed with the
measures obtained from the RTRRMSs based on passenger cars in ranking roads by roughness. Thus, the choice of a particular RTRRMS configuration does not appear critical. The most erratic results were obtained from the BPR Roughometer, which also had the most mechanical problems during the IRRE.

3) Speed Effects - The good agreement between measurements by two different RTRRMS systems holds true only when the tests are performed at the same speed. When the RTRRMSs are operated at different speeds (i.e., a BI trailer at 32 km/h and a Mays Meter system at 80 km/h), the systems will agree in their ranking of roughness only when all of the roads are of the same surface type. Further, the correlation between measures deteriorates as the difference in measurement speed increases. When comparing measures from two RTRRMSs used at one of several speeds (i.e., BI at 32 vs. Mays Meter at 32 km/h and BI at 50 vs. Mays Meter at 50 km/h), the amount of agreement depends on whether the roughness is expressed in terms of an Average Rectified Slope (ARS) or an Average Rectified Velocity (ARV). When measurements are expressed as ARS values (mm/km, inches/mile, etc.), the relationship between measures are generally different for each test speed. However, when the measurements are expressed in ARV units (ARV = ARS x V = mm/sec, count/min, etc.), the relationship between devices is usually the same regardless of speed. Thus, using the ARV, the correlation relationship obtained at one speed will usually apply at another.

International Roughness Index

The need for an International Roughness Index (IRI) is a reflection of the need to have a common scale on which to share data throughout the world relating road roughness to its impact on highway use and maintenance. The IRI must be defined in terms of both a standard scale and the procedures by which roughness measurement equipment can be calibrated to that scale. A rigorous approach would suggest that the IRI should be selected from a number of candidates on the basis of which demonstrates the closest relationship to the variables of
interest—comfort, road users' costs of various types, and safety aspects. At this time, empirical evidence does not exist to suggest what measure of roughness is most closely related to those effects. Studies of such relationships have been based on one (existing) roughness measurement, which is generally selected on the basis of convenience and previous experience of the investigators.

In the absence of such data, the logical alternate criterion for selection is: What measure is most commonly used throughout the world? Without question, the most popular measure is the output of a RTRRMS based on dynamic motions in the suspension of a passenger car-type of vehicle. This measure is the most prolific of all the potential types available at this time. It is obtained with the Mays Meter cars and trailers (as well as most PCA Meters [7]) popular in the United States, Brazil, and other South American countries; it is equivalent to the measurements based on the TRRL BI trailer used in road studies in Kenya, the Caribbean, and India; and it is equivalent to the Australian road roughness measurements based on the NAASRA vehicle/meter system. Thus, by default, the IRI must logically be based on the ARS (or the equivalent ARV) roughness statistic obtained from RTRRMSs.

This roughness scale is not fully defined without statement of the speed (or speeds) at which tests are performed. Speed has been shown to have a significant effect on the roughness measured on a road in this study and many others. As long as measurements are made at different speeds, they cannot be compared directly in any meaningful manner. While a small correlation experiment can always be performed to obtain empirical regression equations to estimate measurements that would have been made by a RTRRMS at a different speed, the regressions are valid only for the RTRRMS used to gather data in the correlation experiment. Also, the equations only apply for the surface types represented in the experiment.

From the highway engineer's perspective, it is desirable to have one standard speed, so that roads can easily be compared on the basis of a single roughness scale. However, there is not universal agreement among highway engineers as to what single speed is best. From the vehicle
dynamicist's point of view, roughness should be measured at the prevailing traffic speed to ensure that it most accurately reflects the dynamic inputs to road-using vehicles. Lastly, from the perspective of public opinion of "rideability," speed is not a critical parameter (i.e., the subjective ratings of "rideability" obtained in this experiment on either the "paved" or "unpaved" road categories had correlations with roughness that were more-or-less equivalent for all speeds). At this juncture, there is no one choice that would be acceptable to all users, nor any expectation that a suggested speed would be adhered to by all users. The problem is particularly accentuated by the fact that the popular BI trailer is normally operated at 32 km/h, which is unacceptably slow for the users of alternative RTRRMSs.

Even though no single speed would be a solution to the problem, progress would be made by defining a limited number of standard speeds. At this time, the speeds of 32, 50, and 80 km/h are natural choices that would be compatible with all RTRRMS systems in use today.

In order to deal with the incompatibility of measurements made at different speeds, correlations between measures made at these three speeds should be conducted as a routine part of any significant study dealing with road roughness. That is, when any of the above speeds is selected as the standard test speed for a study, correlations to measurements at the other speeds should be performed for the road networks under study, with the RTRRMS systems used for routine measurements. This allows the investigators to estimate what their results might have been had an alternative speed been used, and the estimated results can be then compared directly with results obtained in projects elsewhere in the world in which the alternate test speed was chosen. For example, the data obtained in the IRRE can be used to determine such correlations for Brazilian roads, so that estimates can be made of cost equations developed in the ICR project, assuming that the Mays Meter roughness data had been obtained at 32 km/h (as were data obtained in other cost studies) rather than at 50 and 80 km/h. This approach is a compromise, allowing maximum accuracy within a project, while still allowing comparisons.
between projects at some expense in precision when the projects use different test speeds.

As a result of the IRRE, it has been demonstrated that the best calibration reference for RTRRMSs is a direct measurement of the road profile processed via a Quarter-Car Simulation (QCS) to obtain either a Reference ARS (RARS) or Reference ARV (RARV) measure of roughness. The rod and level and the TRRL Beam survey methods, as implemented in the IRRE, are acceptable methods for measurement of the profile. The QCS based on the NCHRP reference vehicle proved to be the most effective means for processing the profile information to obtain a calibration standard for roughness. This, in effect, defines the standard scale for the International Roughness Index. The minimum conditions for calibration are obtained when the Index is expressed in ARV (rather than ARS) units. These conditions are:

- Separate calibrations were required for paved and unpaved roads at speeds of 50 km/h and less.
- Separate calibrations were necessary for asphaltic concrete and surface treatment roads at 80 km/h.

The QI scale, as used in Brazil, proved to be less effective as a calibration reference. It has the same limitations as listed above for the QCS, but also requires separate calibrations for surface treatment roads, separate calibrations for each speed, and does not yield correlations of the same quality as possible with the RARV. The limitations derive from differences in the wave number sensitivity of the QI numeric relative to the typical RTRRMS.

Although QI is not currently the most effective calibration reference, it is based on an analysis (RMSVA) that is simple, easily understood, and therefore worthy of further consideration and development. The RMSVA analysis lends itself to a special purpose "profilometer" that could eliminate the need for measuring profile when the use of the profile is calibration of a RTRRMS. Such a device would need only the same cost/sophistication level as the roadmeters used in the RTRRMSs.
A major issue that needs to be addressed in further work is whether RMSVA can be adequately calculated from direct profile measurement (rod and level, TRRL Beam) and from inertial profilometers.

The APL 25 and 72 roughness numerics showed poor correlation with the RTRRMS measures for most conditions, therefore these numerics are unacceptable as calibration references. One of the numerics—the APL 72 short wavelength index—did not cover a roughness range wide enough to discriminate among unpaved roads, and therefore a change in the APL 72 scale is necessary in order to meaningfully characterize all kinds of roads that exist throughout the world. These findings reflect the fact that the APL analyses were developed with specific objectives in mind for use by pavement engineers in routinely classifying French paved roads, rather than for calibration of RTRRMSs.

In this discussion, hardware devices have not been considered as calibration references. The BI trailer (sometimes treated as a reference in itself) showed very good correlation with the RTRRMSs over the range tested, yet it has not been used at the 80 km/h speed common for many RTRRMSs. The findings of the IRRE cannot be used to verify or deny the ability of the BI trailer or any of the participating RTRRMSs to maintain consistent response properties with time and use; therefore, only profile-based roughness standards are considered.

**Recommendations**

Based on the findings to date that have derived from the IRRE, it is recommended that in future road studies, roughness measurements with RTRRMSs should be limited to measurements at speeds of 32, 50, or 80 km/h only, and correlations between speeds should be acquired as a routine part of the study. Any of the tested meter systems are acceptable, and may be selected on the basis of their compatibility with data acquisition requirements. The RTRRMSs used in the study should be routinely calibrated by correlation against reference roughness measurements on a series of surfaces; those reference measurements being obtained by measuring the profile (by rod and level or TRRL Beam methods) and processing the profile to obtain the RARV or RARS statistic from the NCHRP QCS (as detailed in Appendix F), using a simulation speed
equal to the measurement speed of the RTRRMS. The calibration should
cover the entire roughness range of interest, and separate calibration
equations should be derived for the different surface types covered in
the project. (The calibration equations may prove to be very similar
for different surface types; in the IRRE, only two calibrations were
required: one for paved roads and one for unpaved roads. This simpli-
fication should not be assumed for roads in all parts of the world
until it has been satisfactorily demonstrated.)

The RARV measure recommended is the most accurate of the candidates
that were tested. Yet, because it requires separate calibration equa-
tions for paved and unpaved roads, it is not responding to road profile
exactly the same as the RTRRMSs, for reasons that have not yet been
investigated.

Because there are still significant questions not answered by
this report, and because the IRRE generated a wealth of information,
only partially analyzed, further analysis of this unique data base is
recommended. Areas warranting further work follow:

- Many of the problems involve differing sensitivities of various
measurements on different surface types. The profile information for
these surfaces should be processed to provide Power Spectral Densities
(PSDs), so that the differences between surface types can be quantified.
In addition to this need, a plot of PSD is an excellent characterization
of road profile for use by other researchers.

- The data acquired with the GMR Inertial Profilometer should be
processed to evaluate its suitability as a profile measurement system
applied to calibration of RTRRMS systems.

- The measurements obtained with the APL trailer during the IRRE
should be given further analysis and scrutiny. Because of its simplicity,
the APL trailer appears attractive as a rugged, high-speed profiling
device potentially suited to the environment of less-developed countries.
Though the rod and level and the TRRL Beam are proven to be adequate profiling methods for the calibration of RTRRMSs, the effort required will always be a deterrent to the frequent calibrations that appear necessary with RTRRMSs. Thus the continuing development of rugged, high-speed profiling equipments should be encouraged. It is a concern that the poor correlation of the conventional APL numerics with RTRRMS measurements observed in this Experiment do not accurately reflect on its potential in this regard. Yet limited analysis of the APL data acquired in the IRRE by the LCPC indicates that correlation with RTRRMSs can be improved by the development of new APL numerics for this purpose (See Appendix G). Such further development is to be encouraged. In so doing, it is recommended that attention be given to the direct comparison of the APL profiles with those obtained with the rod and level and the TRRL Beam, to discover the reasons why the direct processing of the APL profiles to produce QI and RARV statistics did not yield better agreement with these other profiling methods.

-The limitations of the RARV in agreeing with the RTRRMSs should be investigated, and alternative vehicle parameters for the QCS (defining a more optimum reference vehicle) should be considered.

-The use of two or more RMSVA numerics to define a roughness standard should be investigated further because its computational simplicity is appealing and also because it could be measured directly with a properly designed instrument without the need for actual profile measurement. A single configuration can be reapplied for different RTRRMS speeds by defining the base lengths to be proportional to speed, thereby providing better calibrations at all of the recommended speeds. Because of some technical peculiarities of RMSVA (see Chapter 3), the ability of an inertial profilometer to produce the same RMSVA as a direct profile measurement must be established before an RMSVA-based roughness measure is standardized.
CHAPTER 5
REFERENCES


3. "Road User Cost Study in India." Reports published quarterly, Central Road Research Institute, New Delhi, India.


9. To be provided


16. To be provided


23. To be provided


